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WELCOME

It is a great pleasure for me to chair this year's Electronics Goes Green conference, the sixth edition since its inception in 2000.

Since the start of our conferences 20 years ago, there has been tremendous progress in terms of greater energy efficiency and less material used per function. The heterogeneous integration technologies of Fraunhofer IZM have helped to propel these gains, beyond the effects of Moore's Law on the semiconductor side.

Still, the total environmental footprint of electronics keeps growing. So the need for more environmentally compatible electronics has not diminished, nor can we stop exploring ways to employ electronics where they can be most helpful for our environment.

Circularity, digitalization, and carbon neutrality are the major developments that once again bring us together for our conference, now in a virtual format – and they are not ideas reserved for academic discourse alone, but ideas that cut to the core of our industrial activities.

As the new conference chair, and speaking on behalf of our teams at Fraunhofer IZM and the Technical University of Berlin, we are working hard to create a virtual format that brings our vibrant global community of green electronics experts together again, invites new players and friends into our circle, and keeps alive the spirit and sense of commitment from our past events.

We all sorely miss the opportunity to meet everyone in person. Despite this, we promise to make this a memorable event with lots of the networking opportunities that you expect from our conferences.

Prof. Martin Schneider-Ramelow

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A ECOPRODUCTS AND UPSTREAM TECHNOLOGIES

A.1 ELECTRONICS TECHNOLOGIES AND MATERIALS

A.2 (ECO)PRODUCTS: DATA CENTERS, NETWORKS, THE „INTERNET“

A.3 (ECO)PRODUCTS: MOBILE DEVICES

A.4 (ECO)PRODUCTS: MOBILITY, WHITE GOODS, AND MORE

B CIRCULAR MATERIALS AND RECYCLING SYSTEMS

B.1 MATERIAL RECYCLING, SORTING AND SEPARATION

B.2 CIRCULARITY OF PLASTICS

C.2 ASSESSMENT: LIFETIME, ROBUSTNESS AND CIRCULARITY METRICS

C.3 CIRCULAR SOCIETY VISION

D SOCIETAL PERSPECTIVE AND COMPLIANCE

D.1 ASSESSMENT: LCA, NON-LCA AND BEYOND LCA

ISBN 978-3-8396-1659-8

A

ECOPRODUCTS AND UPSTREAM TECHNOLOGIES

A.1
ELECTRONICS TECHNOLOGIES AND MATERIALS

A comprehensive database of plastic monomers, additives and processing aids in electrical and electronic equipment

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Abstract

Many chemical substances are used as monomers, additives, or processing aids in the production and processing of plastics. Their releases during their life-cycle, their accumulation in secondary materials or their impact on the recycling process may pose major barriers towards a sustainable circular plastic economy. The increasing demands for recycling of plastics from electrical and electronic equipment (EEE) requires to target all substances with concerning properties used within them and overcome the focus on metals, phthalates and flame-retardants. As a basis, a comprehensive database of plastic monomers, additives and processing aids used in EEE plastics is developed in this study. At least 1'940 substances are potentially relevant for EEE plastics, most of which are used as colorants, fillers or lubricants. In addition, around 550 (potential) substances with concerning properties are identified, 60% of which are currently not adequately regulated under the EU RoHS or REACH. Furthermore, significant data gaps concerning use patterns, applied concentrations and hazard data exist for a majority of the substances.

1 Introduction

Today, it is unimaginable to have electrical and electronic equipment (EEE) without plastics. Plastics are cheap and can provide many favorable properties for EEE such as electrical insulation. The usage of plastics in EEE in Europe increased from 2.59 million tonnes (Mt) in 2015 to 3.17 Mt in 2018, which corresponds to 6.2% of all plastics used in Europe [1]. Meanwhile, the fraction of plastic used in EEE compared to other materials has also increased in recent years [2]. These use trends and policy developments (e.g. EU WEEE Directive, EU Circular Economy Package) will lead to increased amounts of EEE plastics that need to be recycled in the coming years.

Currently, a variety of chemical substances is used in the production and processing of EEE plastics. Residual monomers and processing aids may remain in the plastic material. Furthermore, plastic additives are purposely added to maintain, enhance or impart specific functions of the material. All these substances can also negatively impact consumer and occupational health, the environment, and/or recycling processes and secondary material quality. In particular, substances present in plastics can impact mechanical plastic recycling in the following ways [3], [4]:

- Releases of substances that are not covalently bound to the plastic matrix can occur during recycling. Increased surface area due to shredding and increased temperature during remelting promote releases of substances, resulting in elevated exposure of workers, neighboring communities and the environment [5]–[7]. For example, recycling of common EEE plastics - styrenics (e.g. PS, HIPS, SAN, ABS) - has been found to be associated with higher cancer risks for workers at plastics recycling plants, most likely due to the release of residual styrene monomers [6]. Elevated levels of toxic heavy metals (e.g. Cd and Hg) have also been observed in surface soils and sediments [8] and road dust samples [9] in the vicinity of plastic recycling plants, which can pose risks to local children and ecosystems.
- Substances with concerning properties, including already phased-out substances ("legacy pollutants"), may accumulate in secondary materials or cross-contaminate other material cycles [3], [4], [10], [11]. For example, toys and household articles have been reportedly contaminated by brominated flame retardants and heavy metals due to secondary material from EEE plastic waste [12]–[16].
- Substances in EEE plastics, such as some colorants and other optically active substances, can negatively impact sorting of polymer types by FTIR (specifically black plastics) [17] or negatively impact the color of the secondary materials, e.g., grey or brownish granulates, which are less market desirable for many applications [18]. In addition, some metals are known to accelerate thermal degradation occurring during recycling, thus reducing mechanical properties of the secondary materials [19].

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The increasing demands for EEE plastics to be recycled motivates specific focus on the substances present in plastics from this sector. Currently, research and risk assessments have focused on a limited number of substances, primarily heavy metals, phthalates and brominated flame retardants, while a much broader range of substances are expected to have been used (for packaging plastics around 4’000 substances are estimated to have been used [20]). This discrepancy between assessed and (potentially) used substances likely stems partially from a lack of knowledge on the chemical identities of relevant substances in the scientific and regulatory communities. This ongoing shortcoming has motivated us to develop a comprehensive database of monomers, additives and processing aids in EEE plastics. In addition to chemical identities, we look into use patterns of the substances, including their typical compatible polymers and respective functions. Moreover, a preliminary hazard assessment is conducted to identify (potential) substances with concerning properties that are currently not adequately regulated. Furthermore, critical data and knowledge gaps are highlighted.

2 Materials and Methods

Building on an existing database compiled by the authors, the database of plastic monomers, additives and processing aids (PlasticMAP) [21], three steps were taken in this study to compile the current database of substances relevant for EEE plastics: identification of use in EEE, categorization of uses, and preliminary prioritization of substances (Figure 1).

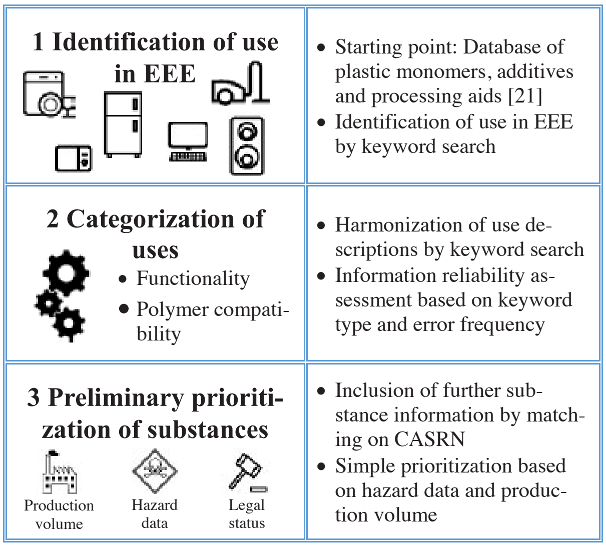

Figure 1: Compilation of database of plastic monomers, additives and processing aids in EEE

Details of PlasticMAP are described in a separate publication [21] and are therefore not repeated here. In brief, PlasticMAP assembled information on plastic monomers, additives and processing aids from publicly accessible sources, including existing regulatory databases (e.g. CPCat [22] and CDR [23] databases hosted by USEPA, registered substances database hosted by ECHA [24]), industrial databases (e.g. SpecialChem Polymer Additive Database [25]), industrial lists [26] and handbooks [27]–[30], and peer-reviewed scientific literature [20], [31]–[36]. Individual substances were included if their use descriptions contained “polymer” or “plastic”. Chemical identity information was extracted from the individual sources and harmonized into one database.

2.1 Identification of use in EEE

To identify substances related to EEE plastics, the use information of the substances in PlasticMAP was analysed using selected keywords for the following individual subcategories of EEE.

- Information and communication technology and consumer electronics (ICT & CE): such as computers, phones, smart watches, TVs, radio
- Cooling, refrigeration and air conditioning devices (CRAC): such as fridges, freezers, air cons
- Large household appliances (LHA): such as washing machines, dishwashers, stoves
- Small household appliances (SHA): such as microwaves, blenders, hairdryers, vacuum cleaners
- Other EEE (Other): such as musical instruments, lamps, photovoltaic equipment

Keywords included subcategory names and synonyms, but also generic terms for EEE (hypernyms), and specimen of each subcategory (hyponyms). Example keywords used for *CRAC* can be found in Table 1.

Type	Keyword	RegEx
hypernym	electrical	(?<!di)electrical
synonym	cooling devices	cool.{0,15}device
hyponym	Fridge	fridge
hyponym	Freezer	freezer

Table 1: Example keywords for the EEE subcategory CRAC and their corresponding regular expression used in the identification of use in EEE.

2.2 Categorization of the uses

For the identified EEE-relevant substances, their functions (e.g. as colorants, flame-retardants, antioxidants) and compatible polymer types (e.g. PET, PA, PVC) were further analysed, based on the information available in PlasticMAP [21]

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2.3 Preliminary prioritization of the substances

To conduct a preliminary prioritization of the substances identified for future research and assessments, additional information such as hazard classification, production volumes and legal status were retrieved from external databases. Hazard classification was retrieved from the EU C&L inventory and the Australian Hazardous Chemical Information System and focused on harmonized hazard classification wherever possible. Those with concerning harmonized hazard classification (e.g. persistent or P, bioaccumulative or B) were highlighted. Production volumes were assessed using the US CDR database hosted by USEPA [23], and the registered substances database hosted by ECHA [24]. Legal status was limited to Europe and retrieved from legal lists, including the restriction, authorisation and SVHC lists under REACH [37] and the EU RoHS directive [38].

3 Results and Discussion

3.1 Substances used in EEE plastics

In total, 1’940 CASRNs are identified to be relevant to EEE plastics. This may still be an underestimate, due to large uncertainties regarding use descriptions in individual information sources (e.g. for a large number of substances, no use description was available, or the use description lacked explicit reference to EEE, despite actual use in them).

Among these 1’940 substances, 470 are so-called UVCBs (substances of unknown or variable composition, complex reaction products or biological materials). In addition, 607 of the 1’940 substances (30%) are found to contain metals or metalloids, and 313 (15%) contain one or more halogens.

With more than 1’000 substance assignments ICT&CE is the most commonly mentioned EEE subcategory. Other categories are only mentioned for few substances (up to 300). The majority of links to EEE are established with generic terms for EEE (such as electronics, electrical, etc.) in the use descriptions. (Figure 2)

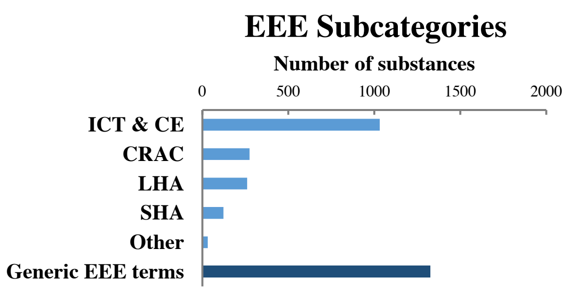

Figure 2: The numbers of relevant substances identified in different EEE subcategories.

3.2 Use profile of the substances in EEE plastics

Most of the substances in EEE plastics may fulfil more than one function. The top three functions, in terms of the number of substances fulfilling them, are colorants, fillers and biocides (Figure 4).

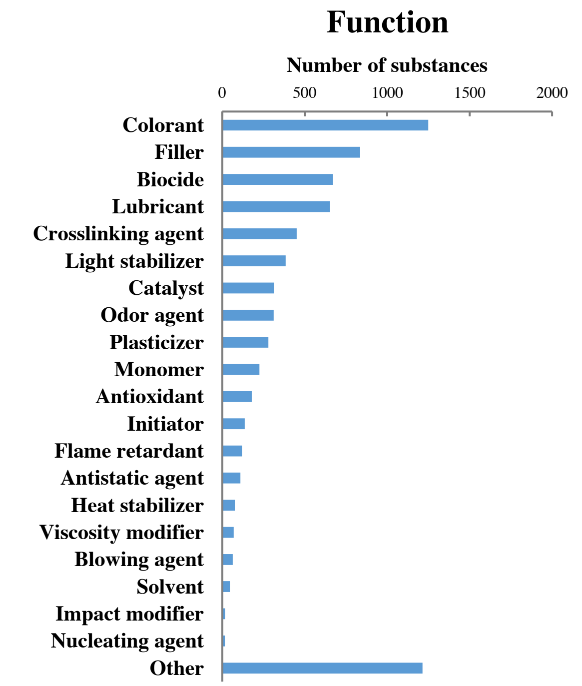

Figure 4: Functions of the substances used in EEE plastics. Note that individual substances can fulfil more than one functions.

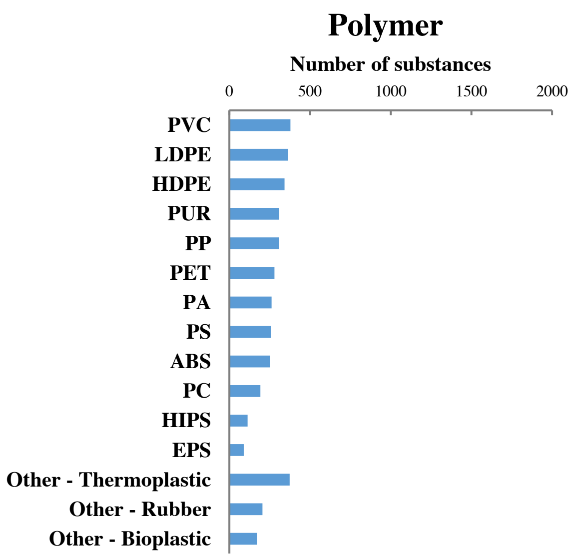

Figure 3: Compatible polymer types of the substances used in EEE plastics. Note that individual substances may be compatible with more than one types of polymers.

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The identified substances are typically compatible with several polymers (Figure 3). More substances are compatible with PVC and PE than with other polymer types. Compatibilities with PVC and styrenics (e.g. PS, ABS, HIPS) are more commonly mentioned for the substances in EEE plastics than for substances that are used in plastics but not used in EEE.

3.3 (Potential) Substances with concerning properties

Among the 1’940 identified substances used in EEE plastics, around a quarter (556 substances) show at least one concerning property, i.e. they are either persistent, bioaccumulative or toxic, according to the criteria under REACH. Furthermore, a majority of these (potentially) hazardous substances (345 substances) are produced in large quantities (larger than 1’000 metric tons per year). Only around 40% of the hazardous substances identified (220 substances) are either part of the SVHC, authorization or restriction lists under REACH, or regulated under the European RoHS directive (Table 2 and Table 3).

Hazard	Total	Regulated[1]	HPVC[2]
Persistent	104	40	71
Bioaccumulative	176	51	80
CMR[3]	325	155	224
Endocrine disrupting potentials	48	22	38
Other severe toxicity[4]	231	131	133
Having at least one of the hazards above	556	220	345

[1] regulated under the RoHS directive or under REACH
[2] high production volume chemicals (>1’000 t/year)
[3] carcinogenic, mutagenic or reproductive toxicity
[4] specific organ toxicity and skin sensitization

Table 2: Numbers of (potential) substances with concerning properties identified in this study.

3.4 Data and knowledge gaps

Despite the variety of information sources used to establish this database, some data gaps remain. As stated above, the number of substances relevant for EEE plastics may still be underestimated. In addition, information on functions and production volumes (for the USA or EU) is known for almost all substances in EEE plastics, while information on compatible polymer types and hazard data is only available for a third of the substances identified (Figure 5).

CASRN	NAME	HAZARD & TONNAGE[1]
31570-04-4	Tris(2,4-ditert-butylphenyl) phosphite	P, B 10’000-100’000 t/yr
80844-07-1	Benzene, 1-[[2-(4-ethoxyphenyl)-2-methylpropoxy]methyl]-3-phenoxy-	B, R 10-100 t/yr
55566-30-8	Phosphonium, tetrakis(hydroxymethyl)-, sulfate (2:1)	P, B 10-100 t/yr
5625-90-1	Morpholine, 4,4'-methylenebis-	B, C 1-10 t/yr
85535-85-9	Chloroalkanes, C14–17 (MCCPs)	P, B, R 10’000-100’000 t/yr
84852-53-9	Benzene, 1,1'-(1,2-ethanediyl)bis[2,3,4,5,6-pentabromo-	P, B 10‘000-100‘000 t/yr
2385-85-5	1,3,4-Metheno-1H-cyclobuta[cd]pentalene, 1,1a,2,2,3,3a,4,5,5,5a,5b,6-dodecachlorooctahydro-	P, B 10-100 t/yr
27083-27-8	Polyhexamethylene biguanide hydrochloride (PHMB)	P, STOT-RE 10-100 t/yr
82657-04-3	Cyclopropanecarboxylic acid, 3-[(1Z)-2-chloro-3,3,3-trifluoro-1-propen-1-yl]-2,2-dimethyl-, (2-methyl[1,1'-biphenyl]-3-yl)methyl ester, (1R,3R)-rel-	B, STOT-RE 1-10 t/yr
94361-06-5	1H-1,2,4-Triazole-1-ethanol, α-(4-chlorophenyl)-α-(1-cyclopropylethyl)-	B, R 1-10 t/yr
120068-37-3	1H-Pyrazole-3-carbonitrile, 5-amino-1-[2,6-dichloro-4-(trifluoromethyl)phenyl]-4-[(trifluoromethyl)sulfinyl]-	P, STOT-RE 1-10 t/yr
101463-69-8	Benzamide, N-[[[4-[2-chloro-4-(trifluoromethyl)phenoxy]-2-fluorophenyl]amino]carbonyl]-2,6-difluoro-	B, R 1-10 t/yr
111988-49-9	Cyanamide, N-[3-[(6-chloro-3-pyridinyl)methyl]-2-thiazolidinylidene]-, [N(Z)]-	P, B, R

[1] The following abbreviations are used:
P – persistent,
B – Bioaccumulative,
C – carcinogenic, M – mutagenic, R – reprotoxic,
ED – endocrine disrupting
STOT-RE – specific target organ toxicity with repeated exposure

Table 3: Substances used in EEE plastics that fulfil more than one PBT criteria and are not regulated under the EU RoHS directive or under REACH SVHC, authorization or restriction lists.

Recommended concentration ranges were mentioned only for individual substances. Furthermore, comprehensive hazard and exposure assessment is hindered by large data gaps regarding hazards and exposure relevant data (such as information on the used EEE subcategory or associated concentrations). Plastics in different EEE subcategories encounter different exposure-relevant conditions (e.g. temperature, typical exposure pathways, including food- or skin-contact). The common use of generic terms in use description (such as electronics or electrical equipment) in different information sources hinders comprehensive and detailed exposure assessment.

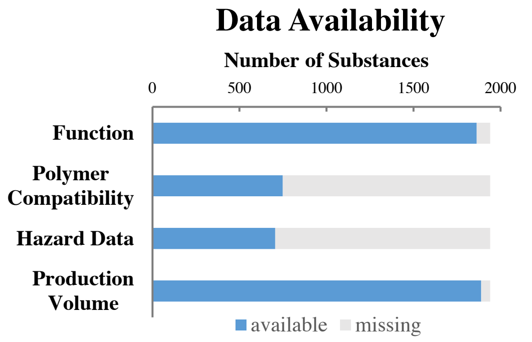

Figure 5: Data availability for different types of information stored in the database.

4 Conclusion and Outlook

Hazardous substances were and are being used in the production and processing of EEE plastics. In particular, a large number of (potential) substances with concerning properties remain inadequately assessed and regulated. Due to the relatively long lifetimes of some EEE products, even substances that are already regulated may still pose threats to occupational and consumer safety and the environment. In general, threats to recycling systems and secondary material quality are currently difficult to predict due to a lack of details on relevant chemicals being used and present in EEE plastics. However, the common use of colorants and metals in EEE plastics suggests that known problems with miscoloured or degraded secondary material may persist.

With this study, we hope to enable broader research on (hazardous) substances used in EEE plastics and improve substance identification in, e.g., emerging non-target and suspect screening analysis.

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Organic and printed electronics, an enabling technology accelerating the transition towards a circular economy?

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Abstract

Digital solutions and disruptive innovations are considered as enablers of the necessary and interlinked European green and digital transformations. As organic and printed electronics are moving from commercialisation to mass production, it is thus important to understand the potential role and impact of this technology on a transition towards a climate-neutral and circular economy. By describing the climate mitigation potential of Heliatek's organic photovoltaics solution, insights are provided on the feasibility to define and integrate ecodesign principles at early development stages. Based on the technological properties enabled by organic and printed electronics the potential for accelerating a transition towards a digitally-enabled circular economy is also illustrated. Mobilising research and fostering innovation is still needed as an essential pathway for developing more holistic knowledge, which will demonstrate and unlock the potential of this technology in this transition, but also to prevent any adverse effects sustaining our current linear economy.

1 Introduction

The recent releases of the European Green Deal [1] and Strategy on Shaping Europe's Digital Future [2] by the European Commission (EC) set out the ambitions and paved the way for Europe's sustainable and inclusive growth in the years to come.

The European Green Deal is indeed Europe's new growth strategy that aims to "transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use" [1]. In parallel, the EC wants "a European society powered by digital solutions that are strongly rooted in our common values", and that enrich the lives of all of its citizens [2]. Europe is thus in the middle of two interlinked transformations, which until those recent Communications have rarely been aligned [3]. Illustrating and emphasising the necessity for this new alignment, EC's President stressed in her Political Guidelines "the need for Europe to lead the transition to a healthy planet and a new digital world" explaining that this twin challenge of a green and digital transformation has to go hand-in-hand [2], [4].

Reinforcing those interlinked challenges and to turn those ambitions into reality, in March 2020 the EC concomitantly released a New Industrial Strategy for Europe [5] together with a new Circular Economy Action Plan (CEAP) [6]. European industry has a clear role to play in a transition towards a climate neutral and more circular economy, and priority is given to key product value chains including electronics [5], [6]. As digital technologies are considered as a critical enabler for attaining the sustainability goals of the European Green Deal [1] and priority is given to high-impact product groups, the role of European electronics industry is essential in these interlinked transformations.

To take a leadership role in transforming the digital landscape and supporting the development of technology breakthroughs from 5G and Digitalisation to the Internet of Things (IoT) and Artificial Intelligence, European electronics industry is continuously looking to expand and penetrate new market opportunities and niches [7]. Considered as enablers and differentiators of European digital transformation [7], new electronics ecosystems and technologies such as organic and printed electronics (OPE) are thus emerging.

Compared to more conventional silicon electronics, OPE are defined as solutions enabling the production of flexible and large-area components. Often characterised by some form factors including their thinness, lightweight, flexibility or again robustness, OPE are considered as a multifaceted platform enabling functionalities and a wide range of novel applications in many application areas and industry sectors [8], [9].

Important application areas include organic light emitting diodes (OLED) and flexible displays, organic photovoltaics (OPV), nearfield communication (NFC) and radio frequency identification (RFID), flexible batter-

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ies and supercapacitor, hybrid system (printed functionality combined with conventional electronics components) and integrated smart systems and components. The main industry sectors currently implementing those solutions refer to automotive, consumer electronics, healthcare, printing, packaging, and smart building [10].

With the ambition of effectively implementing OPE in use cases for which it offers specific advantages in performance, cost or form factor over conventional electronics and enabling new functionalities, OPE are moving from commercialisation to mass production and its market shows enormous growth potential. Sales of products including OPE were over 35 billion US$ in 2019, with the market expected to grow to over 74 billion US$ by 2030 [9], [11].

This on-going penetration in new market opportunities and niches will lead to a proliferation of electronic devices and subsequently new (form of) electrical and electronic waste (e-waste). Today, electrical and electronic equipment continues to be one of the fastest growing waste streams in the EU, with current annual growth rates of 2% [6]. Worldwide, it is estimated that in between 2016 and 2021 the generation of e-waste will increase from 44.7 Mt to 52.2 Mt [12]. Still at a global level, it has been estimated that the share of digital of technologies in global greenhouse gas (GHG) emissions has already increased by half in between 2013 and 2018, from 2,5% to 3,7% of global emissions [13]. The demand, and associated environmental impact related to extraction and processing, for raw materials such as rare and critical metals, essential for both digital and low-carbon energy technologies, is also growing [13].

Digital solutions and disruptive innovations being considered as critical enablers of the European Green Deal, as OPE technology readiness levels are increasing, it is now more than ever essential to more systematically integrate sustainability considerations within their development and production to prevent any adverse effects comforting a linear "take-make-dispose" economy. To steer this effective implementation of OPE and unlock their potential for contributing to the European Green Deal objectives, there is the first pre-requisite to develop holistic knowledge and understand the potential role and impact of this emerging technology on a transition towards a climate-neutral and more circular economy.

2 Objective and methodological approach

By scrutinising initiatives announced and thematic described within the new Circular Economy Action Plan, the objective of this contribution is to illustrate on several dimensions of the circular economy, some opportunities emerging from the development of OPE and challenges to be overcome for sustaining a beneficial contribution to this transition.

Sharing a common participation to the OE-A Sustainability Working Group activities, aiming to identify and understand the sustainability benefits of OPE technology and provide relevant information, guidelines and methodologies for its members [14], the respective authors of VITO NV and Heliatek GmbH, are both active in the deployment of clean energy solutions [15], [16]. This contribution will thus have a specific emphasis on the OPE application area targeting OPV and reflect on an industrial case study.

3 From sustainable products to circular business practices

3.1 Designing sustainable products, less waste, more value

As described under chapter "2.1 Designing sustainable products" of the new CEAP, the EC will propose a sustainable product policy legislative initiative. In line with this new framework and described under chapter "3.1 Electronics and ICT", the EC will particularly present a "Circular Electronics Initiative" [6]. The role of product design in a circular economy is essential, and its importance has particularly been emphasised in this new CEAP.

Product design indeed heavily influences the environmental impact of a product's lifecycle and is crucial for connecting different stages and stakeholders along the lifecycle [17]. Considered as an essential pathway for reaching climate neutrality by 2050 [6], circular economy is a multi-dimensional system-oriented approach defined as "an economic system where the value of products, materials and resources is maintained in the economy for as long as possible" [18]. In this context, product designers can explore different, complementary levers and strategies:

- service-based consumption and products;
- a sustainable sourcing of primary and secondary raw materials through the substitution of rare and/or critical raw materials, or produced from more resource efficient manufacturing processes;
- an optimised resource use;
- an environmentally sound and safe product use through the minimization of the use of hazardous and/or persistent substances as involved stakeholders need to rely on the intrinsic safety of the materials also from an health perspective;

- prolonged product lifetime through durability, modularity and repairability;
- or again, better recyclability and recycling;

Simplified and adapted from a study on the application of those ecodesign principles to plastics in a circular economy, those levers and strategies can be displayed on a lifecycle perspective (see Figure 1) [19].

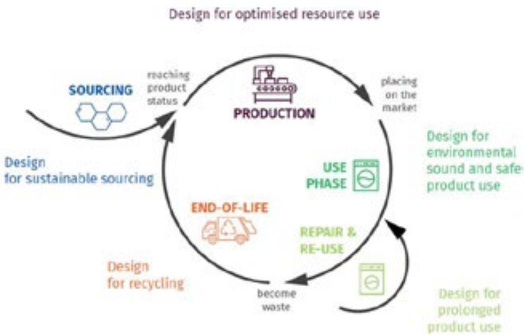

Figure 1: Ecodesign principles in a circular economy, displayed on a material and product lifecycle perspective, simplified from [19]

Still according to the EC, in a circular economy "when a product reaches the end of its life, it is used again to create further value" [20]. Preventing waste generation and ensuring high-quality recycling are also key thematic to be addressed by initiatives listed in chapter "4. Less waste, more value" of the new CEAP [6].

It is thus important for OPE designers, developers and producers to be guided in the identification of different, complementary levers and strategies, contributing to development of sustainable products according to their application areas and industry sectors. As now moving from commercialisation to mass production, gaining knowledge with regards to a responsible and resource efficient end of life management, is also key in a transition towards a more circular economy. In the next section, the climate mitigation potential of a specific OPV solution, resulting from the application of some complementary design principles mentioned above (see Figure 1), will be described in further details. The description of those activities will thus provide relevant insights and eventual inspiration to the OPE community, for a more environmentally-sound product design and research activities that could lead to a positive contribution in a transition towards a climate-neutral and circular economy.

3.2 Towards the decarbonization of the energy production with Heliatek´s OPV solution

As the technology leader in OPV, Heliatek develops, produces and distributes industrial-grade OPV solar solutions for virtually any building surface (horizontal or vertical, curved or flat, rigid or flexible). Heliatek stands for energy solutions designed for various traditional or never been possible before applications. The innovative solar film solution, HeliaSol®, is based on nanoscale carbon-based (organic) molecules that enable ultra-thin, ultra-light and flexible products.

The organic solar solution does not contain any rare materials and is free of toxic heavy metals such as lead and cadmium. In addition, the organic material required for vacuum evaporation of the photoactive triple stack is less than 1 g for 1 m^2 HeliaSol®. Furthermore, the efficient roll-to-roll process with heat recovery, closed cooling circuits and solvent-free processes reduce production-related requirements for energy and materials. Thus, the design of Heliatek's OPV solution includes 3 of the 5 above-displayed (see Figure 1) main ecodesign principles in a circular economy, as introduced in the previous section.

To achieve the climate protection targets, the environmental impacts of all activities related to the conversion of raw materials into finished goods and their end-of-life treatment must be quantified and effectively integrated into the competitive process. The international standards DIN EN ISO 14040/44 provide a structured, comprehensive method to quantify the potential environmental impact of material and energy flows throughout the product life cycle, the so-called Life Cycle Assessment (LCA). To evaluate Heliatek's first product, HeliaSol®, in terms of environmental performance, TÜV Rheinland (Germany) undertook an LCA study throughout the entire life cycle ("cradle to grave"), including all transportation/delivery routes. The effect on climate change is evaluated by the sum of GHG emissions and removals in a product system expressed as CO_2 equivalents results in the carbon footprint.

TÜV Rheinland (Germany) has certified the carbon footprint of the pre-commercial product HeliaSol® to be below 16 kg CO_2e /m², a value which is up to 10 times lower than for crystalline silicon modules [21]. To relate the carbon footprint to the energy generation, the real benefit of a solar product, the results have to be converted into g CO_2e/kWh over lifetime. It depends above all on the module efficiency, the specific annual yield (kWh/kWp) and the lifetime of a solar module. A geographical mapping (see Figure 2) indicates that HeliaSol® have a carbon footprint down to only 3 g CO_2e/kWh in locations with high solar irradiation, comparable to the greenest forms of renewable energies, hydropower and wind power.

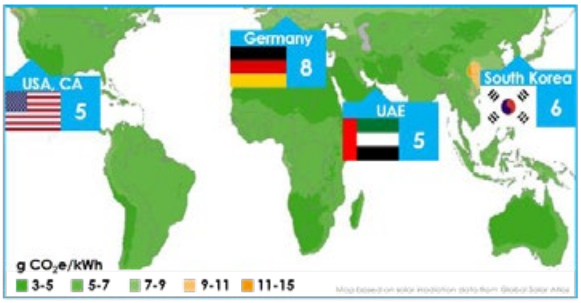

Figure 2: Geographical mapping of the low carbon footprint HeliaSol®
aperture efficiency 10 %, lifetime 20 years, degradation 1 %

A comprehensive product life cycle analysis should identify all potential environmental impacts, covering also the end-of-life treatment of PV modules. In the LCA of HeliaSol®, it was assumed, that cables are recycled and the solar film is incinerated. The flexible solar solution offers a high potential for energy recovery due to its high polymer content of about 98%. With the net calorific value of about 22 MJ/kg, a higher energy generation is achieved through incineration than with wood pellets. The remaining 2% of the films are metal based (copper and tin) and can be extracted from the ash. A recent study entitled "Incineration of organic solar cells" proves that complex acid-related recycling processes for the recovery of metals from OPV are associated with 20% higher environmental impacts than by ash extraction [22]. Nevertheless, Heliatek is working on a feasibility study for a high quality recycling process to evaluate a more resource efficient end-of-life treatment and take it to the next level on the road to circular economy.

The warming of the climate system is unequivocal, and solar energy can play a major role on the toughest and most important battle of the 21st century: enabling increased energy consumption while minimizing the impact on global warming. Overall, the OPV solution not only demonstrates the potential of sustainable product design within the OPE sector, but also offers one of the greenest energy sources among all.

4 Driving the transition through research, innovation and digitalisation

As introduced above, EC considers that Europe "must leverage the potential of the digital transformation, which is a key enabler for reaching the Green Deal objectives" [1]. Those ambitions can clearly be retrieved in the introduction of the new CEAP in which it is mentioned that:

- "Building on the single market and the potential of digital technologies, the circular economy can strengthen the EU's industrial base and foster business creation and entrepreneurship among SMEs. Innovative models based on a closer relationship with customers, mass customisation, the sharing and collaborative economy, and powered by digital technologies, such as the internet of things, big data, blockchain and artificial intelligence, will not only accelerate circularity but also the dematerialisation of our economy and make Europe less dependent on primary materials" [5].

Concrete foreseen initiatives translating those ambitions can be found in chapter "6.3 Driving the transition through research, innovation and digitalisation" of the new CEAP in which it is stated that:

- "Horizon Europe will support the development of indicators and data, novel materials and products, substitution and elimination of hazardous substances based on "safe by design" approach, circular business models, and new production and recycling technologies, including exploring the potential of chemical recycling, keeping in mind the role of digital tools to achieve circular objectives" [5];
- or again and still within the same chapter, that "Digital technologies can track the journeys of products, components and materials and make the resulting data securely accessible" [5];
- Also, in line with the above-mentioned sustainable product framework, and described in chapter "2.1 Designing sustainable products" the EC will "establish a common European Dataspace for Smart Circular Applications with data on value chains and product information" [5].

It is indeed acknowledged that the sound uses of digital technologies, such as the IoT, can enable the implementation of circular strategies through the development of service-based business models, improving the traceability of products through the entire supply chain, or again allowing manufacturers continuously optimizing the performance of both products and production [23], [24]. Initiating such a data-driven cultural change and establishing data-oriented management systems translating collected data into relevant information, can enable businesses in rethinking how value is generated and maximised within their activities. Subsequently, this can be highly beneficial for transitioning from more linear to circular production and consumption patterns. Indeed, and if for instance product ownership remains with the producer, minimising the total life-cycle cost of a product is an economic incentive that can encourage the design for circularity and longer lifespans (see Figure 1) [25], [26].

IoT devices being characterised by their unique identifiers and ability to transfer data over a network without requiring human-to-human or human-to-computer interaction [27], market research estimate that 9.15 billion of those devices were installed in 2018, with a projected increase to 41.6 billion in 2025 [28]. According to those trends and with the rollout of 5G, it is clear that the OPE multifaced technology platform provides the ideal technological properties (thin, lightweight, flexible etc. form factors) for attaching and/or integrating those unique identifiers in any kind of objects, regardless of shape and size, as well as low-cost and large-area sensor solutions enabling the autonomous generation of data [9].

OPE technology can thus play an important role as an IoT-enabler in the different application areas and industry sectors mentioned above. Steering their effective implementation in use cases in which it offers specific advantages in performance, cost or form factor over conventional electronics are clear drivers for the OPE community. However, and in addition, 'bringing electronics where it has not been possible before' for collecting, processing and communicating relevant data necessary in a transition towards a circular economy, also demonstrates a clear potential in the deployment of OPE. Indeed, and in relation with the thematic described in the new CEAP, OPE could thus for instance enable the tracking of components and materials 'where it was not possible before', and provide the necessary information-basis for more resource-efficient business models.

To steer this effective implementation while concomitantly unlocking this potential to enable and accelerate the transition towards a circular economy, there is still some evident research needs, calling for new collaborations and coordinated R&D actions. Methodological approaches based on holistic impact assessments need to be developed for gaining knowledge on the circular potential per application areas and industry sectors. The development of an adequate regulatory framework combining both digital and circular economy agendas is also essential.

To emphasize these arguments, the 5E H2020 project, having for ambition to federate three electronics areas and ecosystems (in which OPE is considered being part of), recently released a vision paper on the role and impact of functional electronics on the transition towards a circular economy [29]. Some of these above-mentioned research needs, have also been emphasised and conceptualised (see Figure 3) by the contributors of this vision paper, among others supported by the OE-A Sustainability Working Group.

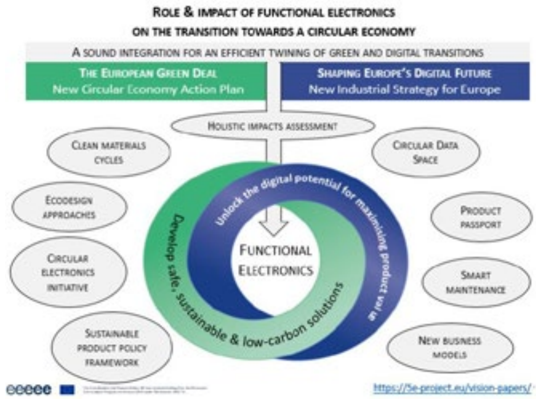

Figure 3: Vision paper on the role and impact of functional electronics on the transition towards a circular economy released by the 5E H2020 project [29]

5 Conclusions

It is clear that this contribution does not aim at providing a one-sided science-based fact answer to the question: "organic and printed electronics, an enabling technology accelerating the transition towards a circular economy?". Based on the identification of hooks between OPE technological properties and European political ambitions, through the screening of initiatives announced and thematic described within the new Circular Economy Action Plan, it rather illustrated some opportunities emerging from the development of OPE in specific application areas and industry sectors as well as challenges to be overcome for eventually accelerating but also sustaining a beneficial contribution to this transition.

This contribution described the climate mitigation potential of Heliatek's OPV solution, a concrete application area of OPE. It has also been expressed that OPE is enabling functionalities and a wider range of novel applications in many other application areas and industry sectors, and is currently moving from commercialisation to mass production. Therefore, it is urgent for the OPE community to systematically develop and integrate ecodesign principles at early research, design and development stages, like the Heliatek's approach shows.

Due to the technological properties enabled by this multifaceted platform, OPE technology has the clear potential for accelerating a transition towards a digitally-enabled circular economy. Improving traceability, transparency and collaboration within and across product value chains and among their stakeholders are current barriers for deploying more resource-efficient business models and accelerating this transition. It is now essential to concretely demonstrate this enabling potential for the OPE technology. It has thus been shown, also with a concrete initiative from the 5E H2020 project, that mobilising research and fostering innovation is an essential pathway for understanding and maximising the beneficial synergies between the green and digital transformations.

As next steps and for subsequently translating this contribution into meaningful guidelines and methodologies for the OPE community, it will be essential to narrow down the scope of this research question and apply it to one specific application area and/or industry sector implementing OPE.

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Material selection for biodegradable organic thin film transistors

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Abstract

Biodegradable organic thin film devices allow flexible electronics devices which decompose after an intended period of operation. Examples are devices that can be recycled by industrial composting facilities or medical implants which are absorbed by the living organism. In literature, the feasibility of thin film transistor (TFT) structures based on various nature-inspired or biodegradable materials has been demonstrated (e.g. [1, 2]). The focus of our work was on biodegradable conductive traces on PLA substrates and TFT using hybrid polymers and now we employ gelatin as gate-insulator and potential substrate. Gelatin as a common food component is a particularly interesting material which has already been investigated as gate dielectric for TFT [3]. As top contacts, we use MoO3/Mg structures and as semiconductor quinacridone. The vacuum deposition of biodegradable conductive tracks on a biodegradable substrate such as PLA is not strait forward due to extremely poor sticking, but can be solved by suitable pre-treatment or interlayers. In this way, we expect that all materials used are suitable for potential application in compostable/bioresorbable devices.

1 Introduction

Electronic devices that can be broken down in a biological environment after a pre-defined period of operating open up novel applications as well as ways for reducing their ecological footprint.

In the following, terms like bio-based, biodegradable bioresorbable, biocompatible and compostable are used. Since there is not yet a generally accepted meaning of these terms, we will first give a brief review on common definitions.

Bio-based materials are composed or derived of biological materials [4, 5, 6]. Examples are bio-based polysaccharides that are produced from separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF) and consolidated bioprocessing (CBP) [7]. The goal is to replace petroleum-based materials by polymers from naturally-occurring feedstocks. With every replacement one should attend the industrial need for the processes and products to be compatible with the environment and with sustainable development [4, 7, 8].

Biodegradability in general is the capability of being degraded by biological activity [4]. A biodegradable implant material like magnesium can be dissolved or absorbed in the physiological environment of the human body [9]. For the degradation process there is for example an active and a passive way for cleaving polymer bonds [10].

Bioresorption or absorption is a qualifier used to indicate that a compound or a device has the ability to be eliminated or bio-assimilated by an animal or a human body [4, 11, 12, 13].

Biocompatibility is a material property which means that a material can perform in the human body without a negative host response (immune response or inflammation) in a specific application. In general this means the missing of allergenicity, carcinogenicity, localized cytotoxicity, and systemic response [4, 14].

A material is compostable if it can be converted into carbon dioxide, humus and heat by compost microorganisms [4, 15].

The first step towards biodegradable electronics devices is the manufacturing of biodegradable conductive traces on biodegradable substrates using vacuum technologies.

In the field of medical implants this opens novel application areas for these innovative electronic components. For example, active medical implants that after expiration of their operating life are resorbed by tissue are possible. Then the patient does not need a second surgical intervention for removal of the implant.

The goal of our work is the development of essential components for biodegradable electronic parts that can be employed for example in such an implant.

This includes in particular

- biodegradable conductor structures
- biodegradable electrodes for collecting electrical signals or delivering electrical stimulation

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- biodegradable thin-film transistors and circuitry
- biodegradable barrier coatings as moisture and gas barriers, and electrical insulation layers

These elements will be integrated into a flexible thin-film device. Conductor structures and organic thin-film transistors are being developed using vacuum technology. The deposition of magnesium under high vacuum conditions is carried out via thermal evaporation.

Magnesium is already employed in clinical environments as an absorbable implant material and it is known as a biodegradable and biologically compatible metal [9]. The challenge consists of depositing this metal upon biodegradable polymer films. Magnesium does not adhere sufficiently to such films under normal process conditions. Some processes for pre-treatment of the substrates are needed. A significant improvement was reached with combination of drying, plasma treatment, and utilization of seed layers. In the result, finely structured high-quality conductor structures could be produced.

2 Conductor structures for biodegradable electronics

2.1 Technology

As standard substrates for the technology described in this work, we use commercial films of polylactic acid (PLA). All results shown here, if not otherwise stated, are obtained on the PLA based film Nativia® NTSS50 by Taghleef Industries. This substrate is certified for compostability according to the EN13432 norm. PLA as a material also is already in clinical use as material for absorbable implants [16].

For potential use in flexible electronics, a procedure for cleaning the substrate before starting the deposition process is required to remove particles. In this work, we use two different cleaning methods, in the following abbreviated as “wet cleaning” and “dry cleaning”. For “wet cleaning”, we use a well-established cleaning procedure for glass or silicon wafer substrates consisting of cleaning in an ultrasonic surfactant bath at 50 °C, followed by a quick dump rinse (QDR, from Arias GmbH, Germany) and spin rinse dry (SRD 101, from Semitool, U.S.) process. One important disadvantage of this cleaning method is strong exposition to water. To avoid the contact to water, we also investigated a simple “dry cleaning” in which the substrates were only cleaned with a nitrogen duster. For drying the substrates after cleaning, we employed either a nitrogen oven or a vacuum oven.

The plasma treatment of the substrates was done using the linear closed drift ion source LIS 38 by Advanced Energy (now Applied Materials). This ion source produces a linear ion beam over a width of 38 cm with an acceleration voltage of 1 kV. As process gas, we employed variable mixtures of oxygen and argon. In the vertical inline configuration the substrate is moved in front of the ion source.

For vapor thermal evaporation of the metals, we used a custom-made single-chamber high vacuum deposition tool (BESTEC GmbH Germany) with heated crucibles as sources. For structuring the evaporated materials shadow masks are used with a distance of about 350 µm to of the substrate. The film thickness was controlled by quartz microbalance controllers, which are calibrated by comparative profilometer measurements. All metal films discussed here have a thickness of 50 nm.

2.2 Magnesium on non-treated PLA

For deposition tests shadow masks are used with a specific test layout. The layout is shown in Figure 1 on the left side. The first deposition where thermally evaporated magnesium should be deposited onto untreated PLA substrates did not show any magnesium sticking on the substrate but on standard glass substrates the magnesium sticks very well as shown in Figure 1 on the right side.

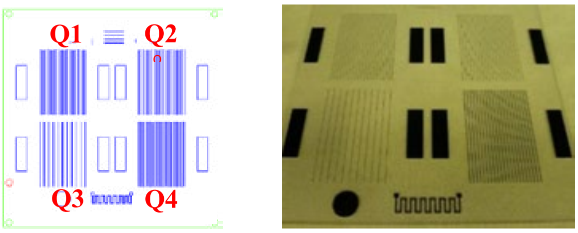

Figure 1: Left: Layout of test-structures. Right: Photograph of magnesium test-structures deposited onto standard glass.

The magnesium layer has a sheet resistance of 2 Ohm/sq, this corresponds to 45% of the bulk resistivity. In comparison to magnesium, thermally evaporated aluminium was used to be evaporated onto non-treated PLA substrates. This results in metallic films with a typical sheet resistance. For Al on PLA, the sheet resistance of a 50 nm thick film is 1 Ohm/sq, which corresponds to about 60% of the bulk resistivity. Both relative sheet resistances are very typical for evaporated films with a thickness of 50 nm. This experiment shows that neither magnesium as an electrode metal nor PLA as substrate on their own pose a general problem but only the combination of both.

The phenomenon of extremely poor magnesium deposition is strongly related to the pre-conditioning of the

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substrate. Even for a process flow with extensive outgassing (“dry cleaning/vacuum oven 120°C 48h”), there is no visible magnesium deposition on the PLA substrate. This occurs on PLA substrates from different suppliers and is not an effect of only one type of PLA substrates. On commercial available PET substrates a visible layer of magnesium is deposited but with many defects. The remarkable phenomenology of this poor deposition is that it depends on the area of non-deposited substrate around the deposition area. Under certain conditions a full area deposition might still give a metallic film, but small structures (like conductive traces) might be affected. In Figure 2 the defect phenomenon is illustrated for the standard test layout on PET film. The layout of the test-structures on 10x10 cm² substrates is shown in Fig. 1. The grid structures Q1-Q4 consist of conductor traces with varying width and pitch (Q1, Q2: w=120 µm, p = 1.2 mm, Q3: w = 120 µm, p = 2.3 mm, Q4: w = 240 µm, p = 1.2 mm).

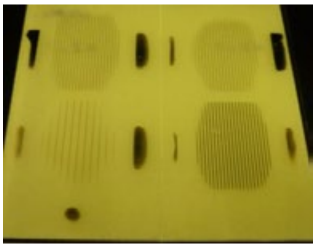

Figure 2: Magnesium deposited test layout on PET.

The PET foil is a commercial foil (Melinex 401CW) with adhesion pretreatment, left part of the substrate with deposition onto untreated side, right part of substrate with deposition onto adhesion-pretreated side). In both cases, the process flow “wet cleaning, nitrogen oven 50°C/3 h” is used. As seen in Figure 1, the characteristic coverage defects are close to non-deposited substrate regions on the PET foil.

With a more advanced pretreatment by LIS plasma or Ca seed layers, the same type of defect pattern as in Fig. 2 is visible on PLA substrates. This directly depends on the effectiveness of the pretreatment. In the best cases, structures corresponding to the structure in Fig. 1 (deposition onto glass) can be obtained.

For understanding the phenomenon of incomplete magnesium coverage, it is important to distinguish between two hypothetical mechanisms: One mechanism might be that magnesium does not stick at the substrate during the deposition process. The other mechanism might be that magnesium is deposited but rapidly corrodes into transparent magnesium oxide or magnesium hydroxide. For clarification of the mechanism, we performed energy dispersive X-ray spectroscopy (EDX) in a scanning electron microscope (SEM).

A sample where a test pattern with conductor structures is deposited onto a substrate with some advanced pretreatment (wet cleaning, nitrogen oven 50°C/3 h, LIS-plasma) is used. In this sample, the deposition of magnesium is already significantly improved by the pretreatment, but the characteristic defect pattern is still visible. In Fig. 3, a photograph of the substrate section Q4 with the defect pattern in the lower right is shown. The indicated area shows a defect area where the metallic magnesium traces are fading out at the outer border of the grid area.

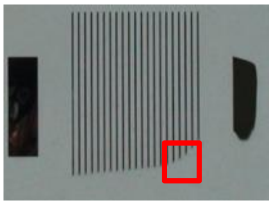

Figure 3: Photograph of magnesium deposited on PLA with defective area.

A SEM picture (material contrast picture set to magnesium peak in backscattering mode) of this region is shown in Figure 4. The indicated area b1 belongs to the range of visible metallic magnesium, the indicated area b2 belongs to the defect area with no visible metallic magnesium.

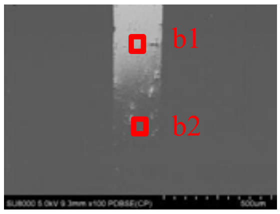

Figure 4: SEM picture of magnesium on PLA.

The EDX spectrum from the metallic area b1 is shown in Fig. 5 on the left side. The prominent peaks correspond to the elements C, O and Mg. The EDX spectrum from the defect area b2 is shown in Fig. 5 on the right side. The C- and O-peaks are comparable to the spectrum of spot b1, they are attributed to the substrate. The peak of Mg, however, is not detectable anymore.

This proves that neither metallic magnesium (as obvious) nor the hypothetical transparent corrosion products are existent in the defect areas. So the missing or incomplete magnesium coverage is not caused by corrosion of deposited magnesium. It is a result of incomplete magnesium sticking during the deposition process.

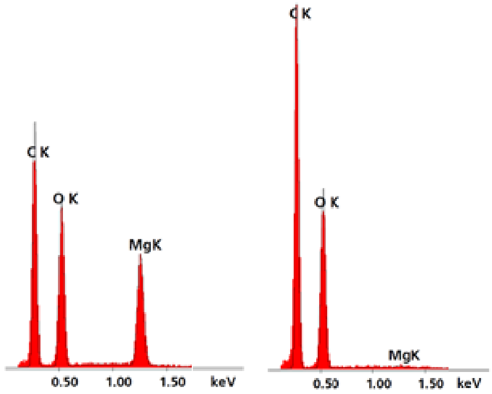

Figure 5: Left: EDX spectrum of area b1. Right: EDX spectrum of defect area b2 (areas defined in Fig. 4).

2.3 Magnesium on plasma-treated PLA

To improve the sticking of magnesium on PLA, we tested other options for the plasma treatment. A standard radio-frequency plasma in high vacuum showed no significant changes. But the high energy plasma treatment using a linear ion source (LIS-plasma, cf. Section 2.1) resulted in significant improvement of the sticking properties. After the optimization of process parameters (oxygen-argon ratio, effective deposition time) and adding a vacuum storage for 7 days before the LIS-plasma there was a process where a large fraction of the test structures is deposited without defects. An example is shown in Fig. 6 (section Q4 of the substrate).

Figure 6: Photograph of magnesium on pretreated PLA (storage in high vacuum for 7 days and LIS-plasma).

2.4 Summary magnesium conducting structures on PLA

A possible process for the deposition of magnesium conductor structures on PLA substrates was found. This is a first sept towards biodegradable electronics devices. A special pretreatment for the substrates is needed to improve the sticking of the evaporated magnesium on the PLA substrates. A combination of vacuum drying and high-energy plasma treatment allows the production of conducting traces with structure sizes in the 120 µm range.

3 Organic thin film transistors (OTFTs)

3.1 Technology

For processing organic thin film transistors there is a large variety of materials that can be used for this devices. We try to use materials which are already in clinical use. As explained, PLA substrates and magnesium conductive tracks are used for the transistor electrodes. For the organic semiconductor, our material of choice is quinacridone. This material is a pigment colour with semiconducting properties [1,17]. For such an organic nonazo pigment, a very bio-inert behaviour without toxic effects is expected [18]. Among a group of natural semiconductors for organic electronics, quinacridone shows the most promising hole charge carrier mobility with 0.1 - 0.2 $cm^2/(Vs)$ [1,17]. As gate-insulator materials for OTFTs, a large variety of materials is shown in literature and we tested some of them. Here we report on gelatin because of good performance in our process flow. In addition, gelatin is fully biocompatible and biodegradable [19] and it is already in clinical use for capsules of pharmaceuticals and food supplements [19] and it is easily soluble in water [20].

All transistors shown here are produced in a bottom-gate top-contact architecture. If no other information is given, the gate electrode consists of aluminium and the top electrodes are made of gold. As mentioned before, quinacridone (provided by TCI Chemicals) is used as semiconductor but we also need a seed layer of tetratetracontane (TTC, provided by Sigma-Aldrich) before the deposition of quinacridone to get a good performance [19]. In Figure 7, a scheme of a transistor stack for the test of gelatin and quinacridone as biodegradable/biocompatible materials is given.

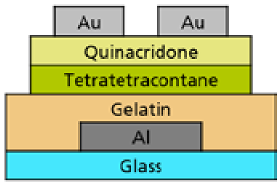

Figure 7: Transistor stack for device fabrication.

All layers for the transistor electrodes and the double layer of TTC and quinacridone are deposited in vacuum technology with shadow masks (channel length = 100 µm and 200 µm, channel width = 2 mm). For the gelatin layer, a solution of 8 w% gelatin (procine skin powder, gel strength ~ 300 g Bloom, provided by Sigma-Aldrich) in distilled water is spincoated on the substrate.

3.2 Evaluation of gelatin

In the first experiments, gelatin showed a visibly much smoother surface roughness compared to other tested

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insulating materials. In Figure 8, examples of fully processed test substrates with ten TFT structures (upper and lower part of the substrate) and a linear test structure (centre part) are shown. The figure shows a comparison between structures with the also tested gate insulator polyvinyl alcohol (PVA, provided by Sigma-Aldrich) in Fig. 8a and stuctures with gelatin insulator in Fig. 8b. As tentatively seen in this pictures and clearly seen in direct visual inspection, there are interferences for the PVA layer but not for the gelatin layer.

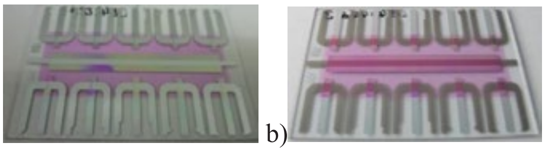
a)  b)

Figure 8: Left: Photograph substrate with PVA insulator. Right: Photograph substrate with gelatin insulator.

Gelatin insulator layers were produced by spin coating and heating in an N2 oven, the used thickness is 650 nm. In case of the magnesium electrodes, a proper treatment of organic polymers is essential for Mg sticking, therefore, we use heating and corona treatment on the insulator. In different processes we tried to enhance the transistor performance and in this way, we achieved TFTs with transfer characteristics (extracted from output characteristics) shown in Fig. 9. The obtained mobility of 0.2 cm²/(Vs) is comparable to reported values for the same semiconductor [1,17].

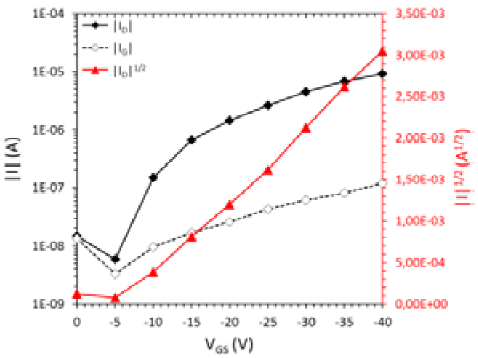


Figure 9: Transfer characteristics for a TFT stack structure Al gate, gelatin (heated in N2 oven + corona treatment), TTC, quinacridone and MoO3 - Mg top-electrodes.

4 Conclusion

With vacuum technology there is the possibility to build functional conductive tracks from magnesium on biodegradable substrates like PLA. In addition, we showed a technology which can be used to process organic thin film transistors with biodegradable/ biocompatible insulator and semiconducting materials. Now, the focus is on the combination of both technologies to get a process where all electrodes and thin film materials are biodegradable/ biocompatible materials on a biodegradable substrate. This technology aims at the future production of biodegradable electronics devices which have a reduced environmental footprint or can potentially be used in absorbable medical implants.

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A Comparative Study of Post-Deposition Treatment Methods for Bio-Based Conductive Inks

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Abstract

This work investigates the ability of several post-deposition treatment methods to enhance the electrical performance of bio-based conductive inks which contain carbon fibres as the functional component. Their potential application in Green Printed Electronics manufacturing is evaluated with respect to their compatibility with high-volume production methods (roll-to-roll processing). Among these treatment methods, photonic flash annealing was identified as the most promising approach to date as it combines substantial conductance enhancements (up to an eight-fold increase), high process speeds and straightforward integration into established high-volume manufacturing processes. To explain its effectiveness, we propose a mechanism that involves a sequence of processes: (1) preferential absorption of the high-intensity light flashes by the ink, (2) rapid localised heating and thermal decomposition of non-conductive ink components, (3) re-deposition of the degradation products as conductive amorphous carbon which enhances the connectivity between individual fibres.

1 Introduction

Non-toxic, eco-friendly manufacturing processes that use renewable resources are crucial for the adoption of green production methods in the electronics industry. Replacing conventional microelectronics production methods with printing technologies is one possible strategy [1]. Printing is already well-established for the industrial manufacturing of electronic devices, but many of the functional inks contain significant amounts of non-sustainable, environmentally detrimental ingredients such as heavy metals. Prime examples are high-performance conductive inks which are mainly based on silver and copper [2]. Carbon based inks using graphene or carbon nanotubes exhibit decent performances but are typically derived from non-renewable sources. In addition, they might pose significant health and environmental risks due to their nano dimensions [3]. Non-hazardous, eco-friendly carbon-based inks exist, but their use is restricted to low conductivity applications. Consequently, developing processes that improve the conductance (i.e., lower the electrical resistance) of functional patterns printed with such carbon inks have the potential to reduce heavy metal and fossil resources usage in printed electronic devices. Conductance increases can be achieved through two main mechanisms: removal of non-conductive ink ingredients (dispersants, rheology modifiers etc.) and improved electrical connections between the conductive carbon particles.

Lignin, the second most abundant plant polymer on earth, is a significant waste product of the pulp and paper industries. We have developed a method to produce conductive, sub-micron rather than nano-sized carbon fibres through the electrospinning and heat treatment of lignin [4]. These fibres, and vapour grown carbon nanofibers, can be formulated into water-borne conductive inks using bio-based dispersants and rheology modifiers [5]. These inks have been successfully printed using a variety of technologies. In this study, the inks were applied with screen printing. However, after adjusting the formulations, inkjet and flexographic printing have also been demonstrated. When printed onto substrates such as paper, bio-based and biodegradable circuits are obtained.

Here, we present a comparative study of several post-deposition treatment methods to improve the conductance of our bio-based carbon fibre ink. Most of the methods presented here have already been successfully demonstrated for metal-based conductive inks [6] and non-bio-based carbon inks [7], [8]. We first focus on the ability to improve the ink's conductance and the induced microstructural changes. The methods are presented in order of increasing effectiveness, initially disregarding other aspects such as process speed, compatibility with industrial manufacturing processes and economic viability. These aspects are then discussed separately, along with health, safety and environmental considerations.

2 Results and Discussion

2.1 Effects on electrical conductance and microstructure

2.1.1 Thermal annealing

Thermal annealing is the established benchmark method for the post-deposition treatment of conductive inks [6]. The maximum temperatures that can be applied are usually limited by the thermal stability of the substrate materials. The papers we use to print onto cannot withstand conditions above 250 °C without significant degradation. Conductance improvements up to a factor of two were achieved by heating the printed ink patterns to 250 °C at a rate of 2.5 °C/min (see Figure 1). Isothermal treatment for extended times (up to 90 minutes) at 250 °C resulted in very similar outcomes. This process is thus both slow and has limited effect on our bio-based inks. This is likely related to the thermal stability of the non-conductive ink components. Faster and more effective treatment methods are therefore needed to improve the electrical performance of carbon fibre-based conductive inks.

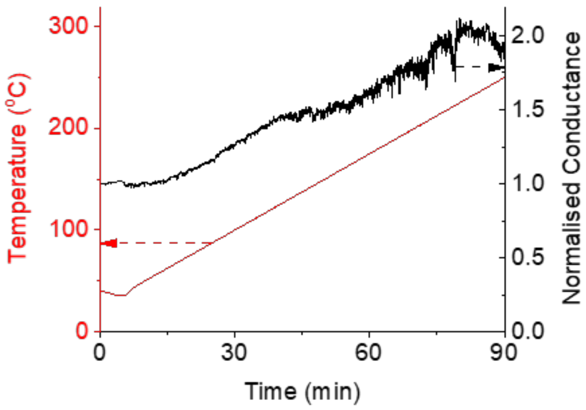

Figure 1: Effect of thermal annealing (2.5 °C/min ramp to 250 °C) on the conductance of a bio-based carbon fibre ink printed on paper

2.1.2 Mechanical compression

The porous structure of the printed carbon fibre ink implies a high proportion of voids which is detrimental to its overall conductance. Densification via mechanical compression is expected to improve inter-fibre connectivity, as demonstrated earlier for graphene-based conductive inks [8]. However, compression up to 1 MPa at room temperature did not lead to any significant conductance improvement of our printed samples. Compression combined with heating did not improve the conductance compared to thermal treatment alone. The lack of conductance improvement after mechanical compression is likely due to the continued presence of the non-conductive ink components.

2.1.3 Microwave heating

Microwaves are known to selectively heat thin metal-based conductive ink structures. This results in extremely fast and massive improvements of their conductance [9]. When applied to our materials system, we observed only inconsistent and moderate improvements, by a factor of two or less. In addition, the paper substrates often suffered from charring or burning, even in the absence of oxygen. We attribute this damage to inhomogeneous radiation density distributions in the resonator cavity or runaway effects due to local overheating [10]. This is likely to be caused by preferential microwave absorption in regions with higher initial conductivities.

2.1.4 Plasma treatment

This technique employs the impact of highly reactive plasma ions, frequently in combination with UV radiation. It is a well-established method for the surface modification of polymers and also positively affects printed conductive ink samples [9]. By selectively degrading and removing the insulating binder/matrix material, the interconnection of individual conductive particles is improved.

For this study, plasmas were generated through two different methods, corona discharge and gas ionisation using a plasma torch. Corona treatment is the exposure to high voltage spark discharges between the tip of an electrode and a metal plate on which the sample is positioned. By contrast, the plasma torch works via the continuous ionisation of a gas stream.

We found that the effect of corona treatment on bio-based carbon fibre inks strongly depended on the distance between sample and electrode tip. Larger distances had a moderate beneficial effect on the conductance up to a threshold (5 mm) above which significant damage occurred to the sample (see Figure 2). This, at first sight counterintuitive, observation can be explained by the lower frequency and higher intensity of the discharge processes at higher inter-electrode distances. Overall, corona treatment achieved a maximum increase in conductance up to a factor of 2.5.

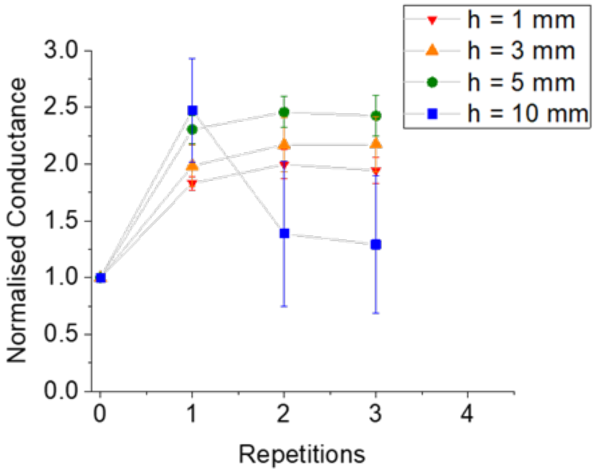

Figure 2: Effect of repeated corona spark treatment on the conductance of a printed bio-based carbon fibre ink at different distances (h) between electrode tip and sample (treatment speed 300 mm/min, voltage 24 kV). Error bars represent standard deviations (n = 3)

Scanning electron microscopy (SEM) revealed the formation of microscopic holes in the printed ink patterns (see Figure 3). We suppose that these holes mark the impact locations of individual sparking events. In their vicinity, the material consisted of carbon fibres mixed with globular carbonaceous material. These globular structures probably are the degradation products of non-conductive components. Raman spectroscopy did not reveal significant differences between treated and untreated samples, suggesting that the total fraction of carbon formed by binder degradation was low. This is also consistent with the fact that the deposits were present only in the direct vicinity of the impact holes.

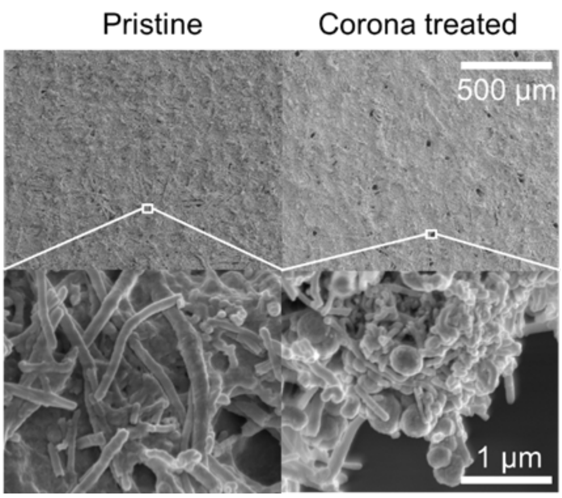

Figure 3: SEM images of pristine and corona treated bio-based carbon fibre ink at low (top) and high (bottom) magnification

For comparison, samples were also treated with a continuous plasma torch, fed either with air or nitrogen. However, the effects of the two feed gases on the ink's properties were very similar. Varying the distance between torch nozzle and sample revealed a relatively narrow operating window for conductance improvements. When too close, the samples were burnt; when too far away, no changes were measured. The maximum conductance improvement factor was three, very similar to the corona treatment. However, we did not observe holes or globular carbon deposits. These structural differences reflect the more homogeneous, uniform and gentle nature of continuous plasmas generated by a torch, compared to the more vigorous, but localised impact of spark discharges.

2.1.5 Laser annealing

Laser treatment is an elegant manner to selectively heat functional components deposited on thermally sensitive substrates. This is achieved either by choosing a wavelength not absorbed by the substrate material, or by only exposing specific locations to the laser beam. Lasers have been widely exploited for the sintering of metal-based conductive inks [11]. Using a carbon dioxide laser (wavelength 10.6 µm), we scanned the sample with the beam (line spacing 200 µm), varying both speed and laser power. The ideal settings were 100 mm/s at 4 W; at these values, conductance was improved by up to a factor of five. Slower scanning and/or higher powers inflicted significant thermal damage on the samples. Further investigation found that compensating a higher laser power by increasing the scanning speed was not successful.

Under identical treatment conditions, laser annealing was more effective and faster on a thinner paper substrate (see Figure 4). This suggests that the total thermal mass of the sample has a significant influence on the annealing processes. A thinner substrate allows higher temperatures as the generated heat has less material to diffuse away. The higher peak temperatures on the thinner paper produce a more effective annealing.

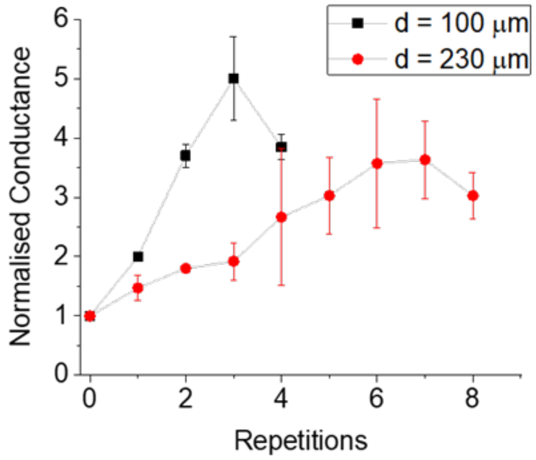

Figure 4: Normalised conductance of carbon fibre inks as a function of laser scan repetitions (4 W, 100 mm/s) on papers of different thickness (d). Error bars represent standard deviations (n = 3)

Raman spectroscopy showed a broad peak emerging between the G and D bands of the fibres after laser treatment (see Figure 5), which is indicative of the formation of amorphous carbon [12]. SEM imaging revealed globular carbon deposits similar to those already identified after corona plasma treatment (see Figure 6). However, here those structures were dispersed throughout the sample rather than localised at certain spots. They are likely carbonaceous deposits formed by the rapid thermal decomposition of insulating ink components. The increase in amorphous carbon content detected by Raman spectroscopy indicates a higher abundance in the laser treated samples. This is also consistent with the stronger positive effect of laser annealing on the samples' conductance values.

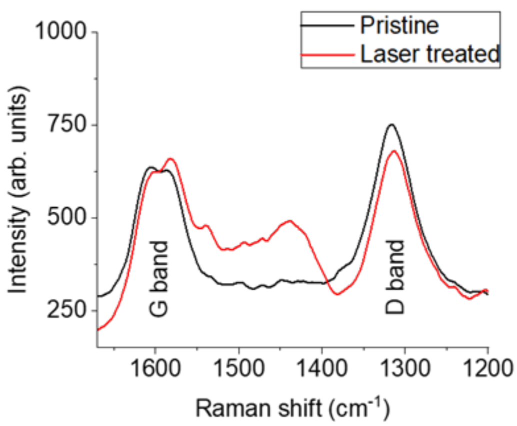

Figure 5: Raman spectra of pristine and laser treated carbon fibre ink on paper (d = 100 µm)

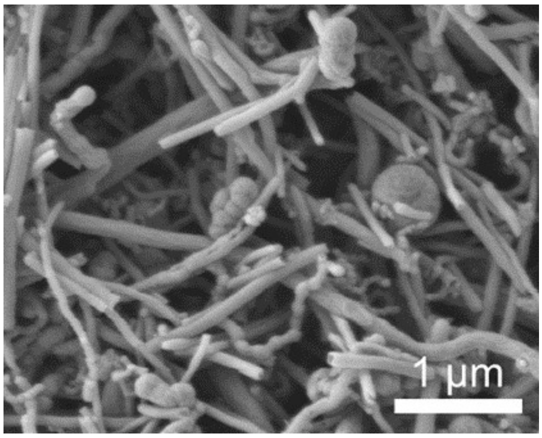

Figure 6: SEM image of a laser treated bio-based carbon fibre ink on paper (d = 100 µm)

2.1.6 Photonic flash annealing

Photonic flash annealing represents one of the most successful alternatives to the traditional post-deposition heat treatment for conductive inks [13]. For metal-based products, it only takes milliseconds and can result in conductivity increases of several orders of magnitude without damaging the substrate materials. It has also been demonstrated for carbon-based conductive inks [14]. We used broad emission spectra Xenon flash lamps with excellent control over parameters such as pulse shape, duration and intensity. The black carbon fibre ink strongly absorbs these light flashes, whereas the white paper does not. This induces intense temperature spikes that are locally confined to the ink. We observed a trend of increasing conductance with increasing energy density, and the process was faster with short but high-power density pulses. However, too high intensities led to partial ablation of ink material, resulting in lower conductance (see Figure 7). Similar results were obtained when samples were treated repeatedly with identical pulses. Optimised conditions improved the conductance up to a factor of eight.

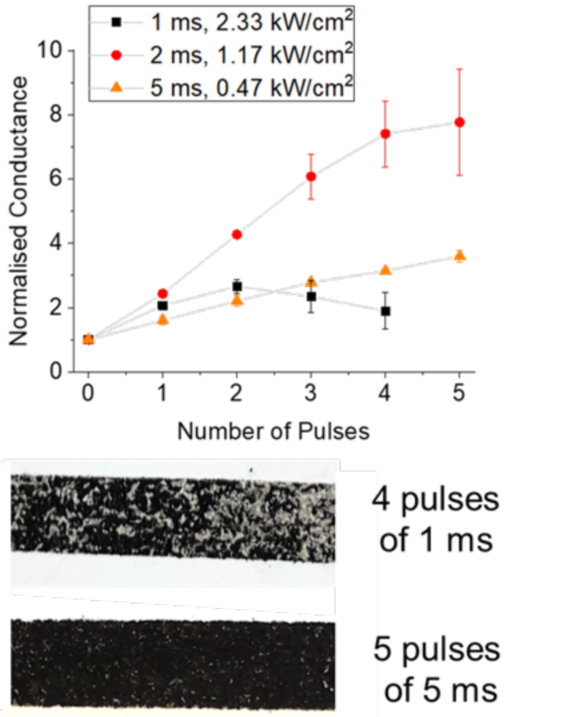

Figure 7: Normalised conductance of bio-based carbon fibre inks treated with photonic flash annealing using light pulses of different durations and power densities (top). Error bars represent standard deviations (n = 3). Samples with (centre) and without (bottom) partial ink ablation due to excessive annealing

SEM and Raman analysis of ink samples subjected to photonic flash sintering revealed a similar situation as already described for several previous techniques. Globular carbonaceous deposits were identified, as was an increase of the Raman peak indicative of amorphous carbon (see Figures 8 and 9). These results are consistent with findings from plasma and laser annealing experiments. Localised, fast and intense temperature increases lead to the degradation of non-conductive ink ingredients which redeposit as amorphous carbon globules. These methods remove non-conductive components or transform them into additional conductive material. Both effects contribute to improving the electrical performance of the printed ink.

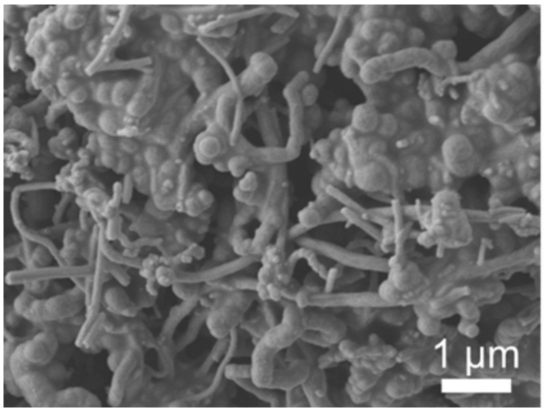

Figure 8: SEM image of flash annealed bio-based carbon fibre ink on paper

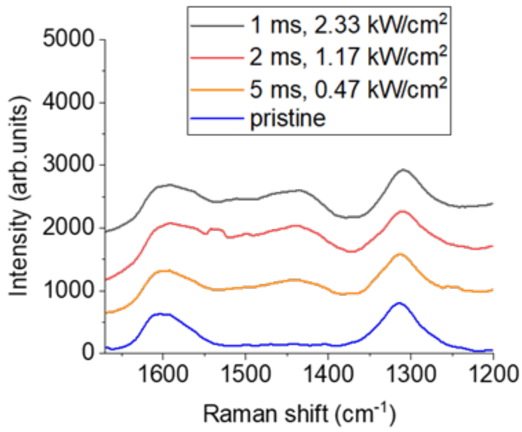

Figure 9: Raman spectra of pristine and flash annealed bio-based carbon fibre ink on paper

2.1.7 Ion implantation

Ion implantation is a technique developed to introduce chemical elements into materials to modify the properties of surfaces and thin samples in a highly controlled and selective manner [15]. The high energy ion impact involved in these processes has also been employed to degrade organic materials [16]. Ion implantation with Helium ions achieved substantial conductance improvements (up to 20 times) but took several hours. It also led to a complete change in micromorphology and internal structure of the carbon fibres, as evidenced by SEM and Raman spectroscopy (see Figures 10 and 11). Specifically, the fibres appeared to be partially etched and the contents of amorphous carbon was massively enhanced. A control experiment revealed that the ion implantation also severely affected the bare paper but did not produce any detectable conductivity. This indicates that the positive effects on materials performance are due to the changes induced by the He ions on the ink components. The value of this approach is mainly for scientific purposes.

The observed structural and chemical changes induced during this process can provide important information to steer the development direction of other methods with higher relevance for practical industrial applications.

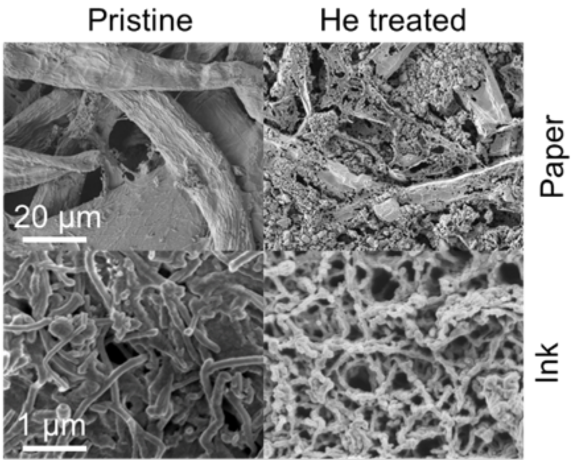

Figure 10: Low (top) and high (bottom) magnification micromorphologies of bare paper and bio-based carbon fibre ink prior to and after He implantation

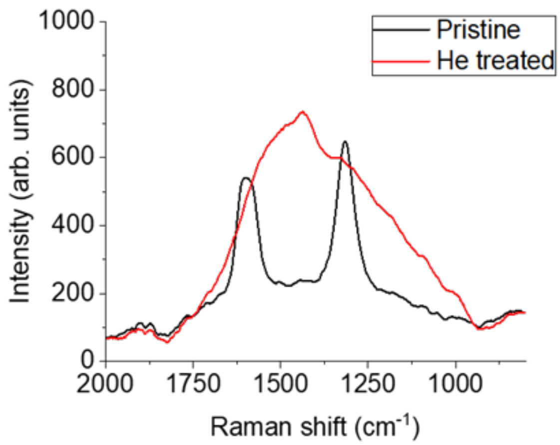

Figure 11: Raman spectra of bio-based carbon fibre ink prior to and after He implantation

2.2 Potential for industrial application

Our results allow a comparison of the impact of various post-deposition treatment methods on the conductance of printed bio-based carbon fibre inks. However, for a successful implementation in a Green Printed Electronics (GPE) production environment, reliability, speed, robustness and scalability also need to be considered. Economic viability in relation to already existing competing technologies is another important aspect. Compatibility with roll-to-roll processing methods is a major benefit as this manufacturing process is widely used in the mass production of traditional (non-green) printed electronic devices [17]. Roll-to-roll processing allows high-volume and high-throughput manufacturing at low costs for products such as antennas and biomedical sensors. On-going research activities are establishing its use for high-value devices such as solar cells and light emitting diodes.

Mechanical compression, thermal annealing and plasma treatment can easily be integrated into roll-to-roll production processes. However, their limited enhancement of conductance makes them less attractive for the processing of bio-based conductive inks. Microwave annealing has limited effectiveness and is challenging to apply in roll-to-roll processes.

Laser and photonic flash annealing are effective for improving conductive carbon fibre inks. Both techniques have been integrated in roll-to-roll production processes. Generally, photonic flash annealing is the preferred method because this technique is less challenging, requires less complex equipment and is suited for high production speeds [18]. Additionally, in our case, the positive effect of photonic flash annealing on conductance is almost twice that of laser treatment. While ion implantation is most effective, this approach is slower and requires complex specialised equipment compared to the other methods in this study. These conditions are presently prohibitive for use in industrial GPE manufacturing, particularly for in-line and roll-to-roll applications. However, research continues to reduce the barriers to applications of ion implantation in in-line manufacturing [19].

2.3 Environmental and health aspects

Current manufacturing processes in the printed electronics industry employ both metal-based and carbon-based inks. The most commonly used metals are copper and silver, which generally outperform carbon when high conductivities are required. With regards to the ecological footprint of printed electronic devices, a reduction in heavy metal use is desirable. It would reduce the reliance on non-sustainable mineral resources and minimise potential releases into the environment at end-of-life. Post-deposition treatment methods that increase the performances of carbon-based conductive inks are therefore likely to contribute to a wider replacement of metal-based products, resulting in a greener printed electronics industry.

Most established carbon-based conductive inks contain graphite flakes, graphene sheets or carbon nanotubes. These are free of heavy metals, but still mostly produced from fossil resources. Replacing these materials with carbon fibres derived from lignin, an underused renewable by-product of the pulp and paper industries, can further reduce the inks' environmental impact.

With regards to consumer safety, a number of nanosized carbon components have been suspected to have negative effects on human health. These concerns are particularly related to carbon nanotubes [3]. The main contributor to their suspected harmfulness is their nanoscale size (< 100 nm) in at least one dimension. The diameters of bio-based carbon fibres derived from electrospun lignin are in the sub-micron regime. Their substantially larger size makes them potentially less harmful.

3 Conclusions and Outlook

We have investigated, compared and benchmarked several post-deposition treatment methods for printed bio-based carbon fibre inks with respect to their applicability in GPE manufacturing. With regards to conductance improvement, varying effects have been observed, from essentially none (mechanical compression) up to a factor of 20 (ion implantation; see Figure 12). However, ion implantation is currently limited with respect to its potential for industrial implementation. Overall, photonic flash annealing is the most promising approach. It combines a decent performance improvement (up to a factor of eight) with already proven roll-to-roll compatibility for printed electronics manufacturing. A comparison of the various technologies, taking into account several performance aspects, is provided in Figure 13.

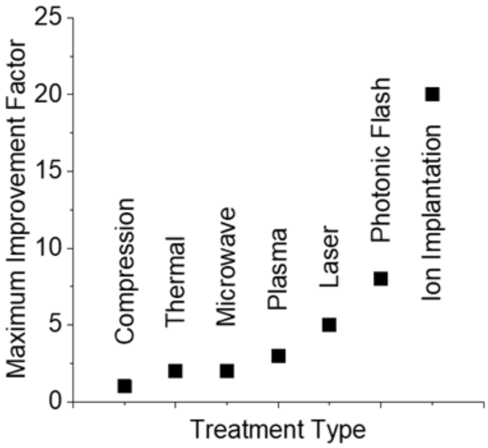

Figure 12: Comparison of post-deposition treatment techniques with regards to their respective maximum conductance improvement factors for bio-based carbon fibre inks

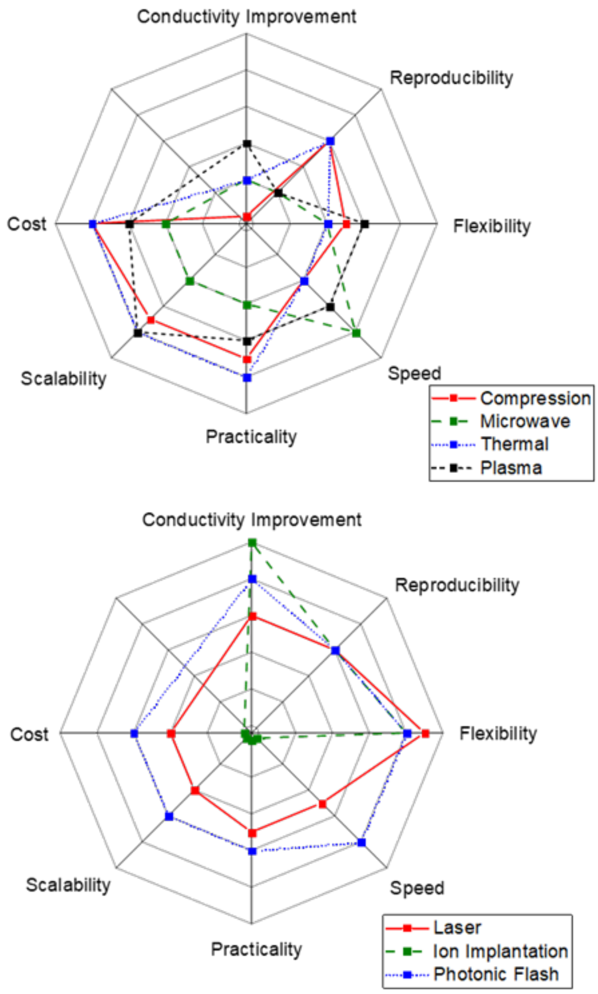

Figure 13: Radar plots comparing various performance aspects of the methods evaluated in this study

For several different methods, the same basic mechanism was ascribed to the observed conductance improvements. It involves the degradation of our bio-based non-conductive ink components (dispersants and rheology modifiers) which are either removed or transformed into conductive amorphous carbon. Experimental support for this proposed mechanism comes from SEM and Raman spectroscopy. The degradation reduces the contents of insulating material and the re-deposition improves the connectivity between the carbon fibres. Both phenomena contribute to the observed improvements in functional performance. The degradation processes are thermally and/or chemically induced. The high temperatures required for thermal degradation can be achieved via microwave absorption, plasma discharge, laser or flash light absorption. The differences in the processes' efficacies are likely resulting from the different extent of the degradation processes.

To achieve a truly sustainable GPE industry, further technology developments are still necessary. We identified photonic flash annealing as a promising candidate to improve printed bio-based conductive inks. However, for our carbon fibre ink the demonstration of the technical feasibility of roll-to-roll processing is still pending. In addition, post-treatment approaches that combine several technologies might be even more effective than photonic flash annealing alone. Finally, a thorough study demonstrating the innocuity of bio-based conductive inks containing sub-micron sized carbon fibres is also necessary.

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Sustainable materials and processes for electronics, photonics and diagnostics

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Abstract

This paper discusses applicability of sustainable substrate alternatives for printed and other roll-to-roll (R2R) compatible electronics, photonics and diagnostics. Substrate candidates include bio-based plastics and cellulose based substrates, including paper, carton board and nano cellulose. This paper takes a case-specific approach for sustainability and besides changing the substrate also discusses other sustainability aspects for a temperature monitoring intelligent package solution. End-of-life processes, such as recycling, composting and biodegradability, will be paid a due attention. The role of life cycle assessment (LCA) as the main tool for quantifying environmental impact is discussed. The paper will summarize a set of selection criteria that sustainable devices have to fulfil in order to function as part of electronics, photonics and diagnostics products and at the same time be compatible with printing and other R2R compatible processes. Innovative component and device opportunities that increase electronics, photonics and diagnostics product sustainability are defined, and industrial expectations towards sustainability is summarized.

1 Background

Europe has a goal to become the world's first climate-neutral continent by 2050. In December 2019, the EU presented the European Green Deal, which is a roadmap for making European economy sustainable while also ensuring that the transition is competitive and inclusive for all of Europe [1]. This forces all industries, including electronics, photonics and diagnostics industry, to think how to find balance between economic growth, resource consumption and environmental issues.

One of the challenges in the electronics industry is that global electrical and electronic waste production is expected to increase from 47 to 72 million tons from 2017 to 2022 with 6.5 Compound Annual Growth Rate (CAGR%) as more electronic products are used [2]. In addition, the global consumption of material resources has increased fourteen-fold between 1900 and 2015, and is projected to more than double between 2015 and 2050 [3]. Just 20% of this waste is collected and recycled under appropriate conditions, with the remaining 80% posing environmental and health concerns [4]. This might result in some rare and valuable materials, also used in modern electronics, to run out. Furthermore, new types of components are merging that will at some point of their life-cycle end up in the biological environment. For example, sensors for precision agriculture, environmental monitoring or intelligent packaging as well as disposable diagnostic devices. These challenges call for actions to decrease the environmental footprint of electronics, photonics and diagnostics products.

There are different perspectives for environmental sustainability, and this paper focuses on these aspects [5]:

1. Use of materials originating from renewable resources, e.g. cellulose based materials or bio-polymer based plastics
2. Use of compostable or bio-degradable materials
3. Use of energy and material efficient manufacturing processes, e.g. R2R compatible printing and other methods
4. Effective reuse/recycle of materials, components and products i.e. circular economy
5. Design of products tailored for circular economy i.e. eco-design, circular design

At the moment, modern electronics are filled with circuit boards on which various metals (e.g. copper, indium, nickel) and composites (FR-4) or plastics (e.g.

polyimide, PET) are soldered together. Some of these materials are toxic (e.g. lead, cadmium) or break down into toxic substances. Electronics made of paper or of other sustainable substrate materials, such as cellulose based materials, bio-based plastics or bio-based composites can be viewed as a potentially cost-effective alternative in various applications. Use of these flexible and foldable substrate materials enables R2R high-throughput additive printing that is considered a more material-efficient process with less material waste during manufacturing than traditional electronics manufacturing methods. Flexible printed circuits offer several advantages compared to rigid circuits, including reduced package dimensions, reduced weight, and optimization of component available space [6]. Electronic Components and Systems Strategic Roadmap (ECS SRA) defines sustainable production as energy-efficient processes that use raw materials in an effective way, including minimized waste typical for R2R based processes [7]. It is estimated that additive manufacturing processes powered by electricity generated from renewable energy, use one tenth of the materials of traditional factory production, resulting in a dramatic reduction in CO_2 emissions and use of the Earth's resources [8]. The use of sustainable substrates also sets new demands for sustainability of ink and interconnect materials, and for their performance and compatibility. Printing ink sustainability can be improved by replacing metals with e.g. carbon based materials.

International Electronics Manufacturing Initiative (iNEMI) defines the main gaps for sustainable electronics as: access to LCA data, eco-design knowledge, materials substitution and availability, and value recovery and consistent metrics [9]. In the following sections we discuss these aspects under the framework of the on-going ECOtronics research and ecosystem project [10]

2 New product innovations based on sustainable materials and processes

New business opportunities for companies operating with sustainability targets have been defined by ECOtronics project:

- Sustainable materials: Materials are required that are environmentally friendly, societal and financially sustainable, and based on renewable resources.
- Eco-design and circular design: Invention of product designs and existing products (re-designs) that increase product life-cycle and lifetime, increase energy and material efficiency, and close the materials loops. Ability to disassemble materials and components results in reuse of materials, and easy separation of materials for recovery. For example, currently 1.5 billion smartphones are sold annually, representing a potential $150 billion of value entering the market. At the end of the product lifetime, much of this value does not return to the material circulation due to inefficient recycling. If materials and components could be reused effectively, much of this value would remain in the system without polluting the environment [4].
- New products with sustainability as competitive edge: Companies developing and integrating electronic devices can use sustainability as their competitive advantage. This will help them differentiate from the competitors, by offering products with similar performance and price, but with sustainable aspects in materials, supply chain, manufacturing processes and end-of-life management.
- Targeting to zero waste concepts: When electronics industry adopts circular economy principles, new processes and facilities are required for efficient material reuse, recycling and renewable material composting.

Environmentally sustainable devices are required for product sectors, such as, intelligent packaging, environmental sensors and disposable diagnostics. Environmental sensors are such devices that end up in the environment at some point of their life cycle. Some of them are left in the environment after use, which calls for biodegradable solutions. Disposable diagnostics are single-use devices that are used in large quantities, thus representing a waste management issue. Intelligent packaging solutions are electronic components integrated into transport or item packages. These components cannot interfere with the existing packaging recycling schemes.

The product case in this paper is a temperature monitoring intelligent packaging solution [11] (Figure 1) that is used as a demonstrator case for ECOtronics. By focusing on a product concept instead of a single component, multiple aspects affecting environmental impact and sustainability are taken into account. The product concept is based on small surface mount device (SMD) components including a thin near field communication (NFC) temperature monitoring integrated circuit (IC) (thickness 40µm) for logging and communication, and light emitting diodes (LEDs) (thickness <200µm) for indication of logging and threshold temperature. The circuit is R2R printed, and the energy module for powering up the device is based on a printed supercapacitor with organic photovoltaics (OPV) as the energy harvesting method [12] implemented with sustainable and non-toxic materials.

Printed diodes and transistors can be integrated for implementing the supercapacitor (SC) loading and conversions circuits. This energy module, having the size of a credit card, is designed for indoor operation conditions to provide 2.3V supply voltage. This solution provides potentially environmentally friendly alternative to batteries.

Figure 1. Rough design for temperature monitoring package.

The following sections will discuss different environmental sustainability aspects for this product case collected during ECOtronics: material selection, manufacturing processes and environmental impact quantification.

3 Material requirements

The requirements for the substrate material come not only from the application specific requirements, but also from the printing process requirements and inks. For a R2R based printing process the typical substrate thickness is between 35-375 µm to enable smooth running of the process. The material should be dimensionally stable even in elevated temperature, which can be up to 140°C during curing and sintering process of the ink and even higher for some inks, but only for a short time. Some inks require UV-curing (e.g. 200 W/cm at 365 nm), which states stability requirements against UV-light exposure. The attachment of the ink and deposition of coating layer may need plasma treatment to activate the substrate surface for better ink and coating wetting or adhesion, so there is tolerance needed for the plasma treatment. Even though plasma treatment can activate the substrate surface, at least for a short time, the substrate should be non-conductive as such to ensure electron transfer only along the printed areas.

From the ink perspective, the substrate should be chemically inert for the solvents and additives normally used in conductive inks (e.g. glycols, pyrrolidone, sulphonic acids, some alcohols, methyl ethyl ketone). One of the main criteria in ink-substrate interface phenomena is proper wetting properties related to surface energy of substrate and ink, hydrophilic-hydrophobic properties, as well as ink viscosity and roughness/smoothness of the substrate surface. The surface energy of the substrate should be relatively high or at least higher than in ink. The most common method to analyse that is contact angle measurement. Hydrophilic-hydrophobic properties and viscosity typically defines the penetration of the ink at least in the paper-based substrates. In those the surface roughness or smoothness also becomes more an issue than in plastic-based substrates. [13]

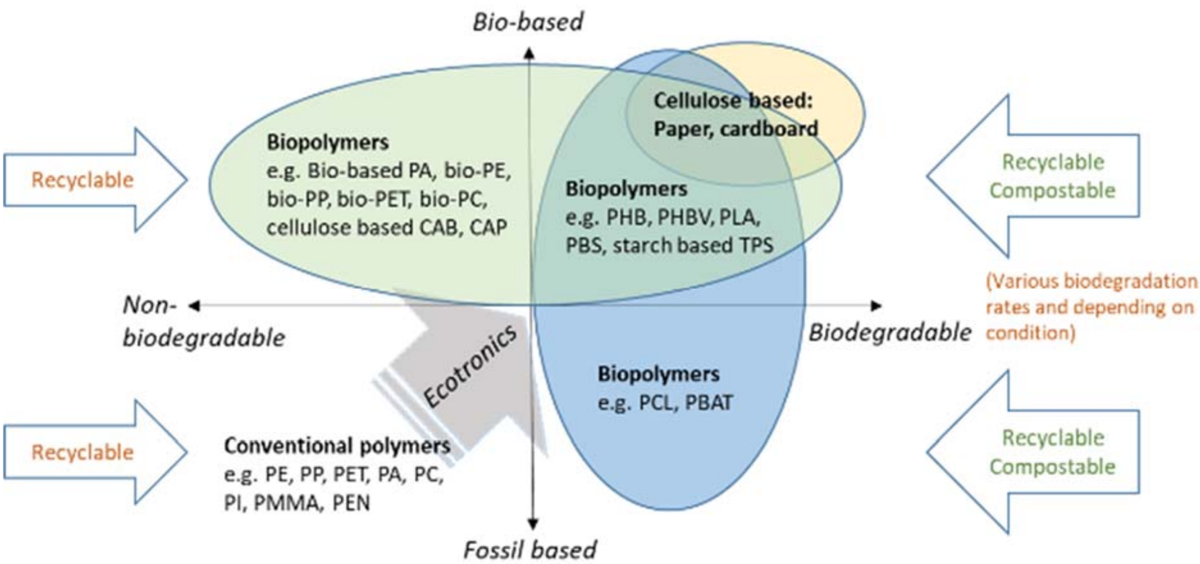

Figure 2. World of substrates used in printed electronics with Ecotronics approach added.

The transition towards sustainable electronics also needs change in substrate material from oil-based substrates (e.g. PET or PI) commonly used in printed electronics towards renewable or bio-based substrates, such as cellulose based papers and cardboards, and biopolymers. Besides being from renewable based origin some of the materials are also biodegradable enabling their use in e.g. environmental diagnostics. All substrates selected for Ecotronics are recyclable. The material selection potential is illustrated in Figure 2.

Material properties of the substrate must be at a sufficient level from the point of view of electronics application, package manufacturing and end-product functionality. Smoothness, hydrophilicity, opacity, temperature resistance, stiffness, strength and convertibility are properties that are achievable at an adequate level from an industrial range of materials.

3.1 Fiber-based materials

Fiber-based materials are versatile materials, however some characteristic features limit their use in some applications. Poor barrier properties and sensitivity to elevated moisture levels are the most significant of them [14]. These properties can be substantially improved by coating them with a barrier layer, where most commonly fossil-based polymer films are used to improve the water resistance of fiber-based materials, but repulping this kind of coated material is difficult. In addition, coating of the fiber-based substrate creates a smoother and low porosity surface and decreases the excessive absorption and wetting of the ink. Together with the surface strength, the coating layer can also improve rub resistance, which enables the production of higher quality printed images. When considering more sustainable materials, bio-based polymers can be utilized for coating. Due to their characteristic features, bio-based coatings often require a combination of different materials to achieve target properties [15]. Multi-layer type coatings are one possibility to improve the material and coating properties, since a single biopolymer layer rarely has properties that can compete against synthetic films [16].

Several commercial material options are available to implement the targeted packaging solution presented in Figure 1. Suitable sustainable fibre-based materials include for example solid bleached sulphate board (SBS), folding boxboard (FBB) and other board alternatives. These are compostable and biodegradable materials that can also be pulped and recycled.

3.2 Bio-polymer based materials

Biopolymers for Ecotronics are selected according to application needs. Selection criteria can be potential for recycling in existing recycling streams, or recycling logistics in future, or whether it needs to be biodegradable. Some of the applications need long term durability and stability during processing and in use conditions. The natural replacement for oil-based polymers is to use their bio-based counterparts (e.g. PET vs. Bio-PET)

3.3 Inks

In addition to substrates, sustainable electronics requires inks which do not contain materials or chemicals of 'high concern' either when ending up in the environment, or disturbing the recycling process. Sustainable inks can be biodegradable or from renewable based raw materials, they contain no heavy metals and have only low or no volatile organic compounds (VOCs) during the printing process. For example, according to the USA National Association of Printing Ink Manufacturers (NAPIM), a bio-renewable ink is derived from plant, or animal origin. These can include resins, gums, oils, waxes, solvents and other polymer building blocks. It can also contain water. NAPIM's Biorenewable Content (BRC) program assigns inks an index number, which gives an independent verification that an ink contains a certain percentage of bio-renewable content [17-18]

In electrically conductive inks the sustainability is highly related to conductive particles used in ink. Typical selection for high conductive purposes is silver nanoparticles containing inks, which can be replaced with aluminium or copper nanoparticles in lower cost applications. To avoid their oxidation sintering is sometimes needed, that however cannot be applied on heat sensitive substrates e.g. some bioplastic or paper. One solution is to go to carbon based such as carbon nanotubes or graphene-based inks or even nano-diamonds. [19-21]

4 Process requirements

One of the building blocks for the ECOtronics demonstrator is OPVs. As part of the energy module, it can harvest energy both outdoors and indoors, utilizing sunlight and artificial light sources even in low light conditions. Until now, OPVs have reached power conversion efficiency (PCE) of 17% under solar irradiation, and 28% under fluorescent light. [22-23] Furthermore, OPVs are able to generate the same level of voltage under various lighting conditions, which demonstrates compatibility for small energy autonomous systems, e.g. in IoT and wearable applications. [24]

OPV structure comprises ultra-thin layers of materials, where each has a thickness typically from a few tens of nanometres to ten micrometres. This means that the material consumption is extremely low. In addition, the fabrication can take place exploiting wet deposition methods, in particular well-established high volume manufacturing R2R processes, namely printing and coating techniques. [24-25]. Recent progress shows 13 % efficiency for R2R fabricated OPV under fluorescent and LED light sources, using materials that have already been up-scaled in larger production quantities to enable R2R fabrication. [24] The fabrication under ambient conditions allows replacing energy-intensive inert atmosphere or vacuum processes, improving the production efficiency through conservation of materials and energy. The energy payback time (EPBT) of OPVs is the shortest among photovoltaic technologies and it describes the time that the solar cell needs to produce the energy required for its production, including e.g. the production of all raw materials. According to the literature, EPBT has reached few months but even a one-day EPBT could be possible in the future. [26]


a)

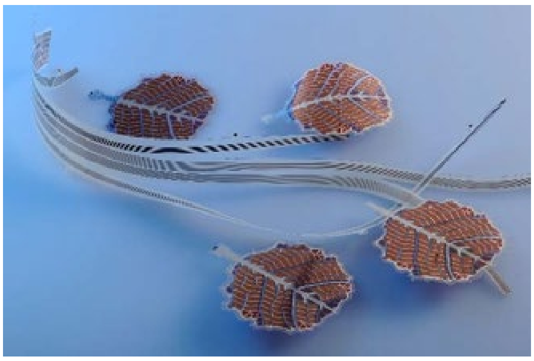
b)

Figure 3. a) R2R pilot fabrication equipment at VTT and b) printed free-form OPVs [27].

OPVs are possible to fabricate using non-toxic, non-hazardous materials. Devices can also comprise materials inspired by nature. For instance, utilization of materials such as amino acids and peptides are possible in charge transportation. [28-29].Fabrication of OPVs using renewable materials that are safe and not suffering from excessive consumption, provides an environmentally acceptable alternative to complement the sustainable energy production.

As a part of the energy module and packing solution, OPVs are possible to fabricate as a part of a monolithic structure. Flexible and lightweight devices allow the printing of customized structures into any 2D shape, providing freedom of design. [30]

5 Environmental impact

Life cycle assessment (LCA) is a method for assessing the environmental impacts of product, service or system throughout its life cycle, i.e. starting from raw material acquisition extending to the grave, i.e. to waste management [31-32]. Life cycle assessment offers a tool for assessing the environmental impacts of a product of a system comprehensively, instead of only looking at the impacts of one life cycle phase (e.g. production), and thus prevents transfer of problems from one life cycle phase to another. In principle, LCA quantifies all the energy and material inputs used, and all the emissions and waste materials produced throughout the product's life cycle. Through the assessment, an understanding of the environmental impacts of the product is established. LCA is based on the ISO standards 14040 and 14044.

Several studies have applied LCA for assessment of printed electronics. These include Liu et al. [33] who assessed the environmental impacts of paper-based printed circuit boards (P-PCBs). Their study found that the P-PCBs have about two orders of magnitude lower impacts than the reference organic PCBs.

Main sources of particularly climate impacts in the printed electronics typically stem from the substrate materials and metals used. For instance, in the case of OPVs, large part of the carbon emissions have been found to stem from the substrate, particularly when it is sputtered with indium-tin oxide (ITO) [34]. In order to reduce the environmental impacts of the substrate materials, fossil-based plastic substrates have been replaced with renewable substrate materials. Use of alternative substrate materials in printed and hybrid electronics not only potentially supports climate actions, resource sufficiency and industrial renewal, but also enables exploring the materials with better technical properties and, improving the user interface experience.

The problem in recycling and reuse of printed electronics typically lies in the separation of the different fractions. The product would be part of the waste from electric and electronic equipment. As e.g. the product studied in this paper would be small in size, it would most likely end up in the shredder light fraction, which typically goes to energy utilization. With the present price rate and technology, it is unlikely that the metals contained in small electronics would be recovered from shredder light fraction or incineration ashes. However, in the future with higher price level and more sophisticated technologies, there is potential for separation of some metals or other substances, from either incineration ashes, or through mechanic separation from the shredder light fraction. Recycling of product components can be advanced through product design. Characteristics advancing utilization include easy removability and maintaining of existing properties to as high degree as possible. Collaboration between recyclers and producers can also enhance recycling and recovery.

A large proportion of the materials used in printed electronics are plastics. Presently only about 20% of plastics in electronics are recycled [35]. One key reason preventing the recycling of the plastics in the Waste Electrical and Electronic Equipment (WEEE) directive is that the waste stream contains several different types of plastics. Furthermore, the recycling process needs to be quite complicated in order to separate pure enough polymers that can be extruded and compounded to secondary resources, which also comply with the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), and Restriction of Hazardous Substances (RoHS) regulations [35]. Bio-based plastics could potentially be composted, but at the moment their share is small making it unprofitable to separate them.

On the other hand, the conventional printed circuit board contains heavy metals such as copper and lead, which are harmful to the environment if improperly disposed. An estimated mass of 20-50 million tons of WEEE are discarded annually, and a major part of them are informally collected and recycled in developing countries [36]. Use of non-metallic materials such as carbon-based inks decrease the overall human and environmental toxicity hazard.

5.1 Recycling

Application of eco-design has a primary role in improving the environmental performance of new products, such as the intelligent packaging demo assessed in this study, throughout their life cycle. A key step in improving the recycling potential of the different components in such applications would be to develop the structures in such a way, that the different layers of materials are more easily separable from one another.

Use of printed electronics in new applications like intelligent packages, increases the challenges related to recycling of the electronic equipment and materials. In the end-of-life, the electronics are collected and treated with packaging waste. Those processes are designed for recycling of plastics, cardboard or paper materials, and the separated impurities usually end up in incineration or landfill, depending on the waste management infrastructure. For effective recycling of the integrated electronics, they should be designed so that they are easily separable either in the source separation phase by the last user of the package, or in the mechanical separation phase, so that the valuable materials can be identified and separated in the further phases for recycling purposes. Both the packaging products and the waste management system has to be further developed for taking into account the increasing amount of integrated electronics and there will be lots of challenges in this development. On the other hand, it is possible to significantly reduce the environmental impacts of the packed products by using intelligent packages. These positive impacts, like reduction of food waste, can be much larger than the impacts of the electronics itself.

6 Conclusions

Resource sufficiency for the exponentially increasing future material needs is a global challenge concerning all businesses. Electronics, photonics and diagnostics industries need to tackle and manage this challenge by i) reducing the use of rare metals and increasing their recycling, and ii) reducing the carbon footprint through implementation of biobased materials as standard materials in printed electronics, energy technology, photonics and diagnostics. However, full exploitation of renewable materials is possible only after understanding and improving the performance of renewable materials, and after developing tailored manufacturing methods taking into account material properties. ECOtronics project aims to develop sustainable materials, processes and methodologies to meet this objective.

This paper has discussed the different aspects of environmental sustainability with a case-specific Ecotronics approach i.e an energy autonomous, temperature monitoring intelligent packaging solution realized through R2R compatible printed and hybrid manufacturing. In short, product sustainability can be contributed and improved through several routes:

- By replacement of fossil based substrate material with biopolymer alternatives. This is enabled through careful selection of the materials according to the application needs with respect to the properties required for the manufacturing process and in the use conditions of the final product. In addition, setting the product-specific requirements related to the waste management is crucial.

- By selection of sustainable functional ink alternatives without heavy metals and preferably based on bio-renewable raw-materials to decrease the use of rare and toxic raw materials. Inks with no or low VOC are also preferred to enable safe and sustainable processing. At the same time, the functional properties, conductivity being often the most crucial one, need to meet the application criteria.
- By optimized process through efficient material use, energy-efficiency, (low) material waste and additive manufacturing.
- By reducing the environmental impact in general by implementing eco-design and circular design principles through minimized material use, shift from fossil based materials to renewable materials, increasing the potential to separate materials and by designing products, which will as such impact sustainability.

To summarize, the printed and hybrid electronics and photonics implemented in Ecotronics demonstrator have a vast impact on sustainability as such e.g. through efficient material use as additive manufacturing and the flexibility for changeover to renewable material alternatives as discussed above. Moreover, through components and products realized using printed and hybrid manufacturing, the impact is increased even further e.g. through printed OPVs providing sustainable energy, lightweight structural electronics enabling fuel-saving in mobility applications, sensors decreasing product waste and loss, and also diagnostic solutions enabling early detection and prevention of medical conditions.

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Electronic Jisso Technology for the New Frontiers of Sustainable Industries

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Abstract

Electronic Industry has been developed greatly among many industries that are producing artificial products. But industries that are harvesting natural resources to products such as agriculture, forestry and fishery or healthcare industry could improve productivity of their own by adopting electronic technology to handle information. That is because our intelligence can be improved by using information processing ability of electronic equipment and can make industry system as productive one. Nowadays the other industries of artificial products like automotive or another mobilizing mechanical product could also improving availability and performance progressively by adopting electronic technology. As the electronic products are utilizing many substances to improve performance we must be careful of the risks that could be increased when many different industrial sectors are involved. The risks are accumulation of risky material in the environment and the shortage of material supply under the poor management of massive production and usage. All industrial sectors are requested to be developed them as sustainable industries. We show the role of Jisso Technology to save material consumption and keep material controllable.

1 Introduction

Electronic Technology is the technology to transform information and energy utilizing electron that is one of the elementary particles of lepton and composing material. Electronic industry produces products applying electronic technology. The major products of this industry are products of artificial ICT (information and communication technology) category. Nowadays we see the world where we can use a lot of electronic product of ICT category in anytime and everywhere. It is the result of the rapid development of micro fabrication technology on semiconductor or Si and opt-electronics. That is to say the world of pervasive electronic equipment as the fruit of technology development to save energy and material. Electronic technology provides us tools to improve our ability of information processing dramatically. Adopting these tools on the frontier industries such as mobility industry, agriculture and farming, bio medical industry, civil engineering and architecture industry and education and culture, we can expect similar result on saving energy and material. But we must be aware of the risks on environment and material shortage by poor management as the electronic industry uses many natural and artificial resources such as metals, oxides, chemical products, rare metals and rare earths to improve electronic performance. Electronic Jisso Technology that is the key technology of making equipment should contribute to relieve problems on sustainability.

2 Electronic technology for a sustainability industry

2.1 A sustainable industry

There is an EU report [1] in 2020 on a sustainable industry but with no definite definition. If we define the industry as everlasting industry that could be provided enough material and energy to produce products based on the meaning of word sustainable, we must discuss about allocation problem among all industries. The other definition could be done limiting discussion as “a sustainable industry is the industry that could increase quantity of production without proportional increase of energy and material consumption”. This definition could not give the basis of everlasting production because it does not mention about upper limit of production. It only says that the consumption of energy and material per unit production is suppressed. To fulfil the meaning of everlasting the industry must be operated in a system where the industry could get all energy and material in production forever. One system model is a model of material recycling. Material put in this model is used repeatedly in production. As all products are to be returned totally after use, to-

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tal amount of material is accumulated during one product cycle that is the time duration from start of first production and the time of first return after use. After one product cycle, industry can be operated using no additional material and energy supplied by the sustainable energy source such as solar, wind without consuming resources. The definition of a sustainable industry should be like this having material return loop. But to put all material in the perfect closed loop in product lifecycle as above must be perfect reversible process in production, use and return. There is no such industry of artificial product. Again the above definition is not sufficient to cover the meaning of the word sustainable that should imply sustainable human life and environment conscious. Of course if we can put material in perfect loop the hazardous substance cannot be leaked out of the loop. But if we cannot the substance could be leaked out and accumulated in environment increasing the risk of human life and environment. By all the above discussion we define a sustainable industry as “industry that could increase quantity of production without proportional increase of resource consumption and use risky material in good controlling system” though it is an imperfect intermediate definition.

2.2 Utilization of electronic equipment in a sustainable industry

In all industries flow of energy and material is controlled by human will. If there is any part of human control (including indirect control such as fertilization in agriculture) the part has possibility to be replaced by electronic equipment. By replacing electronic equipment the system could be an electronically controlled system. In this system the controlling information gets in the electronic processor as electric signal (input signal) and goes out as electric signal (output signal) after processing. All input and output could be multiple. Figure-1 shows functional view of electronic equipment [2]. Usually Input (1) is electric signal and, more generalized case another physical signal could be the Input. The transducer shows the energy converter from the physical signals to the electric signal. Then the Input is connected to Functional module (2) and then to Output (3). There are varieties of output for many applications. Actuators are used to connect different physical signals with each other. The equipment for human sensory use at least one of the outputs must be human sensitive output, but more versatile in another applications such as mobility, manufacturing processing, horticulture and environmental control. The interfaces shown between (1), (2) and (3) are components that are used to electrical connection and mechanical connection with each other. The electrical signal matching must be kept. The interface structure is very important subject of Jisso Technology. Supply (4) is energy source or material source to function the equipment and Exhaust (5) is wasted material, heat loss and other loss along with using it. To make this equipment as sustainable manner is one subject of sustainability and to find the new frontier of application to enhance sustainability is another subject of sustainability.

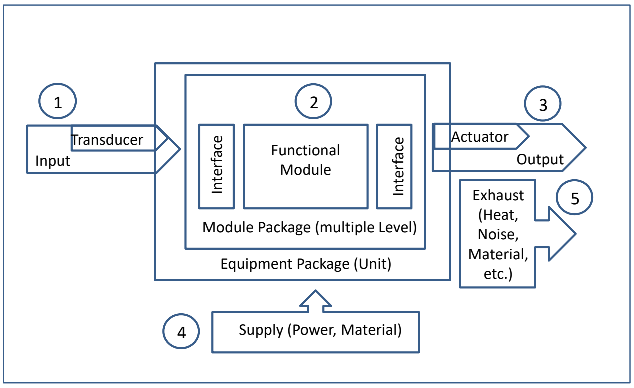

Figure 1: Electronic Equipment (Functional View)

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2.3 New technology to motivate new application in industry

A big advance was appeared in lighting device. LED (Light Emitting Diode) is now replacing incandescent bulb and LCD and OLED (Organic Light Emitting Diode) had replaced CRT (Cathode-ray Tube). Those innovations are still on the way of innovation. CNT (Carbon Nano Tube) application in lighting and electron source is typical example. Together with this innovation the heat management technologies are in progress because these technologies concentrate energy in very small part of components. Therefore the Jisso technology that release excessive energy in small part removes limit of application. The advancement of LED is changing plant factory. In vegetable plant LED spectrum is properly selected to get fast grow of vegetables [3], [4], [5]. The temperature, moisture and fertilization are controlled by remote monitoring [6], [7], [8], [9], [10], [11], [12]. The installation environment of equipment is very different to consumer electronics. Thin flat and light weight lighting device is changing the design of living house. Another progress is progress of secondary battery especially Li-ion/ Li-metal type battery. Drones and Robotics [13] will evolve new applications in the next decade. The technology requirement of those two is different but light in weight and flexibility will be appreciated. Therefore the thickness of flexible printed circuit will be examined by the base material. For example the thickness of insulating layer has very big allowance for breakdown voltage. From the view of insulation of electric circuits, the voltage used is mostly less than 50V. This means that 3μm is enough thickness. But usually more than 12 μm is recommended. Of course it is not decided only by electric performance but safety parameter of mechanical strength that is affected by used Jisso technology. That is if a proper material and technology invented the thickness can be reduced. This kind of factor of safety is sometimes seen in old design.

2.4 Immature technology for the future application

Accelerated charged particle has been developed expecting as a direct patterning method [14]. It can be focused up to nanometer scale beam size and capability to penetrate in irradiated material with small spattering. One expectation is countermeasure to UHV lithography. Though it is not successful at this timing (2020), unique mechanism to modify material has other possibilities like forming MEMS component, micro-component of fluidics, optical and electronic component. We have shown [15] that it can be applied to fabricate micro structures on engineering plastics. The structures could extend the surface function as useful components of RF devices or sensing interface. This function is useful to make small sensing devices. From the view of energy utility it is extremely low for industrial process but challenging to find break though.

3 Deployment of electronic equipment in a sustainable system

3.1 Mode of deployment

Globally there are many objectives to be controlled the flow of energy and material by will. In such a case electronic equipment must be influential to all of the objectives located globally. That is the distributed deployment. The other mode is the objectives are located in a limited location as industrial objectives. That is localized deployment. Another mode is equipment collects information of all objectives but does not act directly. This is combined deployment of distributed and localized. The design of equipment must reflect specific requirements by mode of deployments,

3.2 Requirement for distributed deployment and new technology

In distributed deployment a lot of equipment must be installed in diversified location. To be sustainable, it must be specially considered to reduce resource to produce equipment and supply energy in operation and reliability for keeping long usage. Technical subjects of importance are interface with transducer between objectives and equipment and a power supply. A power supply must cover feedback power after processing. The changing rate of characteristic parameter of objective is very influential to equipment design. For slow rate continual operation is not required. The design of operation duty rate is the most important to reduce power. The operating power less than 50 microwatt [16] will be supplied by energy harvesting collecting background or distributed energy. The power generated by energy harvesting is proportional to the size of power source.

3.3 Requirement for localized deployment and new technology

In localized deployment the limitation of equipment in distributed deployment is removed and the processing capability could be increased to process a lot of information in short time with big power supply. The most advanced equipment is a super computer. A processor for AI (artificial intelligence) is designed simulating human brain system using a huge IC or combined multiple ICs. AIs are emerging technologies and still in big progress and expected to solve various problems [17]. Advantage of electronic technology is capable of making huge processing in tiny space. The material requirement is decided finally by the size of this space. There are a lot of issues on software, Jisso technology, transmission technology and power supply. The power supplied to equipment is finally dissipated as heat. Integration processing unit in space increases the power density and connection density per unit space, the connectivity issue and heat management finally limit the degree of integration. Big processing unit is made using comparable material amount of a building. Performance of equipment from view of sustainability is qualified by the resource consumption per unit information source. To keep many access channels is important to enhance utility of many users. Optical interconnect is best transmission mean in terms of multiplex and transmission speed [18] however limited in signal processing. Therefore optical to electric and electric to optical interconnect are used in both end of transmission line. In a few GHz or lower frequency transmission electric wire and cables are dominantly used for interconnection between signal source and equipment by mechanical contact. Wireless interconnect is difficult to confine signal, contrary it is useful to connect moving signal source.

3.4 Requirement for combined deployment and new technology

Most localized deployment is localized deployment in combined deployment. Prevailing pervasive information terminals and ADAS (Advanced Driver Assistance System) installed vehicles under development are examples of combined deployment [19], [20]. But technical issues are quite different from both applications however same system configuration that collects information from a lot of equipment in the system and processed using huge processor and then return back information to a lot of equipment. Differences are response time, reliability, operating condition, power supply, limitation of physical dimension and mass of equipment. Similar requirements are mobilizing usage and capable to handle motion picture and availability in wide operating area. A combined deployment in plant growing system of agriculture is different. In this case the changing rate of characteristic parameter of plant is very low. In cattle farming, the changing rate of characteristic parameter of animal is shorter than plant but extremely longer than ADAS. Therefore processing capability of electronic equipment could be extremely lower. As the imaging signal contains a lot of spectrum information of objectives it could be the abundant information source in future. Without real time visual imaging data sampling operation mode of equipment could be applicable to agriculture and farming and the power source could be designed based on energy harvesting source. Even though there are differences in motional characteristics, environment and area size of movement in agriculture and farming the combined equipment system of Drone and GPS will be developed rapidly.

4 Subjects of Jisso technology to enhance sustainability

4.1 Direct concern on equipment design

4.1.1 Jisso technology on interconnect with ICs and components

Technical drivers to enhance sustainability of electronic equipment include reliable interconnection, reversible interconnection, material saving, alternative material of low toxicity, sustainable power source, heat management, identification marking for tracing. All these are led by innovation of ICs. The scaling rule [21] in MOS ICs has been contributed to improve performance to meet material saving by convenient principle. That is smaller structure has better performance. It is simple and understandable! However at this timing (2020) performance of ICs cannot be improved by simple reduction of cell size and integration because a cell size of transistor had been shrunk to the critical dimension of quantum physics. But other components are made and assembled by dimensions far from the critical dimension. The input and output are adjusted to the size of information source and interconnected with each other. Jisso technology handles all this matter of interconnection. The technology must solve all issues of combinations between homogeneous or heterogeneous material. There are many options of fabrication and interconnection. The first option is fabrication first and then interconnection. The second option is interconnection first and then fabrication. The third option is fabrication first and local modification by injecting extra energy [22]. The third option could be modified by material choice. At high, mm-Wave or higher, operating frequency the surface utility gets higher importance.

4.1.2 Interconnection and bonding

Interconnection is basic technology of assembling electronic equipment. The subjects to enhance sustainability are low temperature bonding, reversible bonding [23], [24], high durable bonding, bonding with low toxic material and direct bonding [25]. The most ideal bonding is the last one. This method is first applied to bond silicon to silicon, aluminium to aluminium, metal to metal and metal to silicon in a vacuum. But recently the technology has been more universal (metal, semiconductor, plastics) adopting different principle [26]. The advantages of direct bonding are material saving, simple interface structure, thin structure, optically smooth and electrically stable. In case of bonding material is not always disadvantageous but advantageous. It has possibility to improve repairability, add strain relief and extra functionality to bonding material.

4.1.3 Printed circuit board

A printed circuit board is an important and long used component. But it can be said as a component of massive and redundant structure [27]. Therefore the subjects to enhance sustainability are firstly to reduce redundancy as low as possible or to add extra functions in this redundancy. We can found the redundancy in filled structure by polymeric material mostly epoxy resin with flame retardant additives and silica filament or powder. This complicated structure is adopted to keep components in positions and to protect them from environment. But functionality is just connecting components each other by conductor trace. Owing to this filled structure generated heat is confined in deep with no flow channel. Hollow and partial supporting skeleton structure is supposed to be an ideal one. The other redundancy is included in rigid structure. If all circuit components are confined in a rigid board with no idle surface, there is no surface redundancy. But if there is idle surface and there is another component left, we must connect it using another extra component. The idle surface can be used if it is flexible (FPC, flexible printed circuit). Material recovery from FPC is easier than rigid board with compound dielectric structure. As the operating frequency going up surface uniformity is very important because electric magnetic wave is propagate only limited surface of conductor. RF components are easily put on surface.

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Therefore it is feasible that FPC could contribute both higher performance and material saving in opt-electric interface, wireless interface of many applications (agriculture, farming, distribution) and human sensory devices.

4.1.4 Additive technology

Typical manufacturing method is subtracting method like sculpture work. Raw material is cut in shape and cut out part is wasted. The other method is additive method. By this method all part of product is added in shape just on the part. Therefore 100% of material is utilized. This is ideal saving. A MID (molded interconnect device) structure [28] is made by this way and totally replaced printed circuit board on molded casing of equipment. Originally additive method is used to classify the category of manufacturing method as the antinomic of subtractive method of printed wiring board. Later the terminology is extended to mean all technology stated above. Key issues of this technology are materials and adding method. This method provides us ideal process to make but from the view of industrial needs the productivity must be competitive and choices of functionality must be wide. Today we have many printing methods including screen print, off-set printing, stamping, injection, ink jet and photonic method [29]. Combining these methods even 3D or 4D (Time dependent structures) printing is expanding applications. And a lot of functional materials such as polymers, dielectrics, metals, semiconductors, metal oxides and carbons are used for ink. Nano particles show different property from bulky particle. Additive method is best fitting manufacturing method from the view of EcoDesign. A recycling system introducing 3D printing has been proposed to assist CE is proposed in EU [30].

4.1.5 Alternative material

In the past alternative material was sought by the motivation to avoid toxicity. That is start of EU RoHS and Waste Framework Directive [31]. Then motivation was shifted to prevent shortage of CRM (critical raw materials) [32], [33]. Assessment based on above view point has key importance to develop new technologies to make a sustainable industry. Jisso technology will effective to get realistic solutions with recycling scheme.

4.2 Issue in product distribution

4.2.1 Arterial distribution and venous distribution

Industrial activity includes following processes. ① purchasing resource ②production process using resource ③distributing product ④use ⑤discard ⑥ recover useful resource from waste ⑦ collect or extinguish as useless or harmful waste. Usually we call from ① to ④ as arterial distribution and call after ④ as venous but it may be considered waste in ⑥, ⑦ as fuel and ⑧produce heat or electric power. This is value creation in partial circular economy but finally it turned into carbon dioxide discharged into air. Carbon dioxide is one of the greenhouse gases. There are many attempts ⑨ to change carbon dioxide as industrial resource. But at the moment it is just stored underground and deep sea or discharged into air as useless material. All material collected from somewhere in the earth finally is relocated another place after use but it could not be extinguished and still existing somewhere in the earth. Developing Jisso technology we could reduce this useless material that is turned from useful material.

4.2.2 Subject of Jisso technology in production process

All artificial products are made by many components. Therefore the start of production is component making. Then components are assembled and increase value. During production, machine, process condition and material is inspected by design guideline. To meet full producer's responsibility all above process must be traced afterward. A tracing tag that must be carried by each component is important subject of Jisso technology [34].In agriculture above production procedure is different. In this industry process control by machine is took over by environment control and fertilization. The data to controlled product is sequential but the data for plant is distributed and localized and parallel. Equipment to monitor plant is distributed. In case equipment is put apart from human monitoring, monitoring by Drone may be integrated in monitoring system. In this system all equipment can be monitored by tag on the surface for identification. The subject of Jisso technology is to make equipment reliable and low operation power and robustness to environment. Obsolete equipment must be returned to replace or make modification.

4.2.3 Subject of Jisso technology in product distribution and after

The subject of sustainability in product distribution and after is the subject of CE (circular economy). In CE scheme the product must stay long in the market as long as the quality is accepted by user. This is the case of artificial product like electronic equipment. The other case like consuming product like food is quite different. In this case the product is designed based on one time use but distributed by multistep trading. Therefore product identification method may be biometric or visual recording. Even if there is no artificial attachment on products, Jisso technology will take part on monitoring system. From the view of recycling CRM, component design and identification are important subjects of Jisso technology.

5 Jisso technology for new frontier industries

The most expected technical development in next decade will be wireless technology over mm-Wave because the technology can connect moving objects without cross talking. However it is useless if there is no optical transmission network and big data processing system back-up. A tiny module that can be operated by energy harvesting will expand real time application like human health monitoring. New technology for sensing device and Jisso technology will be a key technology for above applications.

6 Conclusion

Recent explosive development in electronic industry has brought us a pervasive equipment world. It means that we can use extensive information processing ability in any time and everywhere. It was done by Jisso technology that is mandate to make equipment. Our intension of this report is to show how it should be used in different operating conditions of different industries. In coming era every industry will evolve to a sustainable industry using electronic technology. But we must be careful about negative impact on environment and shortage of resources. A lot of data processing equipment or terminal collects data globally and creates useful information to act. But it is also in mind that a lot of equipment turns into mixed substance sooner or later. The technology must be prepared in advance.

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Overview of Circular Economy Practices in High-tech Manufacturing Industries

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Abstract

The circular economy is frequently discussed on the level of larger value chains – better: value circles -, adding a lot of complexity and interdependencies to this approach. Individual industries however, can play a significant role to close material and value circles: The environmental footprint of the high-tech sector, such as the Micro-Electro-Mechanical Systems (MEMS), flat panel display, semiconductor and advanced packaging industries, is huge, but a closer look unveils that circular economy practices are already widely adopted. This is due to some specifics of this industry, which are the very high material value, high chemicals throughput and costs, and tools invest. Under these conditions recovery of materials is an interesting business case, but faces also significant challenges, such as the complex recipes to process semiconductor substrates. Reclaim of wafers is common practice in the semiconductor industry and saves a significant amount of embedded carbon for manufacturing high-purity substrates. Reuse of carriers in LED manufacturing, panel level packaging and display manufacturing is technically challenging with costs as driver – and environmental advantages. The rapid technology progress in semiconductor industry builds on cutting-edge manufacturing tools, but what happens to this equipment after a few years? There are some excellent examples, how machinery is upgraded, remanufactured and/or repurposed in this industry. These examples will be discussed in detail in the paper, outlining challenges and solutions. The findings serve as a guideline for the whole high-tech sector to be aware of what is already possible in terms of circular approaches, but also for, e.g. the machine tools industry at large to be inspired by such examples. Overall, increasing circularity in these industries also helps to reduce the environmental footprint of information and communication technology (ICT) and other electronics products, which heavily rely on the upstream high-tech industries.

1 Introduction

The circular economy is gaining momentum through industry and policy initiatives, such as the 2nd Circular Economy Action Plan of the European Commission [1]. Typically, such approaches focus on products and product life cycles. Initially, the focus even has been on recycling of end-of-life products and only in recent years it become common wisdom that the inner loops of the Circular Economy, such as product repair, reuse and remanufacturing are even more important to reduce the material intensity of our lifestyles. Such a product focus, however, requires a significant change in the way business and products are made, involving other players throughout the product life cycle to make the whole circularity work. What is frequently overlooked, but provides ample opportunity for the circular economy, is fostering circularity within industries. Just as post-consumer plastics is much more difficult to recycle than post-industrial plastics, it is worthwhile to put more emphasize on these cycles, as this helps to keep materials in use on the highest possible level, thus reducing the overall material "leaks" of supply chains. Component and technology suppliers are frequently left behind when the circular economy is discussed as they have little influence on product circularity – but they definitely can foster a circular economy for those materials, chemicals, media, and investment goods they have under control.

This paper outlines the broad spectrum of circular activities in the semiconductor and other high-tech industry emphasizing a range of exemplary cases. The aim is to raise awareness for the already ongoing circularity activities with regard to present solutions and to unveil opportunities for industry to implement circular aspects in the environment they can influence.

2 High-Tech Industries

Globally, approximately 10 km² of semiconductor substrates are processed annually for the electronics industry, and 333 km² of LCD displays [2]. The environmental footprint of the semiconductor and flat panel display industry is huge due to cleanroom requirements, complex process recipes, purity levels to be met by these chemicals [3] and the large number of process steps required to manufacture an OLED or a microcontroller chip. This has been analysed in depth for decades now, including Eric Williams paper "The 1.7 kg microchip" [4], which still underestimates the material intensity of chip manufacturing [5]. To illustrate these impacts, e.g. for display manufacturing AUO states scope 1 and 2 carbon emissions of 51,9 kg CO_2-e per m² panel processed [6]. Despite the overall material intensity of these industries, it has to be acknowledged, that reuse and recycling of substances through internal circularity but also external processes is on a high level already. Simply, the high costs for material and media make it an economic necessity to get engaged in circular business practices. An example is the internal reuse of process water: For cleaning processes, wet benches, but also abatement and cooling, water is heavily used in these industries. This makes, i.e. display manufacturing vulnerable to water supply disruptions. Actually, this has been the case in the past repeatedly in Taiwan, where numerous semiconductor and display fabs are located and the high-tech industry was at risk to not having enough fresh water to run the manufacturing processes. This results actually in the fact that the high-tech industry in Taiwan is operating extremely water-efficient with best-in-industry reuse rates for water – just as a resilience strategy. At AUO, as one of the major display manufacturers production water recycle rate, i.e. production water recycling volume per volume of purified water used, is 91,0% as of 2018 [6]. Table 1 shows recent trends in water usage by display manufacturers in Taiwan. For the Hsinchu Technology Park in Taiwan there is even an intra-plant reclaim water exchange under discussion [7], which would mean circulation of recycled water among different manufacturers and industries.

Display manufac-turer	Water use in m³ per m² panel manufactured		
	2016	2017	2018
AUO	0,43	0,43	0,42
HannStar (Tainan site)	0,88	0,84	0,82
CPT	1,59	1,74	n.a.

Table 1: Water recycle rates at Taiwanese Display manufacturers [6, 8, 9]

Similarly, manufacturing equipment in these industries are a huge cost factor. Keeping these tools in use for a longer time is a financial issue despite the extremely short technological innovation cycles. Actually, whole fabs are "reused" for less demanding applications as technology progresses: Although for efficiency reasons much of the semiconductor industry moved towards 300 mm wafers in the last 20 years, the former wafer sizes and related technologies are still found in the market (see Figure 1).

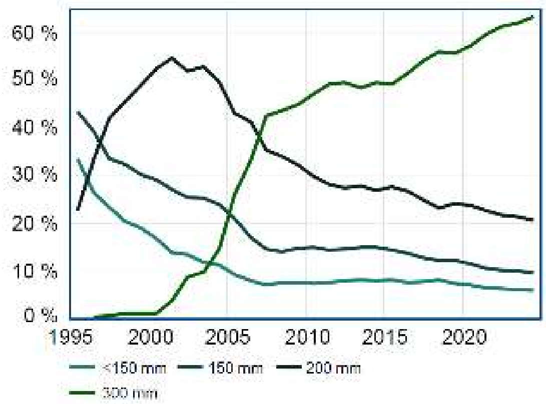

Figure 1: Global semiconductor processing capacity per wafer size [10]

A similar development took place with regard to processed display motherglass sizes, see Figure 2: From a generation 1 size of 270 x 360 mm² in 1990 substrate sizes increased to 2940 x 3370 mm² with the latest generation 11. Similar to the case of semiconductor wafers "older" generations are still in operation and also new fabs for smaller formats are build. Largest motherglass sizes are used for displays of television sets mainly, the smaller sizes of generation 4 and 5 manufacture displays for handheld devices.

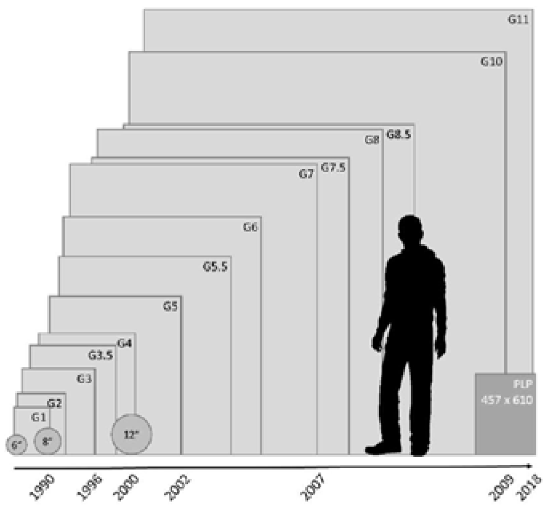

Figure 2: LCD and OLED Display manufacturing generations and year of market introduction, in comparison to wafer sizes and panel size for panel level packaging

These growing dimensions of the processed motherglass requires new and advanced machinery concepts. Tools are typically made for a specific fab generation.

Table 2 provides an overview where in the semiconductor industry circularity in principle can be embraced (examples only).

Domain	Example
Processes	Process gases / chemicals: internal recycling through upgrading quality of regenerated chemicals
	Chamber cleaning gases: internal recycling
	Process waste recycling (external): Achieving better recyclability through process control measures
	CMP (chemical mechanical planarization or polishing) slurry re-use
	Sputter target recycling
Infrastructure	Water recycling technologies
	Material recovery from abatement
Wafers	Reclaim processes
Equipment	Unit refurbishment / reuse market (from high-end applications to less demanding applications)
	System parts refurbishment
	Tool upgrading
	Recyclability, including safe decommissioning

Table 2: Exemplary activities in the semiconductor industry to keep materials and goods in the loop

3 Circular Economy Examples

The following examples illustrate the broad spectrum of circularity approaches in high-tech industries, addressing drivers and barriers. These examples are meant to inspire analogies across industries.

3.1 Process chemicals and gases recycling

The recycling of process gases within a semiconductor fab is challenging but feasible: The purification of the used process gases requires an adaptation to changing process recipes in the course of a batch process. Etch rates as an example are adapted through changed process gas composition as the etching progresses over time.

Helium is an example of an inert process gas used in semiconductor manufacturing in large amounts. Typically, the off-gas is released to the atmosphere, after abatement processes depending on other constituents. Through membrane technology process effluents can be purified and helium can be returned into the manufacturing process [11].

Recycling of greenhouse gases, i.e. perfluorocompounds (PFCs), would have a twofold benefit of avoiding high-impact emissions and reusing process gases. However, despite several tests and trials this is not yet state-of-the-art. Already ten years ago Illuzi and Thewissen [12] stated: “No evaluation resulted in successful re-use of PFC, mainly due to the high-quality demands that are made by the semiconductor industry. Besides, all systems are deemed to be too costly to implement.” This situation has not changed much since then [13]. This example of a not-yet-solved circularity challenge indicates the need for further research and innovation.

Other process chemicals can be purified and recycled at least to an industrial grade for use in other industries. Recycling spent chemicals to an electronics grade with related purity requirements is much more demanding. For an example for recycling of copper sulfate process waste water see 3.6 below.

3.2 Lithography equipment remanufacturing

Lithography processes and tools are key for the shrinking technology nodes in semiconductor manufacturing. Moore’s Law is largely based on progress in lithography technology. The tools for these processes are major assets for any fab. Unit and system parts refurbishment are strategies implemented by some semiconductor tool manufacturers. For lithography equipment this is the case with global market leader ASML: As the technology progresses there is limited use for those tools which were high-end in the 1990. Also the wafer sizes changed since then and a remanufacturing and upgrade of these tools for 300 mm wafers is just not possible. ASML identified the MEMS business for semiconductor sensor and actuator components as a potential target market for remanufactured lithography tools: The MEMS market is steadily growing (Figure 3), and the size of the structures is of much lower resolution than current microelectronics technology nodes.

The lithography equipment is completely taken apart by ASML into individual modules, which are then repaired and tested individually [14]. Note, that a modular design is now essential for such a business model. The modules are then re-assembled and integrated into the remanufactured machine, which might be adapted to a new purpose, such as accelerators or other MEMS, but also for through-silicon via (TSV) applications, where the via within the chip allows for a direct connection from the front to the backside of a chip, or radio frequency chips, which are also typically manufactured on smaller wafer sizes.

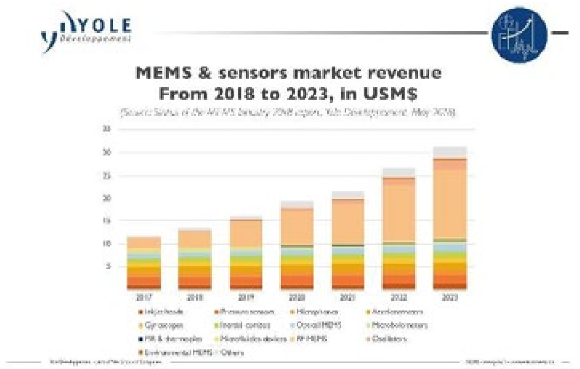

Figure 3: MEMS market development 2018-2013 [15]

Such labour-intensive remanufacturing in particular pays off for high-value equipment.

3.3 Tool component repair

Tools in high-tech industries and parts thereof are of such a high value, that not only OEMs (Original Equipment Manufacturer), but also third-party service providers refurbish tool components and thus, keeping them in (re)use. Optical components in lithography and other laser applications are one such example, where a refurbishment of lenses and similar is a viable business [16].

3.4 LCD repair and rework

Repair of pattern defects in LCD manufacturing is an option to increase the yield of display production. Compared to semiconductor ICs display patterns dimensions allow for repair in specific cases. Mainly laser based processes are applied to reconnect defective circuits, or to remove material to repair a short. Also particle bumps distorting pixels can be removed through polishing and defects of the Polyimide coating can be repaired. Such rework can improve the yield by 5-10% in large size panels at the premature phase [17]. Defects detected after a photolithography development step can be reworked by removing the photoresist from the panel and going through the photolithography process again.

Such improvements in process yield through rework and repair reduces also the carbon footprint, see data from AUO above, of display manufacturing.

3.5 Wafer substrate material recycling and wafer reclaim

Reclaim and reuse processes for gallium arsenide (GaAs) wafers are in place at semiconductor substrates manufacturers: At FCM [18] GaAs and other additives are collected in different process stages and were then returned back into the material cycle involving process waste from customers. 30-70 % of the demand for metallic resources is covered by recycling processes at FCM. To close at least these post-industrial loops is particularly important, as there is no viable technology to recover GaAs from post-consumer sources [19].

In wafer fabs reclaimed wafers are used as test wafers to optimize and monitor manufacturing processes and tools. Silicon contributes significantly to overall material costs in semiconductor manufacturing and reclaiming, thus reusing silicon substrates, reduces costs – but also environmental impacts: High-purity monocrystalline silicon wafers can contribute roughly 5-10% of the overall carbon footprint of semiconductor components. Reclaim involves removing applied material from the surface with dry and wet processes, followed by polishing and cleaning the wafer to restore the silicon surface to a grade, which is sufficient for testing purposes. Through this material removal the reclaim wafers are thinned with each cycle and cannot be reused indefinitely. This reclaim process is offered by slightly more than a dozen service providers globally. The market for reclaim wafers in the semiconductor industry is of a size of several 100 million Euro [20].

3.6 Sputter target recycling

Sputter targets are the metal sources in physical vapour deposition processes (PVD) for the metallisation of wafers with a variety of metals, such as tantalum, tungsten, nickel, copper, precious metals, but also alloys of these and other metals. Once the sputter target is exhausted residual target material can be recycled. This is in particular the case for precious metal sputter targets.

Semiconductor foundry TSMC developed a process to extract from copper sulfate waste liquid, which is generated in its semiconductor fabs, first metallic copper through an electroplating recycling system. The resulting metallic copper is then recycled together with residual target materials into new sputter targets by an external company (Solar Applied Materials Technology). These sputter targets – nearly 10 tons per year - are then used again for metallisation processes at TSMC [21]. TSMC states to recirculate 1.800 tons of liquid effluent and 120 targets per year this way.

3.7 Carrier and substrate reuse

The following examples of carriers and substrates illustrate the fact, that similar technologies are used in different high-tech industries. The individual conditions of each industry define the feasibility of keeping materials (in this case the carriers or substrates) in the loop. Definitely, there are lessons to learn across industries, how to improve circularity.

3.7.1 Flexible OLEDs

For several technologies carriers are used, which just provide stability for following processes or which act as substrate layer for a build-up of other layers, but

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does not make it into the final product. An example for the latter are glass substrates for OLED (Organic Light-Emitting Diodes) displays: For rigid displays the glass substrate constitutes an important structural element, for flexible displays after processing of the OLED layers the glass is separated with a laser-lift off process, where the laser beam is directed through the glass and decomposes a polyamide layer in between the glass and the OLED layers. In theory the glass substrate could be reused for the next processing cycle, but as the glass was already exposed to buildup processes for functional layers, the glass is typically discarded after one cycle [22].

3.7.2 Wafer thinning

The final step of wafer processing is frequently wafer thinning to allow for reduced package heights (see Figure 4), enhance thermal management or to integrate chips in flexible substrates.

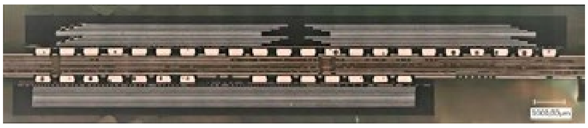

Figure 4: Cross-section of a solid state disk with stacks of thinned memory chips in top- and bottom-side BGA packages

In wafer processing applications, such as wafer thinning, glass carriers are used to provide the required stability of the otherwise fragile semiconductor wafer throughout backside thinning, which is a chemical-mechanical process. The processed wafer is temporarily bonded on the carrier wafer. In these cases the wafer carriers can be reused for multiple processing cycles [23].

3.7.3 Photovoltaics

High concentration photovoltaic cells are very expensive, so different avenues are explored to reduce the manufacturing costs. Since the substrate (Ge, GaAs or InP) is the main expenditure for the manufacturing of multi junction III-V cell, the substrate should not remain in the final product to reduce costs. GaAs accounts for more than 50% of the bill of material cost according to MicroLink [24], and accounts for 84% according to NREL [25]. It is also the best way to reduce the energy and material consumption of the global PV manufacturing because the wafer production is an energy-intensive process.

The technique performed in small-scale manufacturing to reuse the substrate is the epitaxial lift-off. A sacrificial layer is grown between the substrate and the solar cell and selectively removed by wet etching. The etch rate is the limiting parameter since a too fast etch would cause substrate breaking. For 150 mm GaAs substrate, the etch time can be around 10 hours [25]. The solar cell can be transferred to another type of carrier (flexible substrate for example). The initial substrate can be polished and reuse for regrowth multiple times. In the case of GaAs, the substrate can be reused theoretically up to 100 times [25, 26]. For Ge, only 5-10 substrate reuses have been publically demonstrated [25].

3.7.4 Fan-Out Wafer/Panel Level Packaging

Another example is the Fan-Out packaging technology on wafer but also and on large panel [27]. This packaging technique involves a temporary carrier on which chips are placed and embedded into a reconstituted over-molded substrate, that holds them together (see figure 5). By now, wafer level packaging is the dominating technology for extremely compact packages, but moving from packaging on 300 mm or 330 mm carrier wafers towards rectangular panels of sizes, such as 457 x 610 mm² or 600 x 600 mm² allows for new package designs and potentially even higher throughput. These panel sizes roughly correspond to generation 3 sizes of display manufacturing (see Figure 2), so there might a theoretical opportunity – needs to be analysed further – to reuse equipment from these fabs. By removing the temporary carrier, the final package thickness is only slightly higher than the die thickness, enabling very thin packages. Choices for the carrier material are glass and steel. Glass, similar to the lift-off processes for flexible OLEDs – see above –, can be debonded through a laser process. A steel carrier is debonded by a thermal release process.

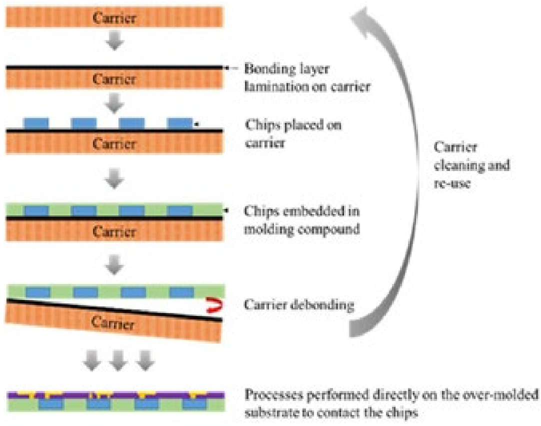

Figure 5: Simplified process flow for Fan-Out packaging (here “chip-first” approach) showing the role and possible reuse of the carrier (wafer or panel size).

Besides environmental reasons, reuse of the carrier is a cost issue: multiple reutilisation cycles are crucial to keep overall packaging costs in a competitive range: In case significantly less than 100 reuse cycles are the limit, the carrier becomes a major cost driver [28]. As this packaging technology is not mature yet, the number of possible reuse cycles for the carriers is not known yet, but there are multiple technical challenges:

- Warpage control: The carrier is subject to several processes, including thermal stress, which leads to warpage, related handling problems and additional stress on the organic panel; this is less an issue with glass than with steel
- Roughness control: scratches on the panel affect the molding process, and dies might not be embedded properly ("flying dies"); steel is more critical in this instance
- Fragility of the carrier: Glass is much more fragile than steel, and a broken carrier within the process means a loss of several thousand packages

3.8 Decommissioning of equipment and gas piping

Proper decontamination of equipment and gas piping in semiconductor fabs is essential not only if equipment is intended for reuse, but also in case of decommissioning for recycling: Remaining gases in pipes can constitute major risks for de-installation staff but also in recycling processes off-site. Some hazardous process gases diffuse into steel and are slowly released over time. This could result in toxic or flammable concentrations. Such risks might require to declare decommissioned equipment as hazardous waste. Thorough decontamination allows for a proper recycling of the equipment.

4 Conclusions

A wide range of circular activities are already existing in high-tech industries, such as semiconductor, display and photovoltaics fabs. Even internal material and media cycles in these plants typically involve external parties, such as gas suppliers who get engaged in gas recycling technology as a new business field. Many equipment providers offer continuous support for maintenance, which also includes repair and upgrades of the tools, as new features become available or the process requirements change. Third party technology companies offer refurbishment of key components, such as optical parts. Last but not least there are tool providers taking back used equipment for repurposing in other industries.

The numerous examples of circular economy activities presented in this overview are summarised in Figure 6, centered around a symbolic process flow – which in reality is passed numerous times before the final product leaves the fab for back-end packaging processes.

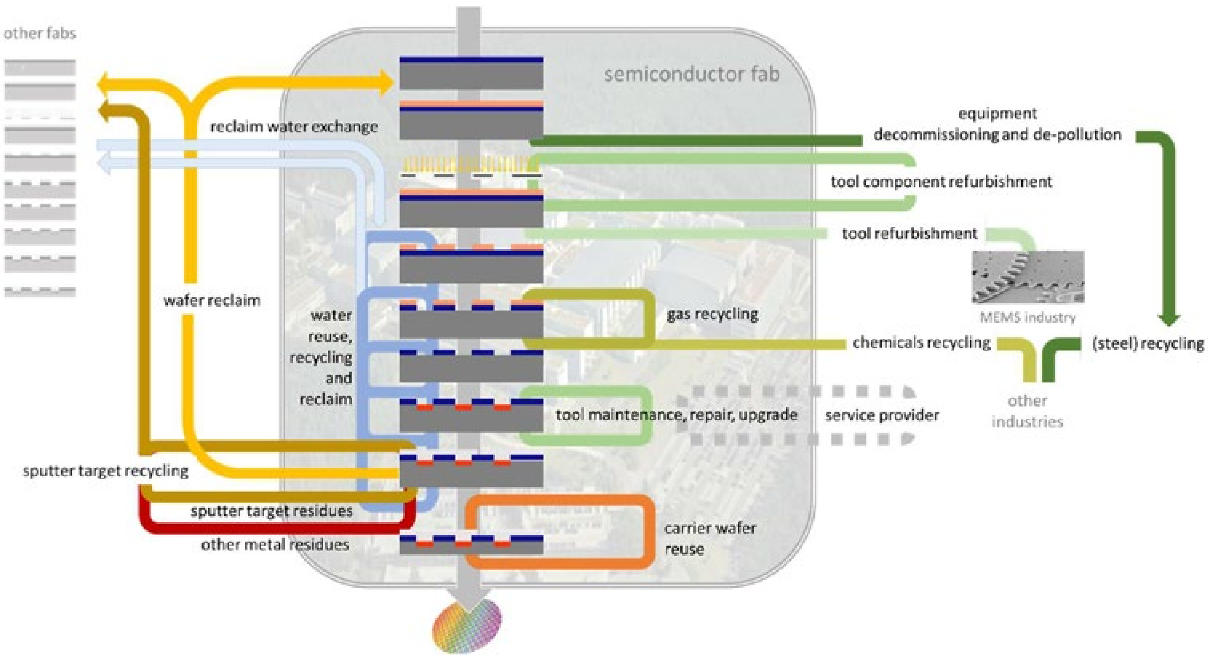

Figure 6: Overview of circularity examples in semiconductor front-end fabs

Circular economy examples are predominantly found, where non-circular practices would have a major adverse impact on costs.

Based on the ongoing circularity activities, the presented examples can act as guidelines for implementing circular economy in further areas of the high-tech industry. It is urgently needed that these industries embrace concepts of the circular economy further as this lowers the immense environmental footprint of manufacturing displays, semiconductors, sensors, LEDs and other key components of our digital world.

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Environmental load reduction technology using low-temperature solder for high-performance semiconductor packages

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Abstract

Recent year, corporate activities require development and investment in consideration of the SDGs, ESG, and global warming and reduction of energy consumption are increasingly required. As one to achieve SDGs, advance data processing such as deep learning and cloud service are required. A semiconductor package that can handle a large chip, a large organic substrate, and high current density is desired. Sn-Bi solder, which is a low temperature solder, is considered to be a strong candidate to achieve both environmental issues and high performance of the semiconductor package. By changing the solder used during assembly from conventional Sn-Ag-Cu solder to Sn-Bi solder, energy consumption can be reduced by 25%. By using Sn-Bi solder, warpage of the semiconductor package and stress of solder joint can be reduced by 50% compared with using SAC solder. In addition, by adopting TLP bonding technology using Sn-Bi solder, electro-migration resistivity can be easily improved.

1 Introduction

In response to environmental issue, lead-free solder has been required since late1990s. Recent year, corporate activities require development and investment in consideration of the SDGs (Sustainable Development Goals), ESG (Environment, Social and Governance). Regarding SDG Goal 13, that is, “Take urgent action to combat climate change and its impacts”, there is an increasing need to reduce energy consumption to prevent global warming [1]. On the other hand, Regarding SDGs Goal 9, that is, “Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation”, high performance computing technologies such as high-speed deep learning and large-scale cloud service are also needed [1].

To achieve such as high-performance computing, a 3-dimensional(3D) semiconductor package that can realize high speed and large capacity is required. However, high-performance semiconductor package requires a large size silicon chip (over 20 x 20 mm) and a large size organic substrate (over 55 x 55 mm). In case of large size silicon chip, CTE mismatch between a silicon chip and an organic substrate is significant problem. They induce large warpage of semiconductor package and large thermal stress at solder joint. And in case of high-end semiconductor package using flip chip joint, the current density at the flip chip solder joint is expected to be in the order of 10kA/cm^2 [2],[3].

Sn-Bi solder, which is a low temperature solder, is considered to be a strong candidate material to achieve both environmental issues and high performance of the semiconductor package. In case of Sn57wt.%Bi (Sn57Bi, eutectic) solder, it is possible to lower reflow peak temperature from 45-90 degrees C. compared with case of Sn3wt.%Ag0.5wt.%Cu (SAC305) solder. Use of Sn-Bi solder can be expected to reduce energy consumption. It is expected that using Sn-Bi solder can be to reduce warpage after mounting semiconductor packages and it is induced to reduced stress of solder joint.

In case of 3-dimensional semiconductor package, applying Sn-Bi solder, it can be reduced the risk of misalignment and crack of solder joints. However, Sn-Bi solder has the risk of re-melting solder during following assembly process and inducing electro-migration. Transient Liquid Phase (TLP) technique using Sn-Bi solder solve these risks. Electro-migration resistivity can be easily increased.

In this report, we will discuss semiconductor packaging technique using Sn-Bi solder joints in terms of reducing energy consumption, reducing solder joint stress, and improving electro-migration resistivity.

2 Reduction of energy consumption using Sn-Bi solder

As mentioned above, Sn-Bi solder is considered to be a good candidate for addressing environmental issues. The melting point and reflow peak temperature of Sn57Bi solder and that of SAC305 solder are shown in Table 1. The melting point of Sn57Bi and SAC305 solder are 137 degrees C. and 216 degrees C. And reflow peak temperature of Sn57Bi and SAC305 are from 150 degrees C. to 200 degrees C. and from 245 degrees C. to 260 degrees C., respectively. By applying Sn57Bi solder, it is possible to lower reflow peak temperature

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from 45-90 degrees C. compared with case of SAC305 solder. Figure 1 shows relationship between reflow peak temperature and power consumption under some profile conditions. The reflow peak temperature of 180 degrees C and that of 195 degrees C correspond to samples for Sn57Bi solder. And that of 245 degrees C correspond to sample for SAC305 solder.

Solder	Melting point/ degrees C	Reflow peak temperature / degrees C.
Sn57Bi	137	150-200
SAC305	216	245-260

Table 1: Reflow peak temperature of SAC305 solder and Sn57Bi solder

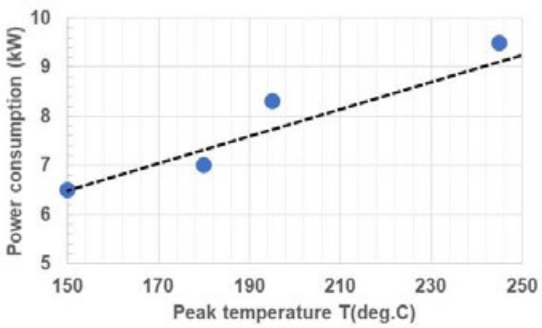

Figure 1: Relationship between reflow peak temperature and power consumption

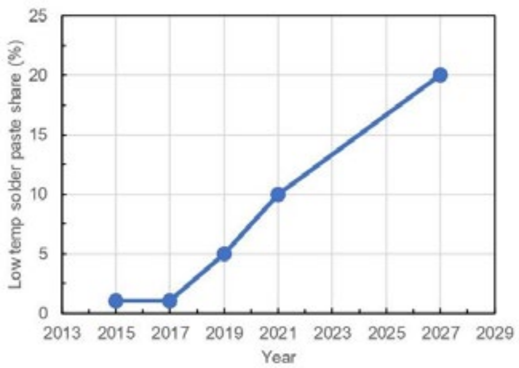

Figure 2: Forecast of low temperature solder share [4]

In the case of applying the reflow peak temperature for 245 degrees C, power consumption was 9.5 kW. On the other hand, in the case of applying the reflow peak temperature for 180 degrees C, power consumption was 7 kW. By changing the solder used during assembly from conventional SAC305 solder to Sn-Bi solder, CO_2 conversion can be reduced by 0.8-1.0kg / h (0.334 kg-CO_2/kWh per reflow furnace). Until now, adoption of Sn-Bi solder has been limited due to its brittleness property. Forecast of low temperature solder share for board assembly by iNEMI is shown in Figure 2 [4]. Environmental, economic and technical point of view, adoption of low temperature solders in electronics assembly is increasing rapidly. The roadmap forecasts that adoption of low temperature solder pastes will reach 10% of all solder paste used for board assembly by 2021.

3 Difference of warpage behavior and stress change between Sn-Bi solder and SAC solder

High-performance semiconductor package requires a large size chip (over 20 x 20 mm) and a large size organic substrate (over 55 x 55 mm). In case of large size silicon chip, thermal expansion of an organic substrate during reflow is significant problem. They induce large warpage of semiconductor package and large thermal stress at solder joints after reflow. The influence of flip chip joining material on warpage behaviour and stress change were investigated. Appearance of test sample, cross-sectional image of solder joints and package specifications are shown in Figure 3 and Table 2. The size of the Test Element Group (TEG) chip was 20 mm x 20 mm x 0.75(t) mm. and the organic substrate was 55 mm x55 mm x 1(t) mm. Two types of solder materials were studied, these are, Sn57Bi and SAC305 solder.

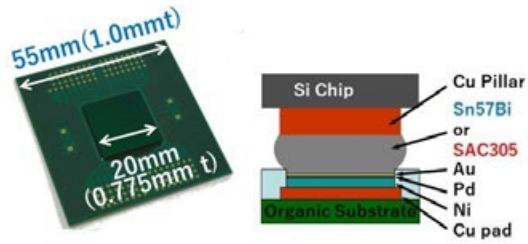

Figure 3: Appearance of test sample and cross-sectional image of solder joints

Item	Feature	Description
Chip	Size	20x20x0.775 (t) mm
	Bump	Cu pillar
	Pillar size	85(dia.) x50 (t) µm
	Bump pitch	150 µm
Substrate	Material	Organic
	Size	55x55x1(t) mm
	Pad diameter	80 µm
	Solder	SAC305 Sn57Bi
	Pad surface finish	Cu / Electroless Ni/Pd/Au

Table 2: Package specifications

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Process and test flow are shown in Figure 4. A TEG chip was mounted on an organic substrate and was reflowed using conventional mass reflow. After reflow, underfill resin was supplied and was cured at 150 degrees C. The full assembly packages were evaluated by thermal cycling test. Microstructure analyses of the solder joints were performed on both Sn57Bi and SAC305 solder by Electron backscattered diffraction (EBSD). Stress change of bump joints area as a function of distance from the canter of chip were evaluated by EBSD analyses.

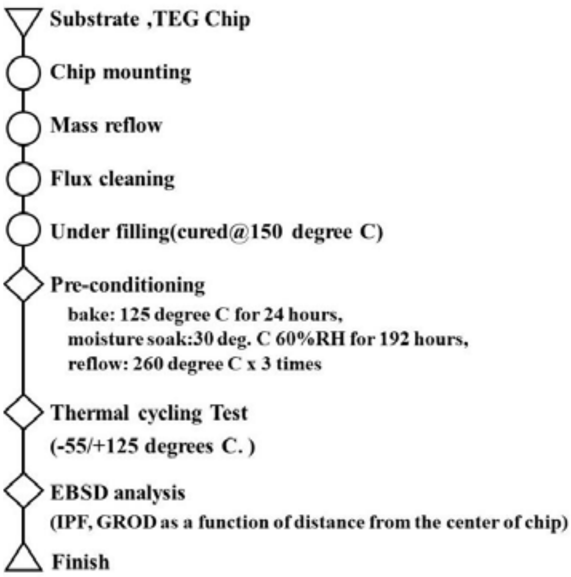

Figure 4: Process flow

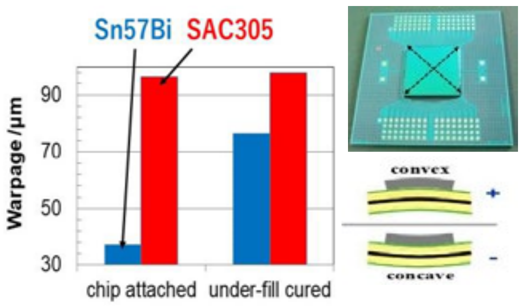

Figure 5: Difference of warpage between Sn57Bi and SAC305 solder joints

Difference of warpage between Sn57Bi and SAC305 solder joints is shown in Figure 5. The warpage after chip attached using Sn57Bi and that of using SAC305 solder were 36 µm and 97 µm, respectively. Applying Sn57Bi solder, the warpage after chip attached was reduced more than 50 % compared with the case of SAC305 solder. Bump failure risk can be reduced after chip attached. Cross-sectional view of bumps after TC test are shown in Figure 6. White area of Backscattered Electron (BSE) image of Sn57Bi and SAC305 solder show Bi atoms and Sn atoms, respectively. Regarding Sn57Bi solder joints, segregation of Bi atoms were observed. And growth of grains were observed during TC test. However, any voids or cracks were not observed. On the other hand, in the case of SAC305 solder joints, large crack was observed at the interface between Cu pillar and solder after TC500 cycles. Change in Inverse Plot Figure (IPF) maps in the edge bump during thermal cycling test are shown in Figure 7. IPF maps were superimposed on their image quality maps. This is a figure which describes the distribution of grain of β-Sn and Cu_6Sn_5. Different colors in IPF maps indicate different crystal direction. Regarding SAC305 solder joints, grains of β-Sn were oriented nearly the same orientation and large grain size of β-Sn were observed at initial. The refining and the randomizing of crystal grain were observed after TC 500 cycles.

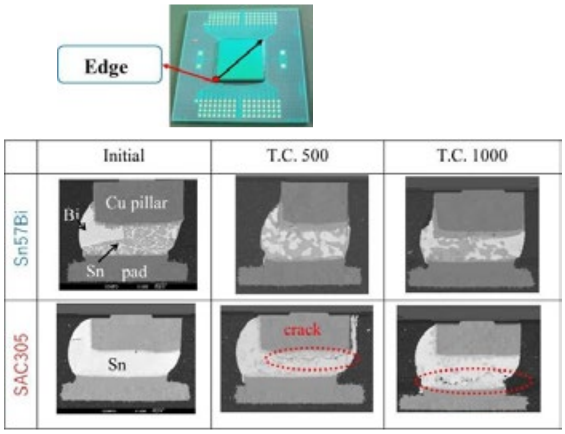

Figure 6: Cross sectional view of bumps after TC Test

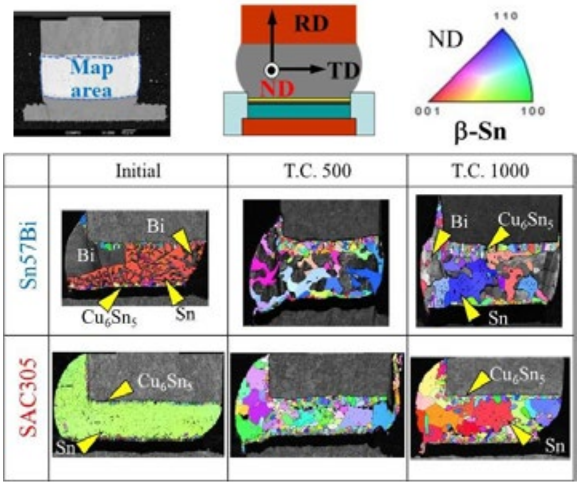

Figure 7: Change in inverse pole figure maps in the edge bump during thermal cycling test

Change in average grain size of β-Sn in the bump using Sn57Bi and that of SAC305 during thermal cycling test are shown in Figure 8 and 9. In the case of Sn57Bi solder joints, the initial average grain size of β-Sn at all locations are less than 5µm and significant change was not measured during T.C. test. On the other hand, in the case of SAC305, the initial average grain size of β-Sn at the Edge, Middle and Center bump were 29.1, 5.7 and 14.1 µm, respectively. After TC 500 cycles, the average grain size of β-Sn at all location were refined less than 5µm. And they were measured less than 5.5 µm after T.C. 1000 cycles. In case of micro solder joint using Sn base solder such as SAC305, the solder joint is consisted a few of large size of crystal grain [5]. It is well known that yield strength can be improved by refining the crystal grain size [6],[7].

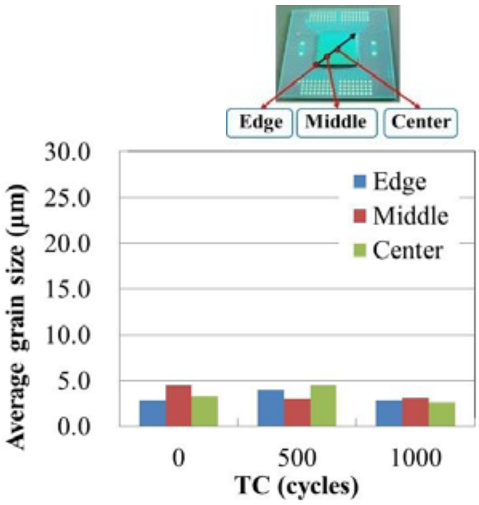

Figure 8: Change in average grain size of β-Sn in the bump using Sn57Bi during thermal cycling test

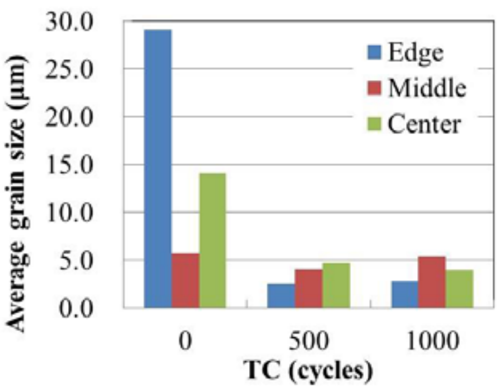

Figure 9: Change in average grain size of β-Sn in the bump using SAC305 during thermal cycling test

EBSD analysis that is analysis method of crystal orientation, they have been widely employed for geology analyses on metal material. Some researcher reported that EBSD analyses provide a correlation between plastic strain and local misorientation [8-11]. We also reported Grain Reference Orientation Deviation (GROD) analysis method that correlates local misorientation with plastic strain, which is one of the EBSD analysis methods [12],[13]. Change in GROD maps in the edge bump during T.C. test is shown in Figure 10. High angle shows high strain. Regarding SAC305 solder joints at initial, regions with high concentrations of high angle (6 to 9 degree) were monitored at the left side of substrate pad and the edge of right side of Cu pillar. After TC 500 cycles, the origin of the micro crack propagation was observed at this position (see Figure 6) and high concentrations of high angle were not monitored at this portion. On the contrary, in the case of Sn57Bi solder joints, regions with high concentrations of high angle around from 6 to 9 degree was monitored at random position of Bi atoms of the bump. However, any cracks or voids was not monitored.

Change in GROD distribution in the edge bump of Sn57Bi and that of SAC305 during thermal cycling test are shown in Figure 11 and 12, respectively. In the case of Sn57Bi solder joints, at initial, GROD value of low angle around from 0 to 3 degree were observed and the peak GROD value showed 0.86 degree. After T.C. test, the GRID distribution decreased slightly around from 0 degree to 2 degree. Regarding SAC305 solder joint, at initial, GROD value of high angle around from 0.86 to 7 degree and the peak GROD value showed 3.15 degree. The peak GROD value was shifted from 3.15 to 0.86 degree after T.C. test. and its distribution shape became sharp. This phenomenon indicates that the stress was relieved due to the refinement of the crystal grain size. This result indicates that the plastic strain of bump with the use of Sn57Bi solder is lower than that with the use of SAC305 solder.

These results indicate that Sn57Bi solder joints is less affected by thermal stress than using SAC solder joints.

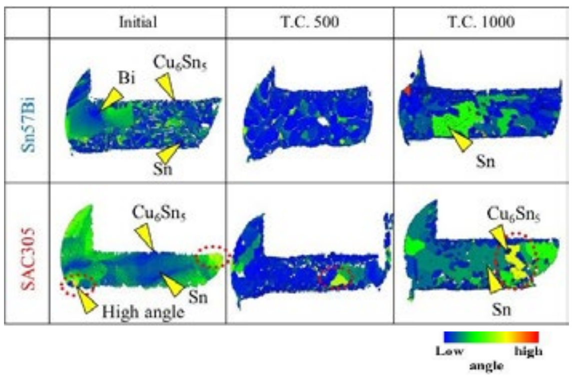

Figure 10: Change in GROD map in the edge bump during thermal cycling test

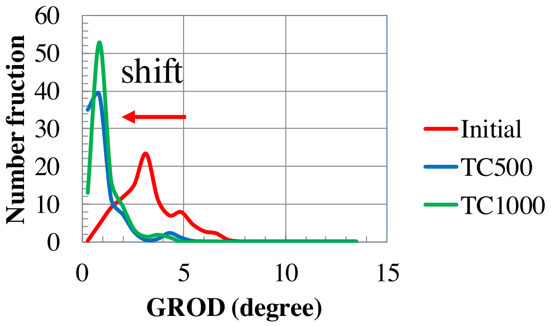

Figure 11: Change in GROD distribution in the edge bump of SAC305 during thermal cycling test

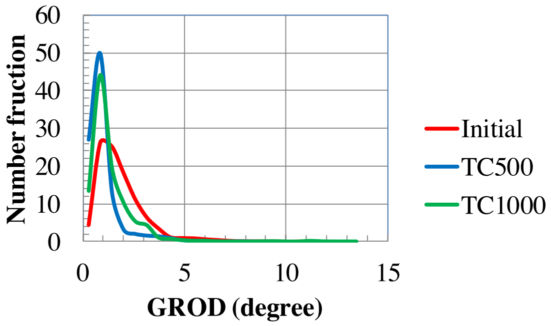

Figure 12: Change in GROD distribution in the edge bump of Sn57Bi during thermal cycling test

4 Advantage of Sn-Bi solder joint in 3D semiconductor package

Recently, 3-dimensional semiconductor package is required for high-end system that realize to high speed and large-capacity computing system. They employ a silicon interposer or an organic interposer to correspond to fine pitch bump connection and high-density bump. But their chip size, semiconductor package size and current density increase year by year. 2.3D type i-THOP® (integrated-Thin film High density Organic Package) was developed [14-16]. Appearance of test sample and cross-sectional image of 2.3D type i-THOP® are shown in Figure 13. 2.3D type iTHOP® has structure in which organic interposer is mounted on build-up substrate. Sn-Bi solder for solder joints between organic interposer and build-up substrate was employed. (i-THOP is registered trademark of SHINKO ELECTRIC INDUSTRIES CO., LTD.)

Figure 14 shows results of warpage and stress simulation for 2.3D type iTHOP® when solder material between organic interposer and build-up substrate was changed. The stress-free point of Sn-Bi solder and that of SAC solder are 180 degrees C. and 240 degrees C, respectively. Warpage after assembly of using Sn-Bi solder and that of SAC solder are -13.2 µm and -22.1 µm. In the case of Sn-Bi solder, strain of solder portion and that of Cu pad are 0.0101 and 0.0131. On the other hand, in the case of SAC solder, strain of solder portion and that of Cu pad are 0.111 and 0.0848, respectively. Warpage of using Sn-Bi solder was about half of that of using SAC solder. Strain of using Sn-Bi solder was clearly lower than that of using SAC solder.

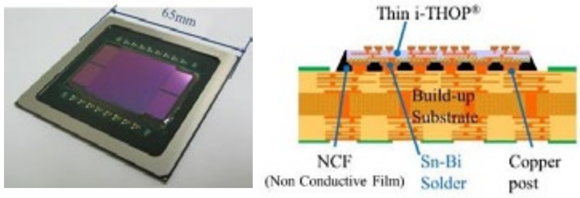

Figure 13: Appearance of test sample and cross-sectional image of 2.3D type i-THOP®

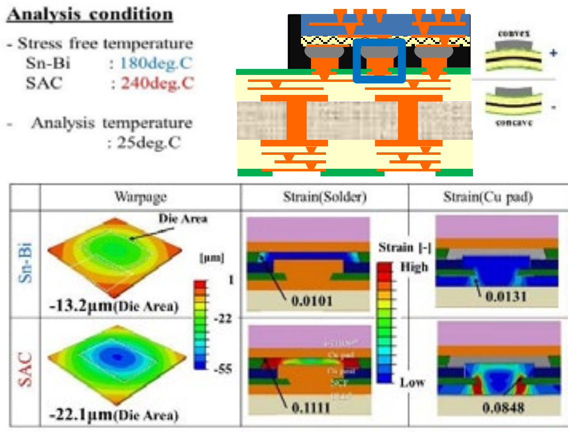

Figure 14: Warpage and stress simulation

In addition, TLP technique using Sn-Bi solder has been employed for solder joints between an organic interposer and a build-up substrate [15],[16]. In case of Sn-Bi solder, re-melting solder during assembly process and electro-migration resistivity at high temperature are significant problems. TLP technique is able to raise the melting point by consuming the Sn phase in the solder to form the Cu-Sn inter-metallic compounds (IMCs). Previous study reported that IMCs have high electro-migration resistivity compared with solder material [17],[18]. Sn-Bi solder alloy system such as Sn57Bi solder has big advantage compared with SAC solder. Since the Sn-Bi alloy system is a low melting point material, a low temperature processes can be employed. And Bi atoms hardly form IMCs with Cu-Sn atoms. The amount of Sn atoms is to be consumed in relatively IMC formation. Sn and Cu atoms can quickly transform into IMCs. Cross-sectional view of Sn-Bi solder joints between organic substrate and build-up substrate is shown in Figure 15. Electro-migration tests were evaluated on solder joints between organic interposer and build-up substrate with 38kA/cm^2 at 125 degrees C. Typical resistance change during electro-migration test is shown in Figure 16. The resistance has rapidly elevated to 4 % at 30 hours. After that, the resistance has dropped to 2 % at 60 hours. And then the resistance has slowly dropped to 0% at 1000 hours.

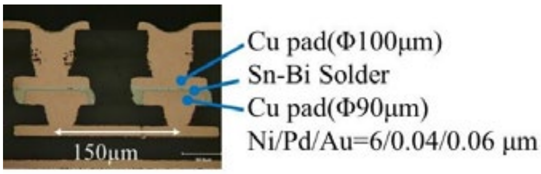

Figure 15: Cross-sectional view of Sn-Bi solder joints between organic interposer and build-up substrate

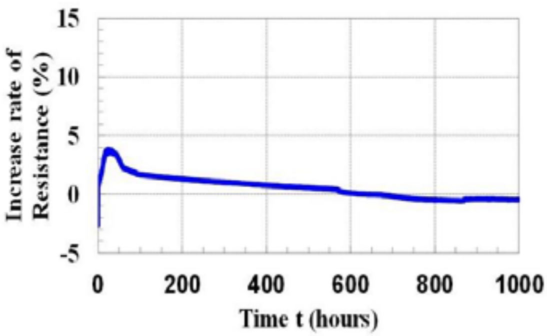

Figure 16: Typical resistance change of Sn-Bi solder joint

Backscattered electron (BSE) image and Phase map determined from EPMA analysis after current stressing are shown in Figure 17. Regarding initial, most of Sn atoms transformed into Cu-Sn IMCs. A slight amount of unreacted Sn phase was detected. After 8h, unreacted Sn phase was hardly detected. And after 1000h, thick Cu_3Sn and thick $(Cu,Ni)_6Sn_5$ phase were detected. These results suggest that applying TLP-like Sn-Bi solder joints between the organic interposer and the build-up substrate is reliable joining method.

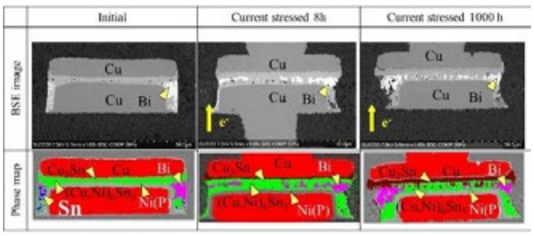

Figure 17: BSE image and phase maps after current stressing

5 Conclusion

By changing the solder used during assembly from conventional SAC305 solder to Sn57Bi solder, CO_2 conversion can be reduced by 0.8-1kg / h (0.334 kg-CO_2/kWh per reflow furnace).

Sn-Bi solder joints is less affected by thermal stress than using SAC solder joints.

Applying Sn-Bi solder joints for 3D semiconductor package, joint reliability is improved.

Sn-Bi solder is considered to be a strong candidate to achieve both environmental issues and high performance of the semiconductor package.

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Chiplets - Exploring the Green Potential of Advanced Multi-Chip Packages

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Abstract

In addition to already widely applied multi-chip packages, a new wave of IC packaging integration is currently taking place. The concepts and first implementations of chiplets promise not only higher integration densities, but also touch upon environmental properties of electronics in terms of resource efficiency, critical raw materials, modularity and re-usability of design blocks. This paper presents examples of chiplets and variations of the concept in comparison to earlier multi-chip packages. Many variants of multi-chip packages are already commonly included in smartphones. Therefore, in the context of environmental assessments, it is highly relevant to use suitable IC data sets instead of generic single-chip package data sets. Unless individual data sets for all IC types become the norm throughout the electronics industry, a configurable calculation model is needed to improve the quality of many environmental assessments.

1 Introduction

Packaging of electronic components is often considered a small addition to the manufacturing of the core functionality of the component. In particular, for semiconductors, or integrated circuits (ICs), the majority of investments, developments and personnel will be focused on manufacturing the highest performing chips with the smallest reproducible features in huge cleanroom facilities. Packaging, on the other hand, is not core business and has typically been outsourced or shifted away to former low wage countries in Asia, such as the Philippines or Malaysia.

Conventionally, the cost of packaging is only a few percent of the component costs, and likewise – though few studies reveal data publicly – packaging will only contribute a few percent to the environmental profile of a component [1].

Current research at Fraunhofer IZM in the field of environmental assessment and cost modeling of microelectronic manufacturing indicates that with advanced packaging technologies and the prominent example of chiplets, the value contribution of packaging increases and in some cases can suddenly contribute dominant effects. These effects would appear both in economic analysis and environmental impacts.

As an introduction to examining environmental aspects of new packaging variants including chiplets, we first need to go through some background information, including the changes in the supply chain structure and some of the technical basics.

2 Introducing Chiplets

Outside of the IC and IC packaging industry, chiplets have not yet been featured in many publications and studies. Yet, they are a game changer that currently determines integration and miniaturization progress of electronics while the driving force of the last decades – Moore's Law – is slowing down.

The word has been around much longer, but the current prevalence of the term "chiplet" can largely be attributed to the U.S. CHIPS research program (Common Heterogeneous Integration and IP Reuse Strategies), started in 2017 by DARPA [2]. Particularly, publications starting to spread in 2018 then led to a wider adoption of the term across the industry. By now, many advanced packaging technologies with multiple semiconductor elements are subsumed under the term chiplets, even if developments predate the CHIPS project.

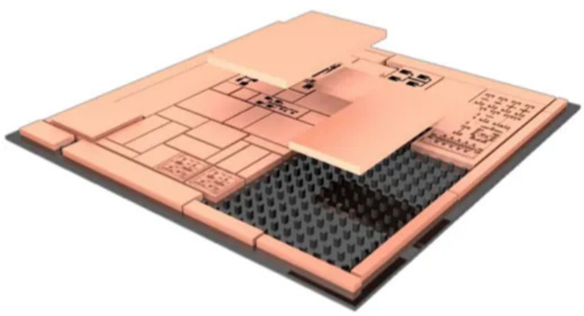

Figure 1: Illustration from CHIPS project: dozens of smaller chiplets are assembled on one supporting interconnect structure [2].

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Instead of manufacturing one large semiconductor chip and then packaging it as single monolithic IC component, in the case of chiplets, the IC design is broken down into various parts. The assembly of these multiple small chips into a complex, and often three-dimensional package leads to highly integrated system components. Examples and details on the technologies involved will follow in the next sections. At this point, we will focus on where chiplet technology will move the electronics manufacturing in a larger sense.

The various small chips (chiplets) that make up the functionality can be designed and produced by individual companies, which then have full control over the segmentation (or partitioning), the interfaces between chiplets and the performance and cost structure. In the past, only the large semiconductor manufacturers could even come close to covering the know-how and manufacturing equipment necessary. Yet, the products already on the market often combine specialized chiplets from different manufacturers rather than from one individual company. In the future, libraries of chiplets are expected to exist, forming ecosystems of companies and designs that are compatible to make up more complex designs.

A component manufacturer could in that scenario choose to only design one proprietary chiplet, relying on a number of chiplets from the library, and adapt the design of the package accordingly. They would then be free to choose a chip manufacturer (foundry) to produce the proprietary chiplet, and to contract another company to integrate all chiplets in the package.

Since the component manufacturer can opt to have no manufacturing equipment at all, it becomes possible and more likely that end-product manufacturers or smaller companies produce their own very powerful and highly integrated designs. It is also possible to manufacture tightly controlled designs in smaller numbers at lower development and production costs, which was one of the original ideas for DARPA to get involved.

The established chip manufacturers keep some of the most advanced processes and designs in-house, make use of external chiplets, where they are not core business (e.g. memory), and possibly concentrate on building a sequence of software-compatible families of high-performance chips. They could also opt to provide their core design know-how, such as processor or graphics processing, as separate chiplets, to ensure a wider market for their architectures.

The question is, who is technically and – more importantly – economically capable to overcome the packaging gap. These new packages necessitate handling of the unpackaged chiplets – therefore requiring cleanroom environments – but should cover scale of production from small high value requests to high volume production. The traditional chip manufacturers, the foundries, the explicit packaging companies, or companies originating from advanced printed circuit board technology could all gain a larger business share of this supply chain. This is the ongoing rearrangement of the value creation chain of electronics.

A number of combined factors explain, why chiplets make sense for the industry now (in addition to access to mature technology options):

- The cost for new fabs increases so that fewer companies invest in new facilities.
- Moore's Law slows down with decreased investment – in addition to reaching physical barriers.
- More chip companies are fabless, and are therefore more open to mixing different manufacturing nodes.
- To achieve performance gains still similar to Moore's Law with slower node shrinkage would lead to very large ICs – or to the close integration of many smaller chips.
- Practically all performance processors are multi-core designs now, allowing easier subdivision into chiplets. Also for highest performance, memory needs to be placed closer to processing units than separate packages ("DRAM") could provide.
- Simultaneously, combining different IC technologies and sensors in one package had already started before chiplets, and has become a significant market.

Moving back towards the more technical aspects, subdividing complex chips into chiplets will potentially:

- Increase reuse of designs, including stability through already proven designs,
- Foster specialization between chiplet providers and even higher optimization of each chiplet,
- Increase production numbers of the individual chiplet and utilization of existing manufacturing capacity,
- Increase the manufacturing yield of chiplets compared to a large chip,
- Decrease system costs,
- Reduce component size (i.e. when 3D integration is part of the packaging technology).

However, all of these principally positive trends do not necessarily occur in parallel and do not apply to every component design. Although there is a considerable potential for improvement – functionally, economically and environmentally – specific cases may not fulfil that potential.

3 Examples of Chiplets and other Multi-Chip Packages

Multi-chip packages have been around for a long time, but have multiplied in technology variation and application over the last years. Practically all products with highly integrated electronics contain one or more multi-chip package nowadays.

The environmental assessment community is only partially aware of this trend and its significant effect on the validity of current life cycle assessments (LCAs). The environmental aspects will be covered in the following section.

Categorization of components cannot be done by package geometry or the geometry of the contacts on the package, as was the case for earlier packaging families. Seen from the outside, the complexity inside the package is not visible and the same outside geometry might be the result of a fundamentally different processing chain.

For those familiar with some packaging families, the components in question generally will be micro-BGA or BGA type configurations (ball grid arrays), or larger assemblies on a small printed circuit board with BGA contacts, the interposer.

die	die, chip or IC are mostly interchangeable in this context: a semiconductor without package
node	or “semiconductor manufacturing node”: the generation of chip manufacturing, characterized by the smallest reproducible feature size, such as “7 nm”
fabless	a company designing and selling ICs, but without own manufacturing equipment. The company doing the manufacturing is a “foundry”
front-end	the manufacturing steps up to a processed wafer or singulated bare die. Further subdivided into front-end of line (FEOL) and back-end of line (BEOL) – not the same as “back-end” (see next).
back-end	the packaging processes of chip manufacturing
yield	the percentage of good specimen coming out of a sequence of processes
first level inter-connect	the electrical connection from the chip to the package
vertical inter-connect	connections running vertically through layers of a package, in particular through silicon vias (TSV), through mold vias (TMV) or through glass vias (TGV).

Table 1: List of packaging terms and concepts.

Before we go deeper into examples, it is time to summarize some of the technical jargon of packaging, for those not familiar with the field. Table 1 lists very brief explanations of the terms and concepts referenced.

A prominent example of a real chiplet design in the market is the Zen2 architecture by AMD, which has been used as the basis for 2nd generation Epyc server processors (“Rome”) and 3rd generation Ryzen desktop processors (“Matisse”), depicted in Fig. 2.

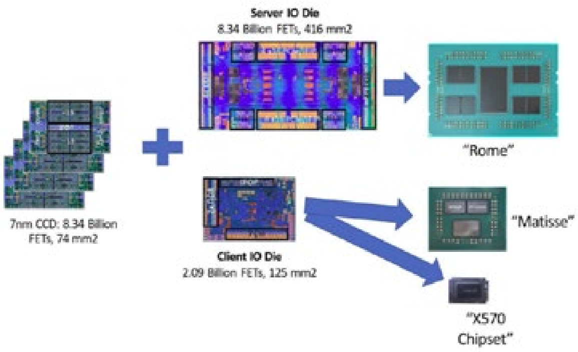

Figure 2: AMD’s use of chiplets to realize Zen2 based processors [3].

AMD released a number of details on the chiplet setup making this a valuable example for further discussion. The basic compute chiplet “CCD” contains 8 processor cores and corresponding cache memory. The package both for the server and for the desktop version is a flip chip interposer, which is a small, high performance printed circuit board (PCB). PCB interposers have been used for processors for a number of iterations already, but usually with only one chip attached, and two chips in very few cases. Some passive components – usually resistor networks, but also ceramic capacitors in other cases – can be seen mounted around the chips. Not included in the photographs is a metal heat spreader, which will cover most of the interposer in the final product.

Other materials, which have even higher performance, can also be used as interposers, in particular silicon or glass. As these are significantly more expensive, they are only used in the package area, where they are needed, and frequently mounted on a larger PCB interposer in return.

Examples of commercial multi-chip modules using silicon interposers and predating the chiplet wave are shown in Fig. 3. Depending on the definition, these could all be called early chiplet designs.

The Intel example uses a technology called EMIB, which is not a silicon interposer as such, but a smaller piece of silicon only covering the area where the chips need to be connected (in the photo only between the graphics processor and the graphics memory on the left). This technology is promoted as one variant to connect chiplets.

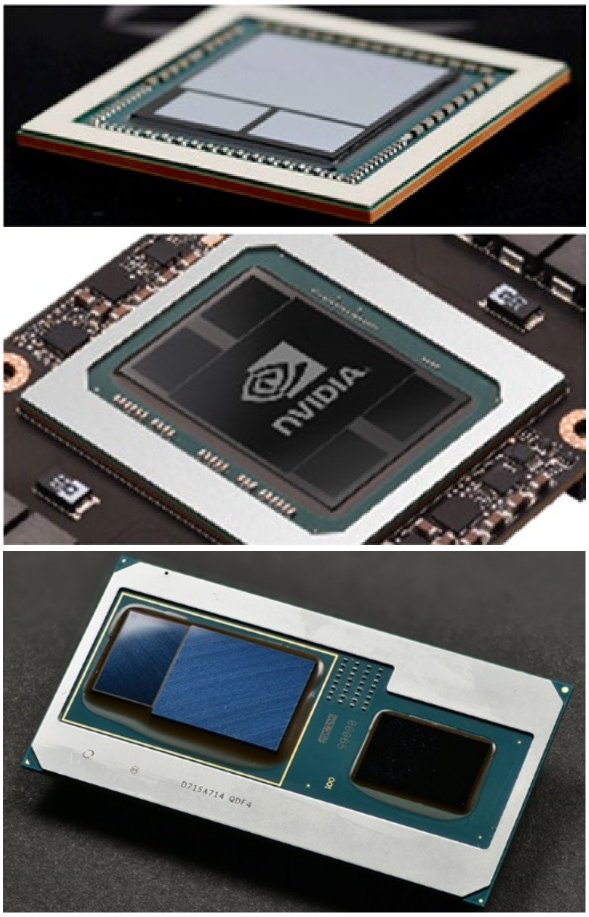

Figure 3: Three commercial products using silicon interposers for multi-chip packaging (top: AMD Radeon VEGA [4], middle: NVidia Tesla P100 [5], bottom: Intel Core i7 mobile 8th generation [6]).

Deriving from the concept publications of the CHIPS project, like the one in Fig. 1, chiplet systems are mostly thought of as mounting various chiplets on one supporting interconnect structure, possibly using a fixed grid of interconnections. In the case of the AMD Zen2 example, the interconnect structure is a PCB interposer, but in many concept drawings this would be a silicon interposer, or even what is called an active interposer.

Active interposers can be programmed after production to determine which pin (or which part of the internal circuits) should be connected to which other pin or circuit. The base technology for re-routing signals after production has been used for many years in components called FPGAs (field programmable gate arrays). An active interposer may contain only few transistors and flash memory to realize the programmable switching connections, or the interposer may be a complex FPGA with additional contact pads on top.

After acquiring Altera, a prominent FPGA manufacturer, Intel in particular has promoted the idea of attaching various chips on top or side by side with an FPGA as one direction for creating even more powerful FPGA families. Using FPGAs or otherwise reconfigurable, active interposers would mean that different combinations of chiplets could be combined without redesigning the silicon interposer for every variant. Chiplets could be exchanged for newer versions or different functionalities, as long as the interconnect grid between the chiplets and the carrier chip stays the same. The interconnect grid would become a de-facto standard across multiple chiplet suppliers.

While active interposers provide more flexibility and lower costs for smaller production runs, passive interposers including the EMIB bridges should be more cost effective for large scale production. All interposer variations mentioned (except the full FPGA with interconnect grid on top) put the chiplets side by side, which is why this is called 2.5D integration. The effect is that the footprint (the area taken up by a component) is always larger than a monolithic integration would be.

Unless there is a compelling reason for placing the chiplets side by side – such as a direct connection to a heat spreader for high performance applications – it is possible to push miniaturization of electronics one step further by combining chiplets with 3D packaging.

Some more variants of 3D packages, which may in turn include interposers as one technology, are shown in Fig. 4.

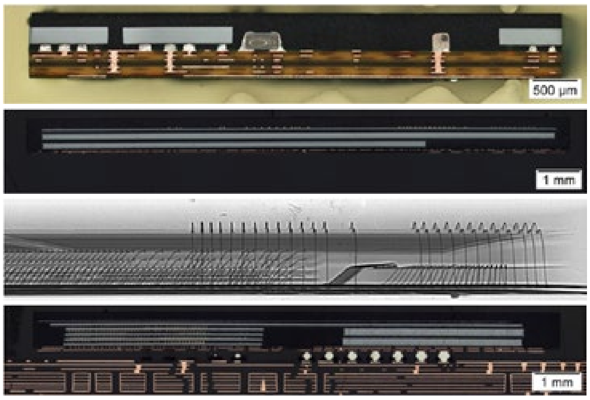

Figure 4: Cross sections of various 3D packaging technologies (sample preparation and photos by Fraunhofer IZM).

More and more such technologies enter the market and appear in all types of products. While the biggest IC modules mounted behind heat spreaders and attached to voluminous heat sinks are probably identified for special scrutiny in environmental assessments, other true 3D multi-chip packages can have very small dimensions and look like conventional single-chip packages.

4 Translation into Environmental Aspects to be Considered

What are the environmental implications of chiplet technology? The implications are two-fold: chiplets could deliver substantial improvements (i.e. lower impacts for same or higher functionality), but could also introduce new critical materials and increase environmental impacts per delivered functionality.

At this point of the development, many environmentally relevant details are still not quantifiable, so we will mainly analyze the qualitative potential for environmental improvements incorporated in the new technology options.

The environmental improvement will depend on many factors of the exact application scenario and life cycle, therefore, determining a potential in a qualitative way will by definition not deliver a prognosis for each specific case.

In general, a new IC packaging paradigm introduces new processing steps and new materials in the production stage in order to drive miniaturization and performance forward, while keeping the costs balanced to the performance gains.

Therefore, on the one hand, environmental analysis on an in-depth technical level is needed to determine the environmental effects of introducing a new packaging technology, such as chiplets.

On the other hand, we need to make sure that environmental practitioners identify and assess multi-chip packages correctly to begin with.

This is in particular of concern where third parties without access to the original design data perform the environmental evaluation. But this can also occur with assessment teams within the company responsible for the end-product. Realistically, they also do not have access to the internal structure of all packages or to full environmental datasets from their suppliers.

4.1 Potential assessment errors with multi-chip packages

It can be shown with a short semi-quantitative experiment, why this second perspective is also the larger concern due to the potential magnitude of errors introduced.

For a product with highly integrated electronics, various studies have shown that semiconductors dominate the environmental footprint of production, in particular the carbon footprint or Global Warming Potential (GWP). Let's assume the main IC contributes 5% of the total product score. This may seem to be a fairly high assumption, but the main ICs together can contribute 50% of the product manufacturing or 40% of the total life cycle impact of a mobile device [7].

In conventional single-chip packages, the packaging processes (or back-end processes) could make up 5 or at maximum 25 percent of the component manufacturing. A misjudgment of the exact packaging technology employed in a package would then lead to errors in the percentage range only – even if the packaging assessment itself is off by 50% in either direction. The error propagated up to the product level would be substantially lower, for example 0.25% with the assumptions of 10% back-end contribution. Fig. 5 shows a simple calculation of magnitude of error, when the IC (size and type) is assessed correctly, but the details of the packaging technology employed are misjudged in the environmental assessment.

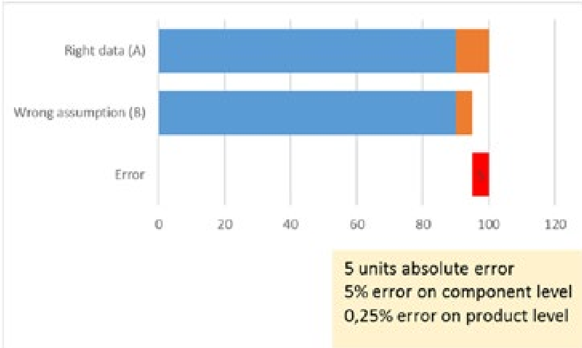

Figure 5: Assessment error through misjudging the packaging technology (arbitrary units).

One exception, where the environmental footprint of the packaging might indeed be off by more than 50%, is misrepresenting the absence or presence of gold [8]. But unless the gold content is drastically different, misrepresenting the exact packaging technology will probably not change the assessment on the product level, and the results are robust.

Erroneously using single-chip package datasets instead of multi-chip packages in comparison could easily lead to 70% error on the component level, or more than 3% error on the product level, as shown in Fig. 6.

In real world examples you could encounter IC packages of medium size and thickness – for example micro-BGAs with 10 by 10 sq.mm footprint and 1 mm thickness – which contain respectively one small IC, one large IC (up to the package size), various different thinned ICs, or 16 to 64 layers of identical chips, in the case of memory. The 74% error bar in Fig. 6, based on assuming one IC instead of four in the package, is by no means the upper limit.

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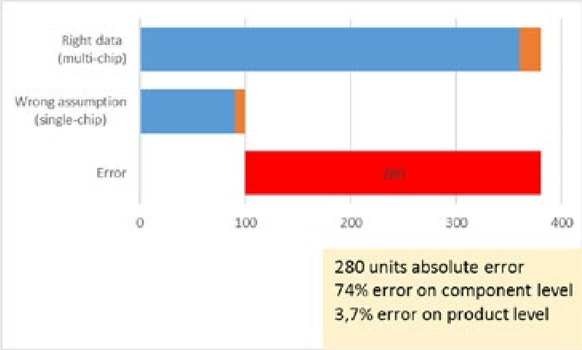

Figure 6: Assessment error from using single-chip data for a multi-chip package (arbitrary units).

As a side note, it may be stated that practically all advanced package types use thinned silicon dies, so the amount of semiconductor material in a package – if declared with precision at all – is not a useful proxy for scaling the main environmental impact of the component.

To assess the trend from multi-chip packages and the impact of specific multi-chip packages further, we will next go through various developments that have led up to the chiplet technology, and build up environmental reasoning step by step.

4.2 Separating some of the packaging effects described

Chip Manufacturing Node

Although this paper is focused on packaging technologies, the ICs to be packaged have a major influence on comprehensive results.

With each scaling down of the chip feature size (e.g. from manufacturing node of 14 nm to 10 or 7 nm), equipment costs increase, but expenditure per chip is generally going down (at least so far that has been the case with Moore's Law). Per functionality (memory size or computational power), the costs of semiconductors have been reduced for decades by following the node shrinkage.

In the past, the environmental expenditure per chip area has also decreased. If the impact per area decreases, then the environmental footprint per functionality decreases even more, because the same number of transistors now need a smaller chip area. Unfortunately, there is no long-term analysis of the environmental trends up to current technology nodes. A comparison of older technology nodes (from 350 to 45 nm) of CMOS logic chips shows a significant decrease of the GWP per die (Global Warming Potential) for the manufacturing processes (fabrication processes, chemicals and silicon). It is directly related to the increasing number of die per wafer. The overall GWP is rising over the years because of the steady increase in power requirements in the use phase for logic chips [9].

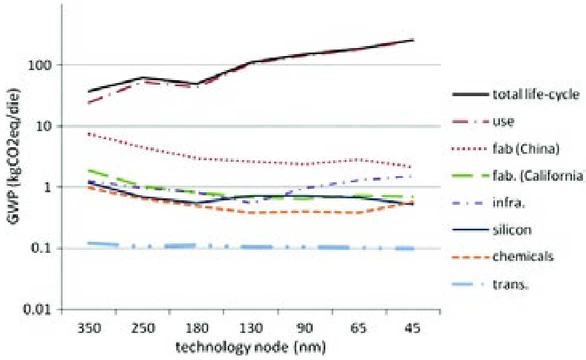

Figure 7: Global Warming Potential (GWP) per die by life-cycle stage of different CMOS technology nodes down to 45 nm [9].

Environmentally, chip shrinkage is a positive trend, resulting in more functionality per environmental impact, and additionally lower power consumption per transistor in the use phase (but actual power consumption per chip may rise as shown in Fig. 7).

SoC or monolithic integration

Although the size of transistors is decreasing with the manufacturing nodes, the number of transistors per chip is typically increasing from generation to generation to achieve higher performance, i.e. increased functionality. Thus, in the past, high performance chips became larger and larger, despite the shrink in feature size.

For a wider range of products it became possible to include previously separate components into one more complex chip, called a system-on-chip (SoC). Integrating many components into one, and choosing the most efficient manufacturing node for the design, generally leads to improvements of the environmental profile of a product.

If the chips become too large, however, thermo-mechanical effects become more challenging and limit the lifetime of the components. On the manufacturing side, larger chips also lead to lower manufacturing yield.

Yield (per active die area)

An established semiconductor process still has random defects across the wafer, leading to a number of non-functional chips in each production run. If very large chips are produced, it becomes harder and harder to produce even one defect-free chip. So even if the defect density is stable and very low, smaller chips will have a significantly higher manufacturing yield than larger chips.

Three major considerations limit the monolithic integration as SoCs:

- The absolute package dimensions might not fit for the intended application (e.g. imagine a 400 sq.mm IC on a smartphone mainboard).
- Front-end yield drops to a point where the gains from SoC integration are negated.
- Reliability issues of large area chips.

Low yield significantly increases environmental impact per component delivered, since the non-functional chips pass through all the expensive processes of the semiconductor manufacturing. Lower reliability could mean a lower technical lifetime of products, potentially leading to premature obsolescence, and again increased environmental impact over the life cycle.

Fig. 8 shows – again in arbitrary environmental units – how a low packaging yield could substantially increase the environmental footprint of a component.

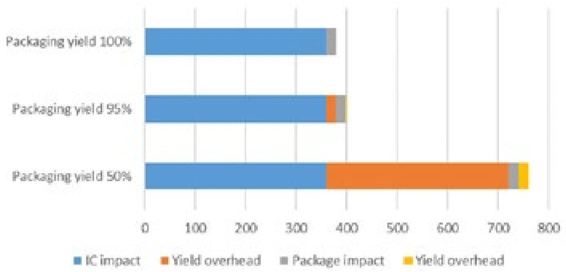

Figure 8: Additional impact allocated to shipped components, if packaging yield decreases (arbitrary units).

Some public reports indicate that front-end yield can be as low as 50 or 70% for new manufacturing nodes, but that would probably not be sustained economically. So, with more complex packaging concepts and earlier uptake of new variants into commercial products, it is conceivable that packaging could yield as low as 50% in the beginning as well, and still enter into mass production.

This would mean that half of the ICs entering assembly would become waste at the packaging stage and that the packaging processes would cause half of the manufacturing impact of each delivered component, even though indirectly. The actual impact is still generated in the front-end processes, but it should be attributed to the packaging.

Chip partitioning or performance penalties of subdivision into separate packages

Dividing a larger functional block into many ICs is not a new approach – in fact generations of earlier chip designs had to find the technical and economic sweet spot of what IC manufacturing at the time could deliver in a monolithic design, and when to partition the function across many packages. Additionally, some functions, like memory or a power amplifier, might be built more efficiently with a slightly different process flow than the rest of a SoC.

Before coming back to advanced multi-chip packages, a short look at the earlier situation with only single-chip packages is warranted.

The main drawback of splitting the IC design is in speed and size. In a simplified way, keeping data or analogue signals on the same chip will deliver maximum speed, whereas routing the signals through the package pins to the printed circuit board and then back into the next package will be significantly slower.

Regarding size there are two main penalties. One resulting from the packaging overhead (area or volume of the package compared to the semiconductor), which will apply for each packaged IC separately. Each signal routed through the package pins will also need a contact pad on the chip plus additional protective circuitry and possible amplifiers (buffers) to enhance the signal. These are structures significantly larger than the standard transistors and the contacts between transistors on the chip.

Material and area overhead of split IC packages

As a reverse of the description of the SoC trend, partitioning one chip into many separately packaged chips will lead to more material use and more area and volume of electronics for the same functionality. Thus, the manufacturing environmental impact for the same functionality will be higher.

What can be gained on the other hand is a specialization of different chip manufacturers, who optimize their partial functionality (e.g. memory) and make sure the interfaces to other chips are open and well documented, so that many designers are likely to choose their chips in their circuit design. As this has been the standard operation of the industry for so long, it is easily overlooked that this was the basis for repairability of electronics on PCB-level for a long time.

This division of labor with a high degree of interoperability and availability of spare parts is lost with SoCs (only one manufacturer supplies the SoC, and may not provide spare parts or public documentation) and is likely lost with chiplets as well.

In addition, miniaturized packages with small array area contacts are much harder to repair than earlier generations of packages. This trend is accelerated and not reversed with chiplet technology.

Reuse and modularity

While the term reuse appears quite frequently in the description of chiplet concepts, there is no connection to reuse in the environmental sense (e.g. a second life for a used component). Chiplets allow design or IP block reuse in a physical embodiment. In manufacturing, it could be said that the same chiplet is (re)used in many different products.

But once the chiplet is assembled, it will receive protective layers of packaging, and in particular with 3D packaging, there will be no way to exchange or upgrade a broken chiplet within the package. FPGA or active interposer technology at first glance would seem ideal for reuse, but the attached chiplets would need to stay accessible (no protection) and the first level interconnects would need to be reversible or at least re-attachable more than once.

Any mention of enhanced reuse or modularity therefore only applies to the manufacturing side, but not to extending the lifetime in the sense of circular economy (compare to [10] for different types of modularity).

Heterointegration

It has already been mentioned that some functionalities cannot be realized with silicon-based semiconductors, or at least not very efficiently. Sensors, high frequency circuits, power amplifiers or electro-optical functions either use modified silicon processing or semiconductors other than silicon. In the past, having these functions in separate packages allowed the maximum functionality on the system level. Now, multi-chip packages and chiplets can also deliver more miniaturization for these cases.

Heterogeneous system integration can combine technologically otherwise incompatible semiconductor families in one package. The result is a SiP, a system-in-package [11].

SiPs contain one or more active component, plus passive components, and potentially even fluidic or optical elements. All advanced multi-chip packaging technologies can be considered SiPs, even if they contain only silicon devices.

Usually, the semiconductor chips are integrated without separate packages, so the packaging overhead is applied only once, and through 3D integration of the individual elements, area and volume of the system is significantly reduced, when comparing to multiple separate packages.

The speed penalties within the package will be significantly lower than the signal transmission through a printed circuit board. Size penalties on the semiconductor area through additional pads and protection still apply (compared to SoC), in particular when the subcomponents of the SiP are designed by different companies. For 3D packages, additional area is also needed for the vertical interconnects (though still saving in total package area).

The distinction between SiP, chiplets and other multi-chip packages is not the most relevant question from an environmental perspective. However, which technology and how many ICs are used in one package is becoming more and more important for environmental assessments.

4.3 Continuation of chiplet example

To round off the analysis, the chiplet example of AMD for Epyc and Ryzen processors will be continued. In addition to technical data of chiplet sizes, number of transistors and manufacturing nodes of the chiplets, AMD also published economic comparisons between the actual chiplet designs and hypothetical monolithic chip designs.

Fig. 9 shows one of the core comparisons from the Epyc server processors.

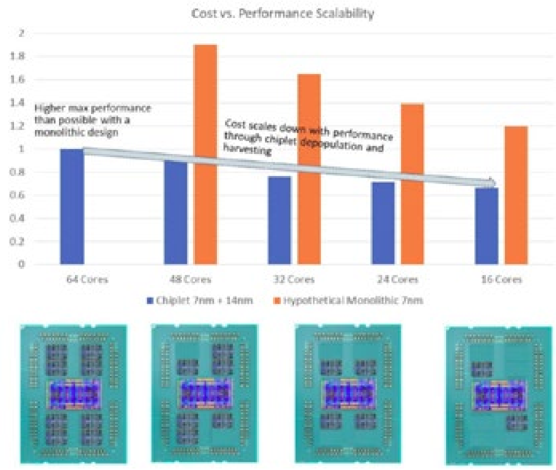

Figure 9: Relative cost comparison of variants of AMD Epyc multicores [3].

By using different numbers of compute chiplets, a wide range of multi-core CPUs could be generated from one design. The chiplet and interposer designs are implemented once for the maximum configuration (in this case 8 CCD chiplets or 64 cores), and by omitting CCDs step by step the costs of the CPUs scale down with the number of cores.

This also means that production volumes of the different core counts can be adjusted according to market demand more easily, e.g. if demand for the 24 core version far exceeded expectations.

The analysis includes the relative costs for designing and manufacturing the processors with 48 or less cores in a hypothetical monolithic chip in 7 nm technology.

The costs would almost double for each processor variant (for the 64 core version there is no comparable design even in 7 nm).

Although this is always dangerous in the details, let's consider using the costs as a proxy for environmental impact. Then the use of chiplets would have reduced the environmental impact in manufacturing per compute power delivered by half. That is a significant achievement in only one generation of chip design.

The power efficiency in the use phase – actually the more relevant parameter for server processors – has also increased drastically, although that might to some degree have been achieved without the chiplet approach.

But for smaller products and in particular mobile devices, the manufacturing phase can be more important than the use phase in terms of environmental impact. Achieving a 50% reduction of manufacturing impact, while delivering higher performance than the previous generation, underscores the improvement potential that chiplets can incorporate.

5 Summary

Chiplets are a continuation of IC packaging trends not obvious to environmental practitioners, because IC packages containing multiple chips are becoming much more prevalent and cannot easily be identified.

Pre-fabricated data sets for LCA or carbon footprint do not yet exist; and even if they would, the choice of the correct data sets is considerably more complicated than for normal ICs. Even within companies responsible for the end-products, the knowledge on the use of multi-chip packages will be very limited. For an integrated sensor package, as one example, even the circuit designers need not know the internal structure, and can use the component as a black box, where only the interface – including the layout – is defined.

Assuming the wrong content only based on external package characteristics can lead to substantial assessment errors. Today, neither are small nor thin packages always the ones containing less semiconductor area, and therefore contributing less environmental impact to the total. Scaling of datasets according to external package dimensions or weight – always a necessity in the past, when manufacturer data for the specific component is unavailable – has become much more error prone even over the last few years.

Under the fairly reasonable assumption, that we will not soon have exact environmental datasets from the original manufacturers for each component variation they place on the market, a cross-industry or independent calculation model is needed. Similar to the idea of "umbrella specifications" for material declarations, it should be possible to reduce the majority of cases to few – once more scalable – configurations. This approach could also be seen as a very specific variant of product category rules (PCR) in the case of carbon footprint evaluations.

Moving away from the "availability of correct datasets" discussions, we would like to point out how "sudden" the dominance of back-end (packaging) processes for environmental assessments in electronics has occurred. 10 years ago multi-chip packages became more common, but mostly for stacks of memory chips. For these, data sheets might even have covered the internal structure or the component. Sensor multi-chip packages followed (i.e. combining read-out, communication and pre-processing chips in sensor packages). Still, until a few years ago, the occurrence in products was very low. Now, accelerated through chiplets, multi-chip packages are commonplace.

While the main environmental impact still occurs in the semiconductor foundries (or front-end processes), the total impact of a delivered IC component now to a larger degree depends on bringing different ICs together through packaging, and whether the yield of the packaging processes is high enough.

In an extreme view, different datasets for exactly the same IC functionality would be needed, depending on whether the IC and the package was produced during ramp-up of production (low yield) or later (higher yield). The higher yield would not only improve the environmental load per component drastically, but also increase the economic viability. The economic variables involved already determine, why the information about yield will never be transparently and publicly available. Sometimes companies have to manufacture at low yield, even if they actually lose money with each component delivered, but they would certainly prefer not to make this public.

At best, instead of real yield values, an average learning curve might be used. But probably, from an environmental viewpoint, we would be very content to have company data public after the yield curve has improved, i.e. allowing the environmentally relevant phase of low yield to be neglected.

In total, chiplets and advanced packaging are improving performance and miniaturization of electronics and are therefore drivers for environmental improvements. Further studies will show, which specific technologies offer the highest gains, and which side effects of a slowing down of Moore's law can be compensated through chiplets and 3D packaging.

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A.2

(ECO)PRODUCTS: DATA CENTERS, NETWORKS, THE "INTERNET"

Data Center Energy Analysis in the Era of Big Data

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Unfortunately the manuscript for this lecture was not available by the editorial deadline.

The power consumption of mobile and fixed network data services - The case of streaming video and downloading large files

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Abstract

There are numerous claims in media about the electricity consumption of video streaming and data downloading over mobile and fixed networks. Reviewing these claims against recent data reveals many such claims to be inaccurate and out of range – often by orders of magnitude. Such claims are typically based on old *energy per data* figures for average use over time that cannot be applied to current very high data usages like video streaming and data downloading. Instead, as a more accurate and relevant method, this paper suggests that power models are used and suggests relevant parameter values for such models. Watching YouTube videos (~1 Mbps) on a smartphone including usage of networks and servers consume about 10 W on average. Streaming Netflix (4-5 Mbps) on fixed broadband add about 7 W, mainly from Netflix/partners data centers (servers), to the near constant 18 W power consumption of an average fixed broadband line including usage of higher order networks.

1 Introduction

Global GHG emissions need to be halved by 2030 to avoid the worst effects of global warming [1] and a halving is possible [2]. To identify accurate actions, it is necessary to get facts and figures straight to enable relevant decisions. This is especially true for media, policy makers and company executives with key roles and the power to influence many others.

At this point, there have been numerous claims about the energy consumption and GHG emissions related to downloading data or streaming video that are unreasonable when checked against relevant measurements and data. One example is the energy figure reported by French think tank *The Shift Project* [3] which translates to an unrealistic power consumption of up to 6 kW for streaming Netflix video, debunked by Kamiya at IEA [4], with a byte-to-bit correction from the think tank [5]. As shown in this study the corrected figure of 750 W is still completely out of range. *The Shift Project* based their claims on old hypothetical future scenarios [6] proven unrealistic (acknowledged by the author of [6] in [10]) by studies that uses up-to-date data from a large part of all networks globally [7-9].

Another such claim is that all downloads of a popular YouTube music video consume about 1 TWh electricity [11]. This energy figure translates to 2 to 10 kW depending on how many sec/min of the video that gets viewed and downloaded (not described by the source). But, as will be further outlined in this paper, viewing a YouTube music video on a smartphone (typical device used) consumes only about 10 W including usage of network and servers.

The common trait of such claims is that they rely on, often outdated, single *energy per data* figures (*kWh/GB*), sometimes based on real network averages, sometimes based on forecasts or future scenarios for which more recent assessments of actual conditions are available. This paper suggests the use of more accurate approaches based on power models considering that a user's average network use is typically represented by longer periods of *no data usage* split up by short periods of low data usage related to web browsing, social media, gaming etc. A very large error is made when such an average, is applied to specific high data usage services like video streaming and file downloading.

Energy per data figures are also associated with the impression that more data result in more energy. This has led to the belief that ICT's energy consumption is increasing fast, which is not the case according to studies of the sector´s actual energy usage [7-8]. More recently GSMA collected data from several large operators regarding their energy usage and data traffic development during the Corona pandemic and found minor changes in the former while the latter has increased a lot [9]: *"The GSMA surveyed several of its large operator members to ascertain the environmental impact of the surge in services such as videoconferencing and entertainment streaming. In most cases, network electricity usage has remained flat, even as voice and data traffic has spiked by 50% or more."*

This paper suggests a shift in how to model the energy consumption of network data services. Energy is a function of power over time and both these components need to be carefully studied and understood. This paper gives a broad understanding of how network equipment has evolved over time until today, how power models for each type of network equipment can be constructed based on real live network data, and show how the power consumption of mobile and fixed network data services can be estimated far more accurately.

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2 Background

This section gives a short data background, introduces several important aspects and definitions, includes a short review of existing literature, and presents a short overview of the ICT sector.

2.1 A long history of real measured data

Ericsson has together with Swedish operator Telia measured the energy consumption in fixed and mobile networks since mid-90's and published several papers [7-8, 12-14] of importance for this study. In particular, since 2010 in a collaboration with ETNO (European Telecom Network Operators), detailed network operation data has been collected and analysed [7]. The data set has been expanded over the years and cover in 2018 about 15 operators with 60 operations in 45 countries.

In addition, a global data set that covers about 2/3 of all subscriptions globally 2015-2018 has been collected. This data collection started in 2005 with 10 operators [12] and has been expanded over the years to include 36 operators from 2015 [8]. The granularity of this data set is lower than the ETNO data set, but the larger sample size allows for more accurate global estimates.

All data used in this paper unless stated comes from these large data sets described above and from additional internal studies of other nation-wide networks.

2.2 Global ICT sector overview

Figure 1 show the ICT sector's electricity consumption and data traffic based on [8], and ongoing updates with 2018/2019 data.

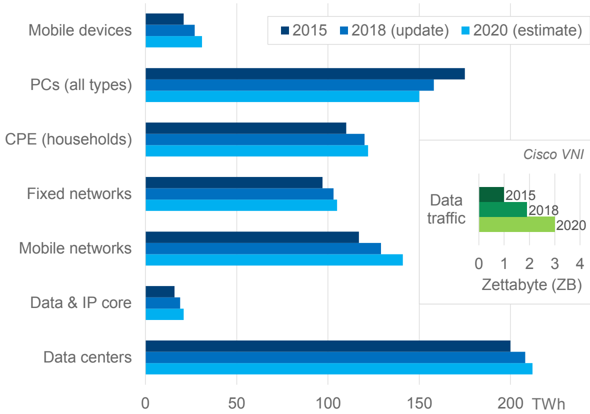

Figure 1: Global ICT sector electricity consumption and data traffic 2015-2020, based on [8]
Fixed networks include PSTNs, LANs and fixed broadband (BB) networks (WLAN/WiFi components included as fixed). Mobile networks include all standards, 2G/3G/4G/(5G).

Based on Figure 1, electricity consumption of networks increases with about +2.5%/year, data centers with +1.5%/year while user devices decrease with -1.5%/year. Number of subscriptions and data traffic increase faster, +3%/year and +25%/year respectively.

Figure 1 can be translated to average power values per subscription, line, user device or similar, also from [8], which gives a better "user" perspective, see Figure 2.

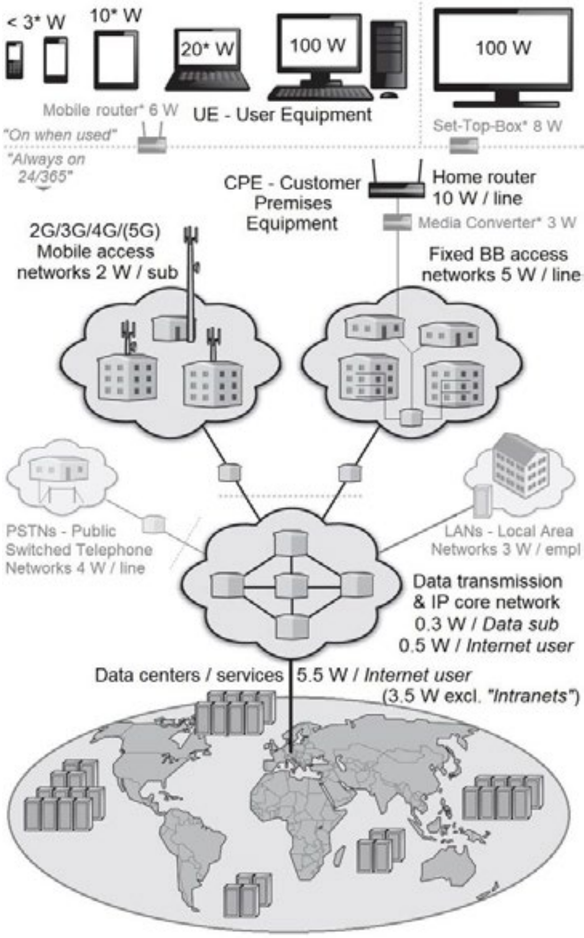

Figure 2: Global ICT sector average power values per subscription, line, user device or similar
* Portable user devices W-figures include charging losses, mobile routers, STBs and media converters are sometimes used (*optional*)

2.3 Low power per user, only a few Watt

The average power consumption per line/user (subscription) is relatively small, only about 2 Watt on average per mobile subscription globally.

The power consumption of the global data transmission and IP core network or the *Internet Backbone* is only about 0.3 Watt on average if the power consumption is split on 8.5 billion human mobile, fixed and LAN broadband subscriptions/users (not counting about 3 billion human "narrowband" users or any M2M/IoT subscriptions), or 0.5 W if split on *Internet users*.

For fixed broadband, the average power consumption is about 11.5 Watt for home routers and media converters and about 5 Watt for the average fixed broadband access network per line/household. A fixed broadband line is typically used by more than one person in a household and the average power per user is then about 4.5-6 W with an average of 3-4 users.

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2.4 A reduction of power but an exponential increase of data

The average power consumption per line or user (subscription) of mobile and fixed network services has decreased over time from their introduction up to around 2010, after it has been stable [8]. This decrease has happened despite data rates and data traffic kept increasing exponentially [8]. The maximum possible data rate has increased from a low 10-60 kbps around 1995 in the order of 10 000 times to 100-1000 Mbps in mobile and fixed networks currently (2020).

2.5 Power is NOT proportional to data

The power consumption of network equipment is not proportional to data traffic or "usage" of the same equipment. This fundamental behaviour, seen in real measurements and described in more detail in section 4, is a key concept in this study. Only high output power mobile base stations show a limited proportionality power - data, but the average variation across base stations in a network is only in the +0% to +20% "window" with an average power typically <+10% from a quite high *idle* power consumption.

2.6 Existing literature

Table 1 list several previous studies that have estimated or measured electricity consumption and data traffic in networks, mainly based on a study by Aslan et al [15].

Reference and year to which data apply	kWh/GB CPE / *Network*	*Network* W/Mbps
Taylor & Koomey, 2000 [A]	# / 7	3182
Taylor & Koomey, 2006 [A]	# / 0.7	318
Weber et al, 2008 - 2010 [B]	(1.2) [C]	(545) [C]
Coroama et al, 2009 [AB]	# / 0.2	91
Baliga et al [16], 2008 - 2010	0.11 / 0.06 [D]	27 [D]
Malmodin et al [13], 2010 [AB]	0.3 / 0.16	73
Shehabi et al, 2011 [A]	0.18 / 0.11	50
Krug et al, 2012 [A]	# / 0.14	64
Suski et al [17], 2014 - 2020	# / 0.024	11
Krug et al, 2014 [A]	# / 0.06	27
Malmodin et al [8, 13], 2015 [A]	0.043 / 0.023	10
Priest et al [18], 2016	# / 0.08 [E]	36 [E]

Table 1: *Energy per data* figures (*kWh/GB*) for fixed CPE and the *network* from existing literature Note: This study does not recommend the use of these figures to quantify

[A] Figures have been obtained via Aslan et al [15] and…
[B] …Malmodin et al [13] unless stated
[C] Weber et al combines CPE and *network* into one single figure
[D] Swedish 2010 data used with Baliga et al model described in [13]
[E] Total figure for both fixed and mobile (3G/4G)

Figures in Table 1 are from or represent average network conditions. However, some of the studies have used these figures for specific high data use cases like video streaming that this paper does not recommend. But most claims in media come from 3rd party uses of these figures multiplied by today's video streaming data and that have led to large overestimations, e.g. [3].

The *network kWh/GB* figures in Table 1 can be translated to W/Mbps figures which indicates the figures are for average low data traffic not to be used for higher data bit rates as they result in power levels not possible (10 Mbps result in 100 W or more).

Baliga et al [16] recommended in their 2009-paper that some network components should be modeled based on use time rather than data in the future. But this recommendation seems to have gone under the radar like our own statement from 2014 about the use of *kWh/GB* figures [13]: *"Further, because those figures are based on average conditions, the results are not relevant for specific conditions, such as very high bit rates and data traffic, as in B2B data traffic, or high-end video conferencing or video streaming."*

Given the discussions above the popular energy intensity per data approach should be replaced with more accurate approaches. Ericsson published earlier this year a report that looked at the carbon footprints of digital services [19] based on more detailed power models. This study digs further into the details.

3 Generic power model

In this section a generic power model that can be used for any equipment or device is described, see Figure 3. Similar power models have been in use within Ericsson for over 10 years, see e.g. [20], and they are still in use, see e.g. [21]. The focus of the paper is network equipment including CPE, but the model can also be used for user devices and data center equipment (servers).

CPE and all network equipment are typically "always on" 24/7 all year round. Even when there is no user data to send or process, the equipment typically consume power at a level close to its average operation point. The power of any equipment can be modeled based on two components, an "idle" power component and a variable power component proportional to data use. The "idle" power component can be described as a basic connectivity data service that enables a user (or subscriber/subscription) to fast connect to and use any network data service or reach another user or be reached by any network data service or another user *at an instant (or close to) high data bit rate*. Just to enable this connectivity requires a lot of the network resulting in a high idle power consumption or *service power*.

The P^{Idle} point can be defined as *no load (no user data)* but including network/system data needed to operate the network/system, e.g. reference/system/sync data in 4G mobile networks [21]. This basic connectivity *service power* consumption is about 2 W per mobile (2G/3G/4G) subscriber, about 1 W for 4G mobile data only and about 6.5 W / 18 W for fixed broadband with and without CPE. These figures include a share of all higher order data transmission and IP core networks (see section 4.5). It is this basic connectivity service subscribers pay for, and data usage is often unlimited at no additional cost (but a small increase in power).

The variable power component of network equipment shows typically a linear proportionality from the P^{Idle} point between power and data usage (load) or can be approximated as such. It is possible to also include e.g. power supply (same proportionality) and cooling (little to no proportionality) so the power model can include the total equipment power which is done in this study. Impact of sleep and off modes (limited in today's networks) can be included in the model proposed. This is an area for improvements, both for real live networks and the model.

The upper part of Figure 3 shows a mobile base station to illustrate the power / usage better as mobile base stations show a larger variation in power consumption. The generic power model can also be used for CPE and fixed network equipment but has then less slope.

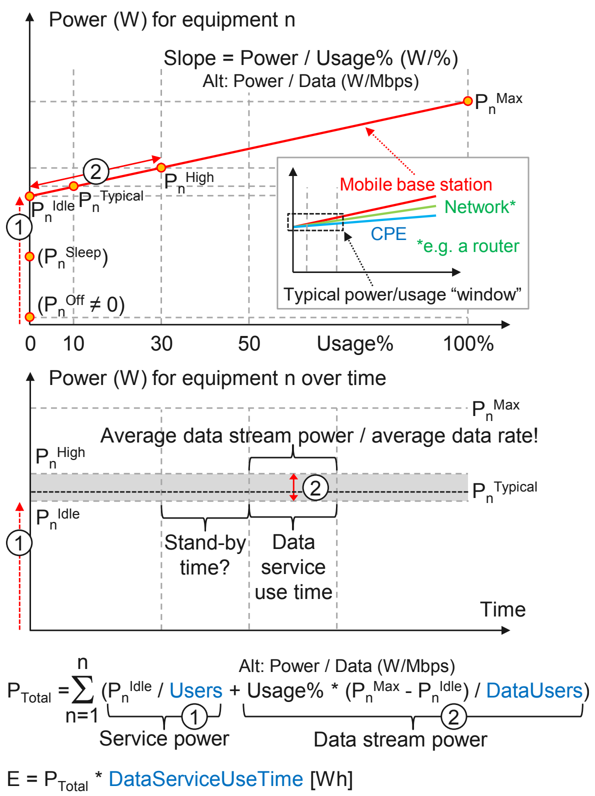

Figure 3: Power model and typical power over time for CPE and network equipment

A user's total data service power is simply the sum of all power shares, both the idle and variable component, for all equipment the data service uses along the network route. Total energy (electricity) E is simply: Total power * time (data service use time).

Additional *stand-by time* may be allocated to a data service, but it is then important to set the stand-by power = idle power, e.g. about 1 W per user for 4G mobile data. This is discussed more in the Discussion section.

4 Power models for all ICT parts

This section describes each ICT sector part with a focus on mobile and fixed broadband networks, how they have evolved over time and how a power model can be constructed based on real live network and individual network equipment data.

4.1 PSTN

PSTNs (Public Switched Telephone networks) is not in focus in this study but is described briefly. In the first measurements of PSTN by Swedish operator Telia in the early 90's, the average electricity consumption was about 40 kWh per active line for network sites and a further 25 kWh for "overhead" like offices, stores and other sites (including also some manufacturing sites at that time). The average today based on the ETNO data set [7] is about 36 kWh (~4 W) without overhead.

4.2 Mobile (broadband) access networks

The first network wide electricity measurement was carried out together with Swedish operator Telia in 1997 in the "08-area" (greater Stockholm area). The electricity consumption of the 2G (GSM) mobile network was about 33 kWh per subscription (sub) and the average for the whole of Sweden was estimated to about 40 kWh. In addition, about 8 kWh electricity per sub was consumed in offices, stores and other non-network sites [14]. The global average in 1997 was estimated to about 35 kWh with individual countries ranging from about 25 kWh to 65 kWh excluding overhead.

The electricity consumption per sub in mobile networks decreased relatively fast 1995 – 2005 as the increased number of subscribers used the same networks. The power consumption has since early 2000's been around 2 W, changing from slowly decreasing to slowly increasing around 2010, see Figure 4 and [8, 12]. At the same time, the increase in possible data rates and actual data traffic has been in the order of 10000 times [8].

The average power consumption currently (2020) in mobile access networks is in the range 1 to 4.5 W/sub for selected countries with a global average of around 2 Watt corresponding to an annual electricity consumption of about 17 kWh, see Table 2 and [7-8]. Most mobile networks include 2G, 3G and 4G services, some networks even 5G today. The power consumption of only the 4G part is around 1 W/sub but since not all networks offer 4G the global average is lower. 4G can be >50% of the power in built-out modernized networks. In sparsely populated countries like Finland and Sweden the 4G power per sub is about 2 W.

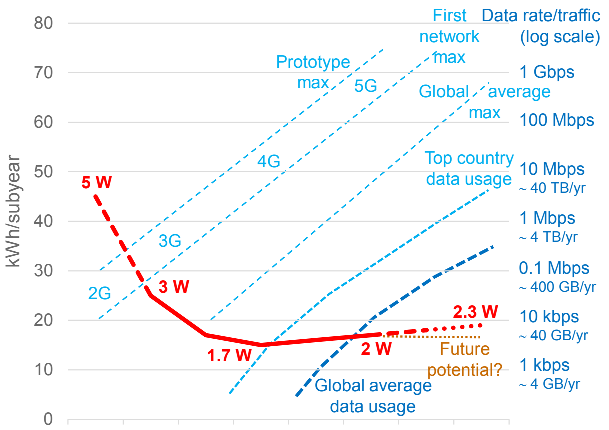

Figure 4: Average power, electricity use and data per mobile subscription over time, based on [7-8]

Year 2018	Capita /km²	Access network	Over-head [1]	Carbon footprint [2]
Finland	16	40 kWh	5 kWh	9 kg CO_2e
Sweden	23	35 kWh	5 kWh	2 kg CO_2e
US (excl. Alaska)	40	30 kWh	4 kWh	20 kg CO_2e
EU-28	110	25 kWh	4 kWh	12 kg CO_2e
China	150	20 kWh	3 kWh	18 kg CO_2e
World	**50**	**17 kWh**	**2.5 kWh**	**12 kg CO_2e**
Germany	240	14 kWh	2 kWh	13 kg CO_2e
India	400	13 kWh	1.5 kWh	17 kg CO_2e [3]
Bangladesh	1000+	9 kWh	<1 kWh	8 kg CO_2e [3]

Table 2: Electricity consumption and carbon footprint per sub in selected countries, based on [7-8]

[1] Overhead = offices, stores, warehouses etc. (all non-network sites) Overhead is NOT included in the power model
[2] Using the country average electricity emission factor
[3] Including on-site diesel generator emissions

4G mobile BB access networks show a larger proportionality between power and usage compared to 3G and fixed BB. Still, 4G radio unit need a certain level of power, about 50% of its max power, to establish and maintain area coverage, keep track of and constantly broadcast reference/system/sync data to possibly thousands of mobile devices and be ready to instantly respond to any input from users and the network.

The additional power consumption is typically between 1 and 2 Watt per Mbps user data traffic. The power is typically lower in small cells with lower output power but can also be higher. New base stations typically operate more efficiently than older ones but can have higher output power. Figure 5 show the proposed power model and real measurements of a medium sized new 4G base station (part of a 2G/3G/4G base station) in a suburban environment. Note that also power for cooling, power conversion, baseband and data transmission is included in Figure 5 – *a whole base station site*.

Based on Figure 5 one could possibly allocate about 60 Watt to the 4 Mbps HD video stream based on the about 30% data share. However, that would be to ignore how a base station operates and what we can measure and see in Figure 5. The power before and after the added video stream is about 215 Watt, the additional power for the video stream is only about 6 Watt (P_{10} to P_{14}). A 4G radio unit can serve up to 1000 subscriptions and before, after and during the video stream, other active users are *served* with data and all subscriptions are constantly *served* with reference/system/sync data. Based on how a base station operates, it is not recommended to allocate any additional "stand-by-time" to any specific usage, especially not based on share of data.

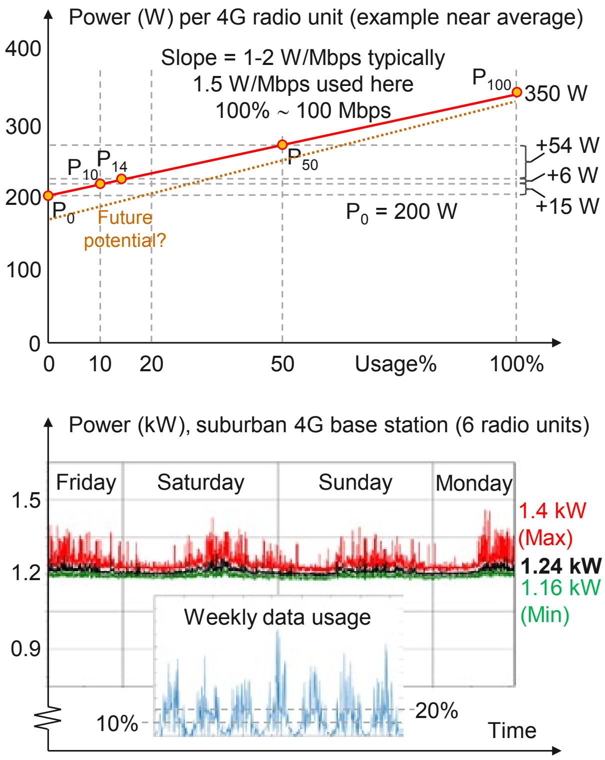

Figure 5: Power and data model for a suburban 4G radio unit / base station (based on real data)
Includes the whole base station (radio units, baseband, power and cooling) and its share of the data transmission and IP core network. P_{10}-P_{14}: 4 Mbps video stream, P_{10}-P_{50}: File download (40 Mbps)

Dedicated data transmission and control & core nodes typically make up about 5% of the electricity consumption of the access network. For the 4G base station in Figure 5 the power consumption of the additional higher order data transmission and IP core network is about 60 W (also about +5%), see section 4.5.

4.3 Fixed broadband access networks

The first generation of fixed BB access lines (ADSL) used existing PSTN lines (copper) and the electricity consumption per line was in the range 5 – 10 W and for the modem 10 – 15 W. The power consumption improved fast from >20 Watt to <15 Watt in a few years. For a short period of time, additional routers were needed to get more LAN and WiFi connections but that changed with modem/router combo products that also

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started to include IPTV and IP-telephony functionality. The average power consumption is about 11.5 Watt for the average mix of home routers and media converters with a wide range of about 6 – 30 W.

Year	CPE	Access network	Core network
2003	1st gen. modems: 12.5 W, 110 kWh	1st gen. ADSL: 7.5 W, 66 kWh	5 W, 44 kWh
2007 2010	Modems/routers: 13.5 W, 118 kWh	2nd gen. ADSL: 5 W, 70 kWh	3 W, 26 kWh
2015	Home router: 11 W, 96 kWh	Mix of all technologies: xDSL, fiber, cable-TV: 5 W, 44 kWh	1.5 W, 13 kWh
2018	Home router+*: 11.5 W, 101 kWh		
2018	Media converter: 3 W, 26 kWh	Used for fiber lines (about 50% share of lines 2020)	

Table 3: Average power and electricity use per line in fixed BB access networks, based on [7-8, 14]

* Includes also a share of media converters used for fiber lines

The power consumption per access line currently (2020), is in the range 2 W to 10 W with an average of 5 W for all main BB access technologies: xDSL, fiber and cable-TV [8, 14]. Older fiber and cable-TV lines typically consume more and new lines less.

Figure 6 show the power consumption of a typical fixed broadband line with an average share of the core network included (see section 4.5). The power per line have been reduced with about 25% 2000-2020. At the same time, the max data rate and average data traffic per line have increased >100 times [7-8].

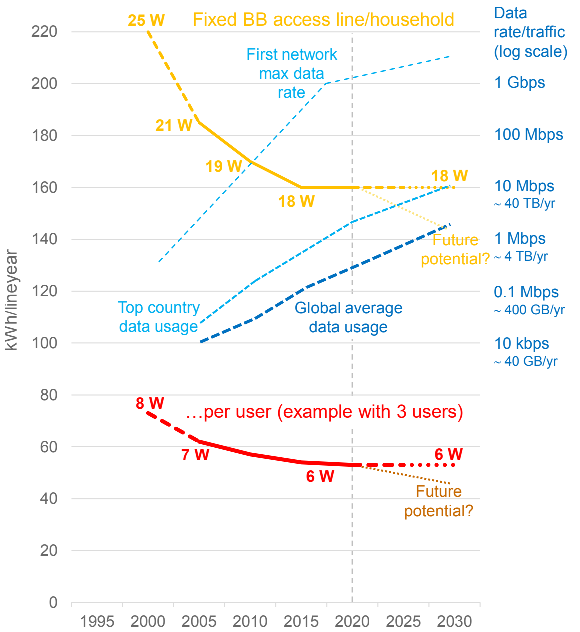

Figure 6: Average power, electricity use and data per fixed BB line over time, based on [7-8, 14]

Figure 7 show the proposed power model for an average fixed BB access line and how the power varies with different data uses and number of users, 3-4 users typically per line. As shown in Figure 7, an average *energy per data* figure over time cannot be used for high bit rate use cases like video streaming and file downloading as such numbers can be >100 times too high for those conditions, see Figure 7.

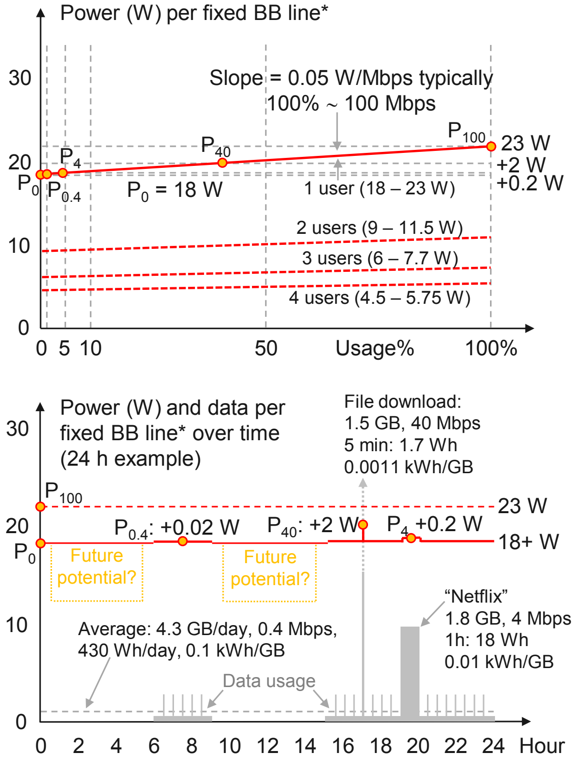

Figure7: Power/data and power/time (24 h) model for a fixed BB access line* (household)

* Includes CPE (home router) and all components of a fixed BB access network per line and its share of the data transmission and IP core network

The power consumption of a home router depends on first the model but then on services included in the subscription, how it is configured and the number of active connections/users in the household, but power variations are small, and after set-up/connections the power variation is even smaller. A fixed BB subscription and the home router can include IP-telephony (~1 W), IPTV (use of dedicated LAN-port), typically 4 LAN-ports (~1 W/port), WiFi (~2 W) and WAN connection and main module (~3 W). Several devices per user can be connected but this study recommend splitting the power on number of users as it is simple, and a user typically uses only one device at a time.

It must be noted that to allocate all power to one user in a household with e.g. 4 users is doing the impossible as one user only can use a share of the router, e.g. 1 LAN-port or share of WiFi. A more complicated split based on router component use would probably yield even lower power figures per user, but the simpler per user model is preferred here.

4.4 LANs - Local area (access) networks

LANs are not in focus in this study and are only described here briefly. The first measurement of LANs at

Ericsson was carried out in Sweden in the mid 90's. It was difficult and not a primary goal to separate the LAN part from all other equipment like servers and storage that was mainly hosted locally at that time. The result indicated a power consumption of 10 Watt or more per active employee. New studies were done 2005-2010 "before and after" large IT modernizations and the LAN-part dropped from about 7 Watt in 2005 to about 3.5 Watt in 2010. The average power consumption in today's LANs have decreased further but due to the increase of WLAN equipment the average power is still about 3 Watt per active employee.

4.5 Data transmission and IP core network(s) (or just *core network*)

In the ICT network studies in Sweden 2010-2015 [14], the electricity consumption was constant in absolute terms, but there was a shift in electricity consumption from data transmission equipment to the IP core network, from link equipment to routers.

In 2009, Ericsson studied video conference data transmissions between offices in Sweden and the US including the Swedish core network and a high-capacity Atlantic optical submarine cable system (TAT-14) with help from operator Telia [22-23]. The average power consumption was estimated to about 2.5 W/Mbps (one direction), the Atlantic cable represented 0.5 W/Mbps. The hop count was 20 plus the Atlantic cable counted as only one. Today, 10+ years later, the same data transmission uses <1/10th of the power, see Table 4.

Today it is possible to have a data throughput of >1 Gbps per Watt in edge/metro routers and >3 Gbps per Watt in core routers and the variable power/data is only about 1/10th of that. Not to forget data transmission equipment with repeaters that are like routers in terms of power. Table 4 summarizes selected data for the core networks described in this section.

	Average per Data sub / Internet user	Split Fixed line / Mobile sub
Sweden 2010-2015 [12-13]	0.8 W / 1.5 W	3 W / 0.3 W
Europe/World 2015-2020 [7-8]	0.3 W / 0.5 W	1 W / 0.15 W
Typical router data	**Δ power**	**Total power**
Edge/Metro router [A]	0.1 W/Gbps	1 W/Gbps
Core router [A]	0.03 W/Gbps	0.3 W/Gbps
Ericsson 2009 study [21-22]	**2009**	**2020**
Routers (20)	0.7 W/Mbps	0.1 [B] W/Mbps
High capacity optical links with repeaters	1.3 W/Mbps	0.1 [B] W/Mbps
Atlantic optical submarine cable system including "data centers" at both ends [22]	0.5 W/Mbps	0.05 W/Mbps

Table 4: Data transmission & IP core network data

[A] These figures are similar to figures used by others [24-25]
[B] Proportions between routers and links modified based on [14]

The power model for the core network is the sum of the network route equipment (number of hops). Based on the data in Table 4, the following simple summary model with a fixed service power component and a variable power/data component is proposed:

Fixed BB power = 1.5 W + 0.03 W/Mbps
Mobile BB (4G) power = 0.2 W + 0.03 W/Mbps

The above model is a bit cautious and power is probably lower in real live networks as the ETNO Europe/World data suggest [7], (see section 2.1). Number of hops and an Atlantic hop is on the high side.

4.6 Data centers / services

Data centers / services show unique behaviours for each application. A global/regional/country average cannot be used to estimate a specific data service. Data traffic is not proportional to energy consumption. Netflix share of global data traffic was about 15% in 2018 but its share of data center electricity consumption was only about 0.2% [4].

Netflix global electricity consumption 2018/2019 including their use of other ICT companies' platforms (like Amazon and Google) divided by total video hours (about 50-65 billion h, about 250-300 EB), result in about 5-7 W per average video stream (4-5 Mbps) [4]. Note that non-streaming servers and other electricity consumption at Netflix (e.g. offices) related to production and other business activities is also included.

YouTube are here estimated to about 1 TWh (a lower estimate of <0.5 TWh can be found in [17]). With a much larger user base, less average use time and video quality, and much less overhead (own production) per video, the resulting power and electricity consumption are estimated to be less than half per video (time) compared to Netflix.

Table 5 shows key parameters for several well-known data services. Many of the well-known data center / services have a low power and energy consumption per user. Even if we sum FAMGA + Netflix and split their total electricity use on 3.5 billion Internet users (excluding some countries), the resulting power (1.1 W) and energy (9.4 kWh) is modest.

Year 2018 unless stated	AEC TWh	Users million	Use time (h/day)	Average W*/W*/kWh
FAMGA+N	33	3 500	na	1.1 / na / 9.4
Netflix	0.3	125	1 h 11 m	0.27 / 5 / 2.4
Netflix 2019	0.45	155	1 h 11 m	0.34 / 7 / 3
Facebook	3.4	2 400	40 m	0.16 / 6 / 1.4
Google	10.1	3 500	1 h	0.3 / 8 / 3
YouTube	1	2 000	11 min	0.1 / 2.7 / 0.5
Wikipedia	0.003	*Any stats result in low power/energy**		

Table 5: Examples of data center / services power/energy figures and use statistics

* Energy split on 24/7 all year round, next W-figure: energy split only on use time, Wikipedia user stats not known

4.7 User devices (discussion)

User devices are not in focus of this paper. But for the sake of completeness their role in relation to data services (e.g. video streaming) is discussed briefly.

Desktop PCs and TVs consume in the order of 100 W in operation [8]. One simple rule is then: If an application or data service can be run on a smaller and more energy efficient device like a laptop, tablet or preferably a smartphone, power and energy consumption can be reduced substantially. Other studies have come to the same straight-forward conclusion, e.g. [16].

The additional power for streaming is mainly related to the data center / service as it mainly occurs over fixed BB (and WiFi) with low additional power. An optical disc player's stand-by consumption over a year is as large or larger (1/0.3 W before/today) than the average Netflix subscription (0.3 W, 3 kWh). The manufacturing of DVD's/BD's and the disc player, operation of the disc player and physical travels make the traditional physical way of watching a film more energy and material consuming. Streaming is a good example of dematerialization.

As video streaming has allowed watching e.g. TV-series and movies even on smartphones and tablets, there is probably a large hidden power and energy net saving effect of streaming. There are less TV's on in a household, also the primary TV is on less time, and PC usage show the same pattern of less use [8, 14]. Another probable positive effect of a high data bit rate is that user devices like TVs and PCs need to be on less time for upgrades and downloads of files (or file sharing). File sharing used to consume lots of power 10-20 years ago as primarily PCs were left on for hours to share files. To try to quantify this net power saving effects of streaming is an area for future research.

5 Total results - Conclusions

This study does not recommend using single *energy per data* figures (*kWh/GB*) as they are typically based on old average conditions and they lead to large overestimations for today's high data use cases like streaming video or downloading large files. The power consumption of mobile and fixed network data services can be calculated in a simple way according to Figure 8 based on the power models proposed in this paper.

In contrast to media reports [3,5,11], streaming YouTube and Netflix videos do not consume a lot of power. Watching a YouTube video (~1 Mbps) on a smartphone including network and server consume about 10 W and not >1000 W. Streaming Netflix adds about 7 W, mainly from Netflix/partners data centers (servers), to the near constant power consumption of a fixed broadband line of about 18 W.

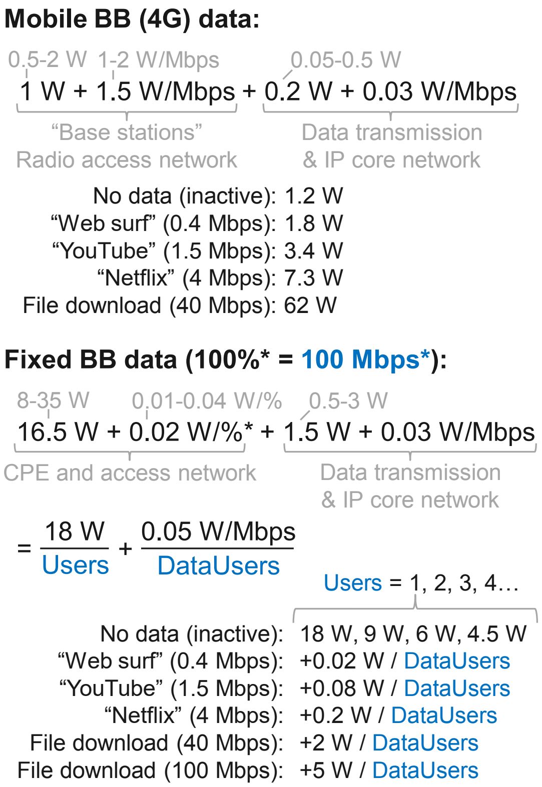

Figure 8: Simplified power model for mobile and fixed data services with ranges and key results

* The data rate varies a lot between different fixed BB access subscriptions but the power variation with data rate is marginal

Number of users in a household and number of data service users, e.g. 2 data users watching Netflix in a household of 4, must be considered for fixed BB data. The last step to calculate Energy (E) is to integrate power (P) over time (t) which in the simplified form is:

$$E = P_{Use} * t_{Use} (+ P_{Stand\text{-}by} * t_{Stand\text{-}by}) \text{ [Wh]}$$

Streaming saves energy and materials compared to e.g. traditional optical discs and as streaming let us use tablets (< 10 W) and smartphones (< 3 W) there is a large "hidden" net effect when we turn off our PCs and TVs (about 100 W) to be quantified by future research.

6 Discussion

This paper suggests more detailed modelling of energy consumption of network data services beyond often used energy intensities per byte which are mostly not representative and relevant for the purpose. Energy is a function of power over time and both these components need to be carefully considered and understood.

Energy per data figures (kWh/GB) are typically network wide metrics that can be used to understand a network and how it evolves, but further use is limited. Such figures should not be used to calculate an energy consumption related to a specific data service based on amounts of data. The reason is simple, power and electricity consumption show little to no proportionality to data due to the idling consumption of involved equipment. An average kWh/GB figure can be >100 times higher as an average vs in specific very high bit rate use cases like large file downloading, see Figure 7.

The use of the proposed power models in this paper instead of often used *energy per data* figures is supported by several strong arguments based on observations of real networks their behaviour over time:

- First, the power model is built on real live network data from a long period of time including up-to-date data from a large part of all networks globally.
- The proportionality between average power consumption and data for network equipment is very weak. Additional power consumption per additional data is very low.
- Subscriptions with unlimited data is becoming standard. The business model can be said to be aligned with the power model or vice versa.
- No connection between power consumption and data use is seen in history. Historic data shows data rates and data traffic have kept increasing exponentially (slowing down slowly) while power consumption has decreased per subscription or line.
- An instant high bit rate is wanted/needed for all data use, not only streaming and data downloading. For video streaming and file downloading a delay of a few sec can be accepted as they last much longer. Such delays are not accepted when we browse the web, social media use, gaming etc.
- "Network electricity usage has remained flat, even as voice and data traffic has spiked by 50% or more." GSMA studied the impact on networks from the recent lockdowns due to the Corona virus [9]. Again, no proportionality power - data.

One argument against the proposed power models is so-called *network stand-by time* are not considered. But stand-by time can easily be added by multiplying the *no data (inactive)* power with an appropriate stand-by time. But the real question is: Should any stand-by time be allocated to any use time at all?

A mobile base station serves in the order of 1000 subscriptions. Any allocation of stand-by time must be from times when the base station tracks up to 1000 users and serve up to 100 or more active users with data. For mobile, the stand-by power is in all cases marginal, and hard to justify. The same thinking can be applied to a fixed broadband line. Each person/user in a household and all devices are typically constantly connected. And to allocate all power to one user is physically impossible as a user use only one LAN-port or a share of the WiFi, main module and WAN-connection and so on. And for stand-by time it is the same as with base stations (WiFi ~ small base station), other users use the equipment and are connected to it. Any allocation of stand-by time becomes hard to justify.

An unintentional effect of using average *energy per data* figures for specific high data use cases is that the energy figure implies that a very long stand-by time have been added to the actual data use time. Real live network measurements show it is impossible to consume that amount of power. For every video hour typically >10 h stand-by time have been added and for file downloads this can be >100 times. This study does not recommend adding any stand-by time but if it is done, it must be carefully considered and quantified.

We need to learn that there is a certain power associated with being able to instantly be reached or reach most humans on the planet and get access to most knowledge and entertainment ever created, and an ever-increasing number of data services (*Internet*). The power consumption does not start when we use it, it is there all the time.

7 Acknowledgement

This study would not have been possible without the 20+ year-long collaboration with Dag Lundén and his colleagues at Swedish operator Telia. And thanks to Dag's colleagues at other ETNO operators, up-to-date detailed network operations data has been made available for our studies otherwise hard to come by.

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Limits to exponential Internet Growth

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Abstract

Since the global ramp-up of the Internet, its throughput and the associated bitrates have been growing exponentially. As a consequence, the related negative environmental impacts, i.e., most notable, the global warming potential, grew exponentially as well. The growing Internet bitrates lead to respectively growing transport bitrates or throughput per equipment. For equipment that is deployed outside of the core-network, this growth is compensated for by increased energy efficiency. However, the energy consumption of the core-network is steadily increasing. In addition, the increase of energy efficiency in electronic switching and fiber-optic transport is approaching some fundamental limits in the next 20 years or so. Ultimately, for both, switching and photonic transport, this will be the Shannon-von Neumann-Landauer (SNL) thermal limit. The SNL limit defines a lower bound for energy, either per switching event or per bit transported, which is defined by quantum thermal noise. This will lead to an increasing fraction of the ICT contribution to global energy consumption and its associated emissions. The latter is partly offset by the speed of conversion towards renewable energies. This poses the questions how long bitrate growth in our networks can persist, and when physics will ultimately stop this growth. The alternative might be that the Internet becomes the ultimate energy-consuming machine globally.

1. Introduction

Since the global ramp-up of the Internet, its throughput and the associated bitrates have been growing *exponentially*. This can be tracked in the standard reference for Internet throughput, the Cisco Visual Networking Index, VNI, [1]-[3]. It is shown in Fig. 1 where the log scale of the Y-axis is to be noted. The traffic growth is driven predominantly by video traffic, as can also be derived from [3].

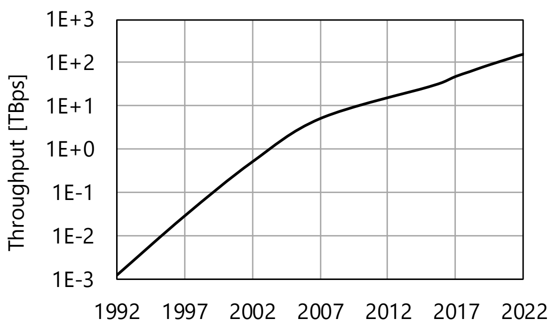

Fig. 1. Global Internet traffic [1]-[3]

The main components of the Internet are wired (access and backbone) and wireless (access only) networks, data centers, and end-user equipment. The networks interconnecting users and data centers account for ~25% of the total resulting energy consumption and associated emissions. They split into backbone or core and access (incl. wireless) parts. The core networks consist of aggregation switches, routers and fiber-optic WDM (wavelength-division multiplexing) long-distance transport. For these equipment classes, some 80-90% of the environmental impact are determined by the use-phase energy consumption, which can be derived from lifecycle analyses [4]-[7]. This is particularly true for the global warming potential (GWP), that is, emissions of greenhouse gases (GHG, i.e., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3)).

In this paper, we will discuss Internet growth trends including their saturation effects and conclude that nonlinear bandwidth growth will (have to) come to an end within the next two decades or so.

2. ICT Environmental Forecasts

As a consequence of the persistent traffic growth, the related negative ICT (information and communications technologies) environmental impact grows as well. This holds for all environmental impact categories: GWP, resource depletion, ozone depletion, various toxicity parameters, acidification, eutrophication, etc.

The most important impact of the persistent traffic growth in ICT is on the GWP. This is primarily driven by the related use-phase energy consumption. The energy consumption, in turn, is driven by the

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increasing traffic, or bandwidths, which is analyzed in more detail in Chapter 3.

Energy consumption is further increased by the trend toward increased *wireless* video downloads in 4G (LTE) and 5G mobile networks. Compared to download in fixed-access networks with broadband copper- or fiber-based access, this requires substantially more energy even if WLAN is considered for the in-house part of fixed access. This is quantified in Fig. 2 [8].

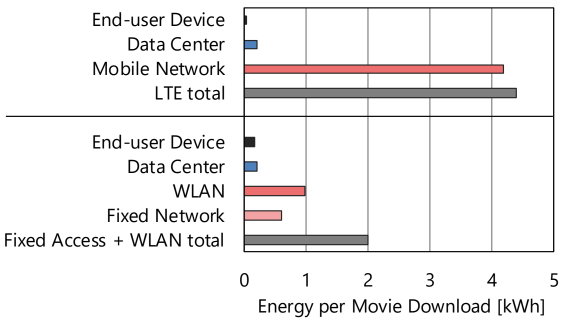

Fig. 2. Energy-consumption comparison for download of a 9-GB high-density movie [8]

The growth trends (bandwidths, wireless video usage) lead to increasing ICT energy consumption. This is also forecasted for the next couple of years, as is shown in Fig. 3 [9]. Here, the ICT energy consumption for Germany has been forecasted. Total growth is comparatively moderate (in particular compared to older forecasts). This is driven by decreasing end-user-equipment consumption. Data centers and in particular networks, however, show relatively strong increase. The main reason is that these ICT parts have to cope with high accumulated and increasing bandwidths.

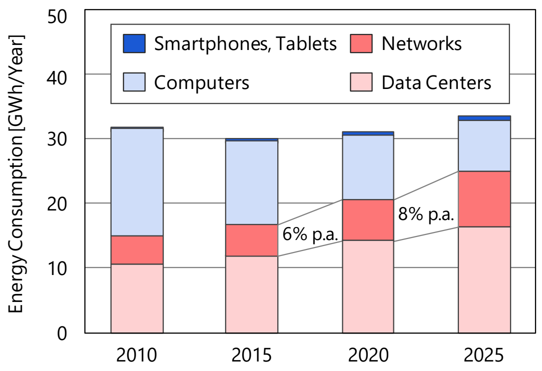

Fig. 3. ICT energy consumption in Germany [9]

Regarding the ICT networks, a bit more than 50% are attributed to the wireless part, the rest to the fixed networks. The wireless part is also forecasted to grow faster [10]. In turn, this is driven by 5G rollouts.

Increasing ICT energy consumption leads to increasing ICT GHG emissions. As shown in Fig. 4, this increase has been (and will be) somewhat slower than the energy-consumption increase. This is due to the fact that over time, the related electricity emission factors (with dimension [kgCO_2e/kWh], that is, the amount of kilograms of carbon dioxide equivalents per kWh that is generated) decrease following climate actions toward a higher degree of renewable energy. Note that Fig. 4 shows global ICT emissions.

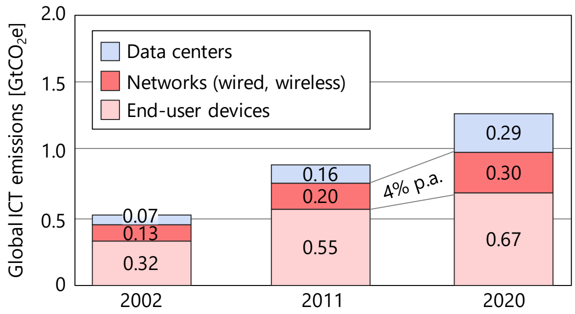

Fig. 4. Global ICT emissions [10]

Given the threats of global warming and general resource depletion, the ICT environmental-impact growth is critical. In Chapter 4, we will show that this negative ICT effect is compensated by positive environmental effects. However, in the next chapter, we will also show that the ICT sector itself runs into certain problems within the next two decades or so.

3. Trends and Fundamental Limits

The exponentially growing bitrates of Internet applications lead to respectively growing throughput per ICT equipment. In the last one to two decades, this increase has been overcompensated *for end-user equipment* regarding energy consumption and related emissions due to strong gains in energy efficiency. This was mainly achieved by replacing desktop PCs and cathode-ray-tube monitors by laptops and flat screens, in particular the ones based on LCD or OLED (liquid-crystal display, organic light-emitting diodes).

ICT data-center and network equipment also got more efficient. However, it also had to cope with the accumulated bandwidths of an increasing number of applications. For core-network equipment (switches, routers, and WDM transport equipment) it has not been possible to cope with this bandwidth growth by gains in energy efficiency: as a result, *core-network equipment, over time, consumes more energy*. This has been investigated by several authors, including own research in particular for WDM equipment [11]-[14]. Results of these studies are summarized in Fig. 5.

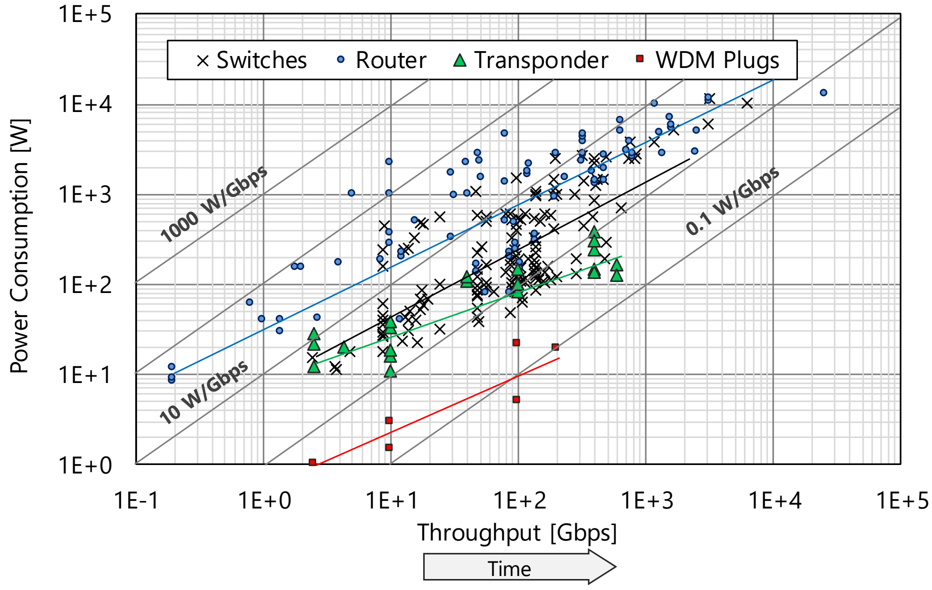

Fig. 5. Power consumption of core-network ICT equipment [12]-[14]

Note the log-log scale of the diagram. The X-axis also pretty much reflects a time axis, albeit at almost linear scale.

For WDM equipment, two classes of equipment are shown, transponders and pluggables. The former provide higher performance, e.g., long-distance capability, and have less compact form factor and higher power consumption, compared to pluggables. They are used in long-haul core networks, whereas pluggables are used toward the access and in data-center interconnects over limited distances.

Over the last three decades or so, all equipment classes achieved substantially higher throughput. However, total power consumption per respective piece of equipment also grew. In Fig. 5, the development toward higher power efficiency can be derived from the colored trend lines that are crossing the isolines of constant power efficiencies (0.1…1000 W/Gbps).

As an example, the power efficiency for WDM transponders improved by a factor of ~50 from approximately 10 W/Gbps in the mid-90s to almost 0.2 W/Gbps for the latest generation in 2019. This could not cope with the bitrate increase. For fully-loaded systems, they developed from 40 Gbps to ~8 Tbps in the same period, i.e., a factor of ~200.

The power-efficiency development for (our) WDM transponders is shown in Fig. 6 [14]. With the exception of the 40-Gbps class around 2006, it followed a straight trend in log-log scale.

The trend curves so far do not indicate that efficiency might over-compensate bandwidth or throughput growth in the near future. On the other hand, the VNI forecasts regarding bandwidth (or traffic) growth so far have been reliable, which can be derived when comparing current numbers with old forecasts.

In addition, there are quite a number of applications trends that have the potential to actually fuel the bandwidth growth. This includes 5G, Industry 4.0, Internet of Things (IoT), HPC (high-performance computing) together with big-data applications like the LHC (large hadron collider) or the SKA (square-kilometer array), and 3D-high-resultion video streaming.

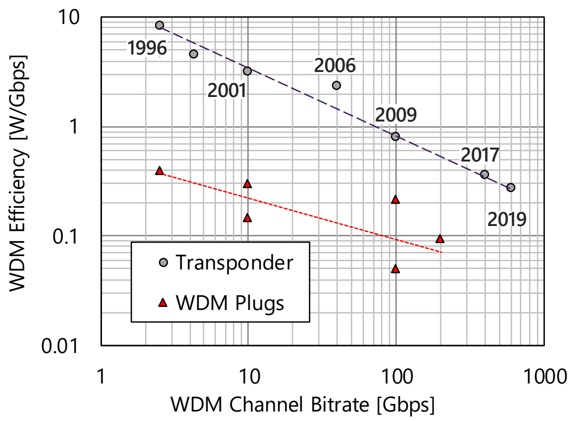

Fig. 6. Power efficiency development for WDM [14]

In addition to bandwidth growth which is likely to be sustained over the next couple of years, we are approaching another problematic area. *The increase of energy efficiency in electronic switching and fiber-optic transport is approaching some fundamental limits in the next 20 years or so*. Ultimately, for both, switching and photonic transport, this will be the Shannon-von Neumann-Landauer (SNL) thermal limit [15]-[17].

In electronic switching/computing and signal transmission, the per-bit energy is lower-bound by the Shannon-von Neumann-Landauer (SNL) limit:

$$E_{\text{bit}} \geq E_{\text{SNL}} = k_{\text{B}} T \ln 2$$

Here, k_{B} is Boltzmann's constant, and T is absolute temperature in Kelvin. Minimum size and switching time of a machine at the SNL limit can be derived from Heisenberg's Uncertainty relation:

$$t_{\min} = \hbar/\Delta E = 0.04 \text{ ps}, x_{\min} = \hbar/\Delta p = 1.5 \text{ nm}$$

Here, ΔE and Δp are the energy and momentum uncertainties, and $\hbar$ is the reduced Planck constant, respectively. The power dissipation per unit area of such a machine is given by, with size-limited density of switches $n_{\max}$:

$$P = \frac{n_{\max} E_{\text{bit}}}{t_{\min}} = 3.7 \cdot 10^6 \text{ W/cm}^2$$

This switch has *only a factor of 6 less size than 22-nm node CMOS technology* (complementary metal-oxide semiconductors with physical gate length of 9 nm). Its power density is $4 \cdot 10^4$ larger than end-of-ITRS (International Technology Roadmap for Semiconductors) projections. It would thus require *forced* cooling. The minimum per-bit energy then becomes

$$E_{\text{bit}}^{\text{total}} = E_{\text{bit}} + \frac{T_{\text{a}} - T_{\text{dev}}}{T_{\text{dev}}} E_{\text{bit}}$$

$T_{\text{a}} = 300$ K and T_{dev} is the device temperature. The resulting total bit energy is shown in Fig. 7 (a is the minimum switch size).

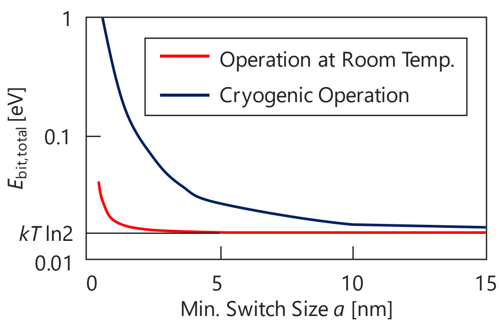

Fig. 7. Bit energy as a function of switch size [16]

The practical consequence is *the end of combined density / switching-speed scaling*. Without disruptive developments, minimum switch size will stop somewhere below, but close to, 5 nm.

According to Fig. 8, this is confirmed in [18]. Here, the gate-length decrease is predicted to stop around 4 nm, and it does so within the next 10 years or so. In addition, the corresponding energy asymptotically approaches a value that is more than a factor of 100 higher than the theoretical SNL limit.

Even if scaling development proceeded below 4 nm gate length, the fundamental SNL limit would be reached roughly 10 years later, as can be derived from Fig. 9 [19].

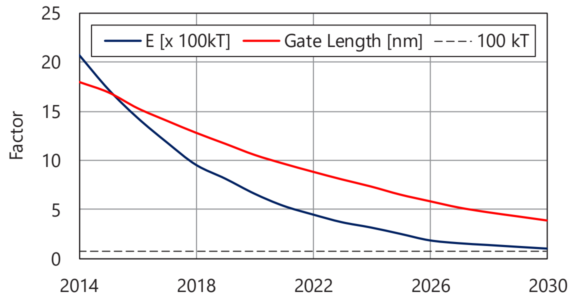

Fig. 8. Energy vs. gate length, alternative limit [18]

Here, another interesting threshold is marked – the photon energy at the wavelength of 1550 nm, which is the center wavelength of almost all commercial WDM systems. So far, no commercial WDM systems have reached this sensitivity. This means that certain practical limits may be reached even earlier than the ultimate SNL quantum limit.

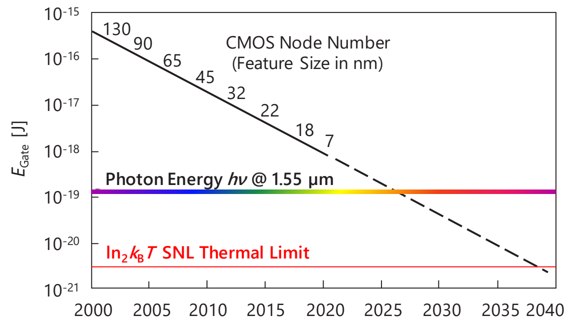

Fig. 9. Development of semiconductor-gate energy and fundamental limits to energy efficiency [19]

The fundamental downscaling limit also lower-bounds further efficiency increase for the equipment classes considered so far. This will become apparent in the next 10 years or so.

In addition, and related to data-center equipment, further saturation effects already became visible. As a consequence, there has been strong increase in energy consumption for the highest-ranking HPC machines over the last four decades (from ~150 kW around 1980 via ~700 kW in 2005 to 17 MW in 2014) [20].

Again, with increasing performance requirements, there does not seem to be a way out of this situation since CPU performance is almost saturating, as can be derived from Fig. 10 [21], [22]. This may lead to simply scaling the number of CPUs, which will lead to energy-consumption increase since in addition, gain through parallelization saturates (Amdahl's Law).

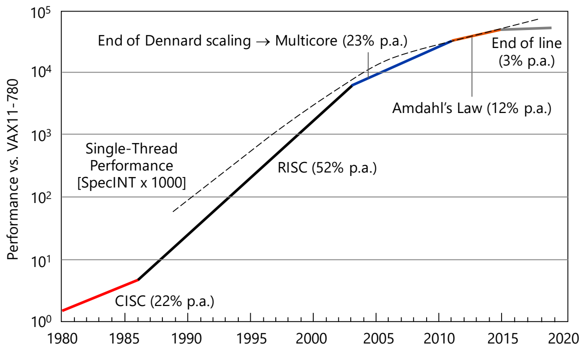

Fig. 10. Development of CPU performance [21], [22]

Storage equipment in data centers is facing saturation effects as well. The main media for mass storage – tape, HDDs (hard-disk drives) and optical disks (CD, DVD, Blu-ray) – show slowed-down increase in further areal density. The latter is relevant for cost and resource efficiency. For HDDs, there is also an effect on energy efficiency. This effect is small for tapes and optical disks since both are used for back-up or archiving only where the respective drives can be switches off for most of the time.

The areal-density development is shown in Fig. 11 [23]. Holographic techniques may become an alternative (either for storage or archiving), but so far have not seen substantial deployment.

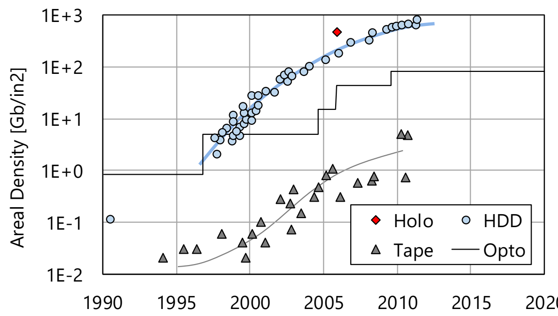

Fig. 11. Development of storage density [23]

Areal density has an obvious impact on per-device total storage capacity. Therefore, the increase of the latter is slowing down as well. This is shown in Fig. 12 for HDD and flash memory [24].

Only optical data storage (ODS), which started with CDs and is developing toward Nano-photonics, is predicted to further scale. However, it has not yet seen significant deployment.

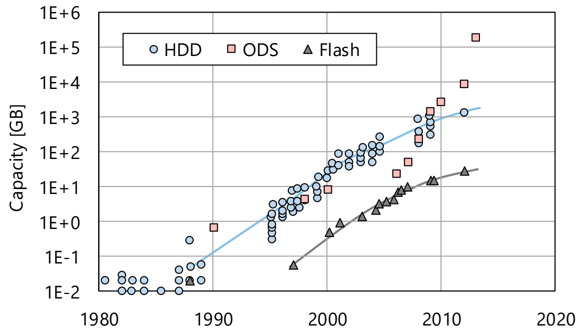

Fig. 12. Development of storage capacity [24]

With increasing bandwidth requirements, the saturation effects may lead to the necessity to simply use more of what is available. Ultimately, this will further fuel energy-consumption increase. In [25], [26], the global ICT energy consumption has been predicted beyond 2025, taking into account strong growth that is primarily mobile-driven. The result is shown as the black solid curve in Fig. 13.

The red curve in Fig. 13 shows the resulting GWP. Here, electricity emission factors that are linearly decreasing from 0.4 in 2020 to 0.3 in 2030 have been used. Under these assumption, significant increase in ICT energy consumption and GWP is to be expected beyond 2025.

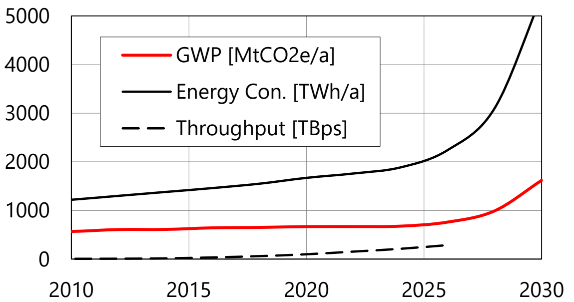

Fig. 13. Forecast of global ICT throughput according to [1]-[3] (extrapolated to 2026), and yearly ICT energy consumption and GWP [25], [26]

The forecasted GWP increase is critical since it may achieve some 5% of total global emissions in 2030. This is demonstrated in Fig. 14. Here, the global emissions according to [27] are shown up to 2020, where decarbonization must be started when global warming is to be limited. Strong growth of ICT emissions may interfere with such decarbonization. Fig. 14 also shows the well-known Keeling Curve (smoothed, i.e., not showing the per-year behavior) [28] that describes the global carbon concentration.

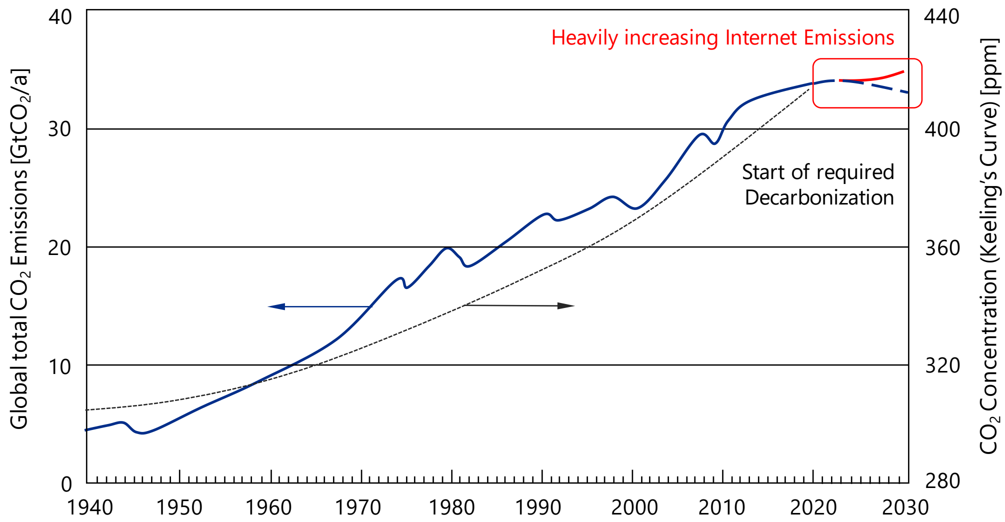

Fig. 14. Global emissions and potential ICT contribution, and carbon concentration ("Keeling's Curve") [27], [28]

4. A Way out?

It is unrealistic to simply request bandwidth-growth limitation. Some relevant applications may require this growth, and without the growth, an economic Internet crisis is likely to occur. Therefore, ways out of the switch-scaling dilemma are blurry at best. This affects all basic ICT functions including optical transport. Scaling energy efficiency will become more difficult. The same holds for gate size and related logic-gate performance and density, including storage densities. With increasing bandwidths, this will lead to the necessity to use more of what is available by that time.

Disruptive new developments are not clear right now. Theoretically, concepts like entropy-preserving switching (or thermodynamically reversible computing) can break the SNL limit, but they may not be acceptable in practice because the energy advantage comes at the cost of switching speed [15], [17].

Other technologies like carbon nanotubes [16] or biological-cell processors [17] may allow to get close to the SNL limit (i.e., closer than CMOS technology). However, they do not yet present mature technology.

Therefore, risk is that the Internet either consumes rapidly growing amounts of energy, or that its energy (and likewise resource) consumption in turn limits the bandwidth growth and the number and/or kind of the applications. The former can make the Internet the biggest energy/resource-consuming machine on Earth, the latter has the potential for a global economic crisis.

There is one important aspect that can relax the emissions situation, which results from the energy consumption. This aspect is sometimes referred to as *Green-by-ICT* [29]. It refers to emissions savings in sectors other than ICT that are *enabled* by ICT. The most relevant sectors that can be made significantly more efficient regarding energy consumption and emissions are manufacturing, energy (e.g., the power grids), buildings, mobility, and agriculture. According to [30], the carbon-saving effect on a global scale can be *almost a factor of 10 higher than the ICT emissions* themselves. It can thus help to achieve the climate targets of the UN [31]. This is indicated in Fig. 15. It shows a zoom into the upper right part of Fig. 14 where in addition to the ICT emissions, the potential Green-by-ICT carbon savings according to [30] are displayed.

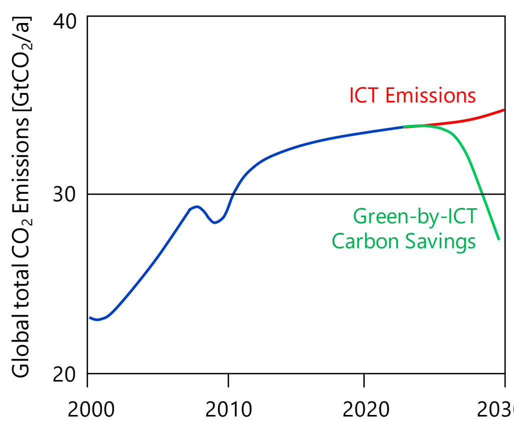

Fig. 15. Detrimental ICT effects on global warming vs. Green-by-ICT carbon savings [27], [30]

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A white paper from British Telecom [32] even stated a factor of almost 19, albeit with regard to the UK only.

Green-by-ICT will not solve the energy-efficiency problems of ICT that are to become apparent in one to two decades. Neither can it solve any of the resource-depletion problems that may result from using an increasing amount of ICT equipment. The latter is one of the *Green-of-ICT* aspects as described in [29].

These detrimental effects must be addressed by treating bandwidth as a precious resource rather than flat-rate abundance. This may include:

1. People get charged for internet use on an environmental-cost basis
2. Companies like social-media providers get charged per bandwidth
3. High-resolution content is subject to cost penalties

This has to be complemented by certain technical improvements like smart caching that help reducing in particular the video-download burden.

In addition, resource depletion must be tackled by a substantial increase in resource efficiency, i.e., by strictly following circular-economy principles.

In turn, ICT most likely will become the most relevant enabler for massive decarbonization in other sectors.

Conclusion

The global ICT sector is running into a scaling problem. Ever since the ramp-up of the Internet in the mid-90s, it has seen exponential bandwidth growth, and the gains in energy efficiency could not compensate this growth. Meanwhile, further slow-down of efficiency improvements is seen, and it is at least unclear if disruptive future developments like biological-cell processors can be exploited quickly enough. This affects all major equipment classes in ICT networks and data centers, possibly with the exception of end-user equipment.

This poses the questions how long bitrate growth in our networks can persist, and when physics will ultimately stop this growth. The alternative is that the Internet becomes the ultimate energy-consuming machine globally. To prevent this, Internet use should be charged according to its environmental cost.

Acknowledgement

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Architecting Datacenters for Sustainability: Greener Data Storage using Synthetic DNA

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Abstract

Global digital data generation has been growing at a breakneck pace. Although not all generated data needs to be stored, a non-trivial portion does. Synthetic deoxyribonucleotide acid (DNA) is an attractive medium for digital information storage. If kept under appropriate conditions, DNA can reliably store information for thousands of years [1]. It also has a practical estimated density of 1 Exabyte per cubic inch, which is much higher than commercial data storage media.

Buildings, infrastructure, electronic computing, storage, and networking equipment, and other physical resources all contribute to the environmental impacts, particularly, emissions, energy and water consumption, and waste generation of digital data storage. DNA data storage has the potential to limit these impacts by drastically reducing the resources required to maintain very large volumes of data.

In this paper, we describe how to store digital information in synthetic DNA, present a cradle-to-grave life cycle assessment (LCA) of archival DNA data storage, and compare the resulting environmental impacts with those of traditional hard disk drives (HDDs) and tape storage based on greenhouse gas (GHG) emissions, energy usage, and blue water consumption (BWC). We conclude that DNA shows promise when compared to HDDs and tape, and we follow that conclusion with a discussion of how further innovation in biotechnology could be used to improve the sustainability of future datacenters.

1 Introduction

The rate of digital information generation far outpaces increases in our capacity to store it. According to IDC, the “Global DataSphere” (all digital data generated globally) is expected to grow from 44 Zettabytes (10^{21} bytes) in 2020 to 175 Zettabytes in 2025 (approximately 32% per year) [2]. IDC predicts that about 10% of all data will be stored, and 49% of that will be in public clouds. This will result in demand for over 8 Zettabytes of storage. Currently, magnetic media such as HDDs and tape are used for a large percentage of long-term cloud data storage. However, these technologies may be unsuitable for the world’s increasing storage requirements.

Two notable data storage evaluation metrics are data density and durability. Figure 1 compares storage technologies: each bar represents the data density of each storage technology broken into recent volumetric data density information and projected volumetric data density (based on limitations in scaling practical storage systems). The bottom text shows the typical durability for each technology. Tape storage, currently the densest commercial storage medium at a demonstrated density of over 37 Gigabits/mm^3 [3], also has the best durability. Unsurprisingly, tape is typically used for archival storage. However, data stored on tape still needs to be rewritten onto new media every few years, which can take days. Millions of cartridges would be needed for the 8 Zettabytes of data that IDC predicts will be stored in public clouds by 2025. Other commercial storage technologies could be used to store this data, but that may only aggravate the problem because they are either less dense or durable than tape.

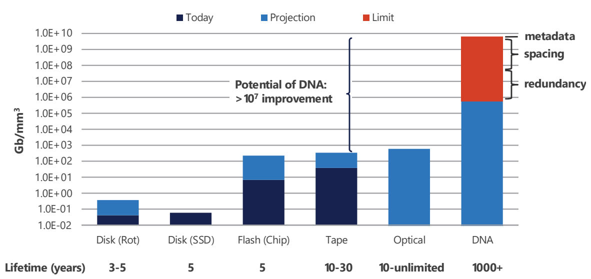

Figure 1: Comparison of data capacity and durability across data storage technologies.

DNA has been investigated as an alternative archival data storage medium [4]–[7]. As shown in Figure 1, DNA has a theoretical density of over 1 Exabyte/mm^3 (i.e., 1,000,000,000 Gigabyte/mm^3) and durability on the order of hundreds to thousands of years — both of which make it quite attractive for this application. A practical implementation requires overheads such as metadata, including object identifiers, addresses, and logical redundancy for error correction, physical spacing and physical redundancy. Fortunately, even at this lower effective density, DNA still offers a clear advantage over other commercial media at an estimated density of over 1 Exabyte/in^3.

The main environmental impacts of data storage libraries result from the physical buildings, storage equipment, infrastructure, data access, and environmental control necessary for their operations. Each of these elements produces GHG emissions, energy and water consumption, and waste disposal burdens. The significant gains in density and durability from DNA data storage should thus result in a lower environmental burden.

Past DNA data storage research has covered the implementation of improved system architectures [5], [8], preservation techniques [9], [10], and automation [11], [12]. However, DNA's sustainability aspects have remained unexplored until now. In this work, we performed a cradle-to-grave life cycle analysis (LCA) of a hypothetical full production DNA data storage system (using multiple chemistry options) and compared it with other storage technologies on three metrics: GHG emissions, energy use, and water consumption. Our findings suggest that DNA data storage could have lower environmental impacts than both HDD and tape storage.

2 DNA Data Storage Basics

DNA 101

A deoxyribonucleotide acid (DNA) strand (also known as an oligonucleotide) is a linear polymer composed of sequences of four natural nucleotides (A, C, G, T) that are commonly referred to as bases. In nature, two complementary strands are typically paired into DNA's famous double-helix structure. It is possible to predict interactions between DNA strands in a double helix based on their sequences due to base-pairing interactions (A binds to T, and G to C). From an information storage perspective, since the interactions are known, the information on one strand of the double helix is redundant with its complementary strand.

Storing data in DNA

DNA data storage is a method for storing digital information in synthetic DNA strands. Storing information in DNA starts with converting a sequence of bits into a sequence of nucleotides. Figure 2a shows a simple example mapping between bits and bases — every two bits in a sequence are translated into one of the four nucleotide types. For example, in Figure 2b, the binary string 01101100 maps to the DNA sequence CGTA. Although appropriate for illustration, such a simple mapping is rarely used because synthetic DNA is prone to errors (base deletions, insertions, and substitutions, and missing sequences). In practice, encodings are more sophisticated, and error-correcting algorithms are often employed to improve the system's robustness [1], [6]. Once the sequences that represent the bits to be stored are determined, the next step is to create the molecules that represent the sequences through a process called DNA synthesis.

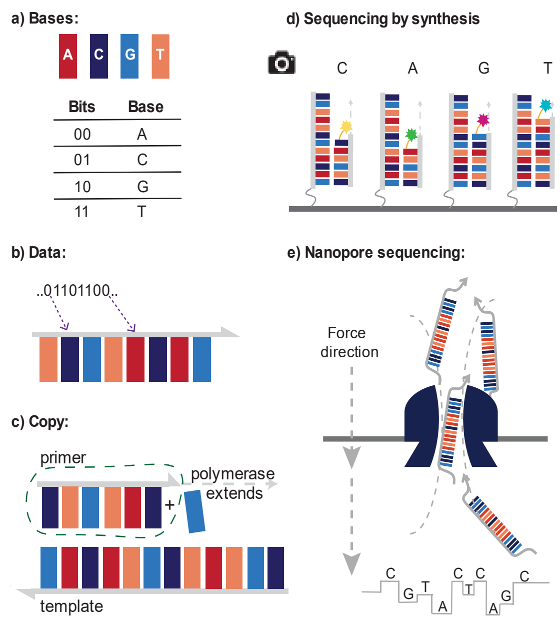

Figure 2: DNA basic overview. Fig. 2a shows the four nucleotide bases (A, C, G, T) and a simple mapping of bits to bases. Fig. 2b provides an example of encoding data in DNA. Fig. 2c highlights the ability to copy the DNA using polymerase chain reaction (PCR). Fig. 2d provides an overview of how DNA is read using sequencing by synthesis, where incorporated bases are fluorescently labelled. Fig. 2e shows a schematic of how DNA can be read using a nanopore sequencer.

DNA synthesis

Synthesis of *de novo* oligonucleotides has traditionally been performed through a process called standard synthesis or phosphoramidite synthesis. This process occurs in cycles composed of four complex chemical steps for the addition of a single nucleotide [13]. These steps are: (1) deblocking, which enables the next base to attach, (2) addition, which adds a blocked base (i.e., a chemically modified base that prevents additional bases from attaching), (3) oxidation, which strengthens the newly formed bond, and (4) capping, which adds a group that prevents further strand growth where addition has not happened in the current cycle. Standard chemistry relies heavily on organic reagents, such as acetonitrile, which can be volatile, flammable, and toxic. Despite these challenging handling issues, standard synthesis has been used in the biotechnology industry for the past 40 years due to its maturity as a process [14].

Enzymatic synthesis is a nascent alternative approach based on using an enzyme called terminal deoxynucleotide transferase (TdT) to add bases to an existing DNA strand. Although much less mature, in recent years this type of synthesis has generated interest as a promising method for *de novo* DNA synthesis [15]–[17]. Enzymatic DNA synthesis is expected to require fewer steps, and it is performed predominantly in aqueous salt buffers that mimic biological pH — an easy-to-handle solvent.

DNA replication

DNA can be easily replicated through a process called polymerase chain reaction (PCR), as shown in Figure 2c [18]. In this reaction, a short priming oligonucleotide (a short strand of DNA, about 20 nucleotides in size) binds to the template DNA strand to be replicated. A polymerase (i.e., an enzyme that "completes" nucleotides missing in the double helix) then extends that priming sequence and "fills in the blanks" by incorporating complementary bases as it zips along the template to form double-stranded DNA. This reaction can be repeated many times to generate the desired number of molecular replicas.

DNA sequencing

The two most common techniques used for reading DNA are sequencing-by-synthesis (e.g., Illumina sequencing instruments) and nanopore devices (e.g., Oxford Nanopore Technologies sequencing instruments). Both use aqueous buffers, so their handling is easier than in standard synthesis.

In sequencing-by-synthesis, illustrated in Figure 2d, the DNA strand of interest serves as the template for a polymerase to create a complementary strand using fluorescent base types and blocking groups to ensure one base addition per cycle. Each fluorescent base emits at different wavelengths and can be monitored and distinguished optically during that cycle [19]. The fluorescent group is cleaved at the end of the cycle, allowing sequencing to proceed to the next cycle.

In nanopore sequencing, illustrated in Figure 2e, the strand of interest is pulled through a voltage-gated nanochannel. As the strand is translocated through the channel, bases perturb the current differently to generate a unique current signature that can be inferred to map back into those specific bases [20].

Putting it all together: DNA data storage system

A DNA data storage system uses the multistep process outlined in Figure 3. First, since there are limitations on the length of synthetic DNA sequences (about 150 to 300 bases in length is typical today), data to be stored in DNA is partitioned into smaller pieces (about 15 to 30 bytes) before being mapped into DNA sequences, given a sequence number, or index, to identify their position in the original file, and augmented with additional error correction information. These bit sequences are then mapped to sequences of the four DNA nucleotides.

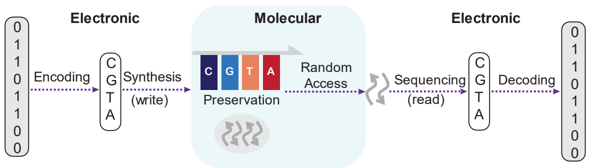

Figure 3: Overview of DNA data storage system.

Once data has been encoded into DNA bases, the sequences are written into physical DNA oligonucleotide strands through standard or enzymatic synthesis, typically using a 2D array platform that creates multiple unique DNA sequences in parallel in a single synthesis run. Array synthesis may employ fluidic deposition, photolithographic, and electrochemical synthesis techniques [13].

After synthesis, the oligonucleotides on the array are removed from the surface and pooled to create a complex mixture of DNA strands. Each DNA pool may contain multiple files and inherently does not provide spatial isolation of the data. The pools are deposited in a DNA library, which is then spatially organized and addressed, so multiple pools can be stored on the same substrate.

To retrieve a file stored in DNA, the pool is physically retrieved from its library, and the file is accessed using PCR, which selectively copies the DNA oligonucleotides that encode the data sequences to be recovered. PCR's selectivity is accomplished by assigning different primer sites to each of the files stored in a pool and later using complementary primers associated to the file to be read in the PCR reaction [8]. The molecules are then sampled and sequenced, and the data is error corrected and decoded back into the original file.

3 Life Cycle Assessment

In this section, we compare the environmental impacts of traditional archival data storage media (HDD and tape) with DNA-based storage media. We conducted this analysis through a screening-level LCA to identify potential areas of concern. We also performed a cradle-to-grave analysis using GaBi LCA software and quantified GHG emissions, energy, and BWC for each storage media.

3.1 Model assumptions

Functional unit

To accurately compare the LCA results, we defined a common functional unit across the storage media. Because all the products store data over time, we defined our unit of comparison, or functional unit, as 1 TB of data stored for a year with a read rate of 10% (100 GB) for that year (note that this comparison is for archival storage, so read performance was not a factor). We included a 2% data sensitivity case to test how variations in data access patterns affect the results.

Geographical boundary

Infrastructure for energy, waste treatment, and other processes vary across regions and can significantly impact LCA results, so we standardized our model using United States data, including for grid energy and material production.

System boundary

The cradle-to-grave assessment covered three main stages for each storage media: (1) production, (2) use, and (3) end-of-life. Figure 4 outlines process-flow diagrams for each storage type. For production, we inventoried the raw materials required to fabricate each type and its associated manufacturing inputs (such as heat, power, water, and chemicals). For use, we modeled the energy necessary for writing, maintaining, and accessing a 1TB functional unit of archival storage. We assumed that the datacenter building infrastructure would be equivalent across all storage methods and limited it to what was directly required for storage. This was a conservative assumption: datacenter physical infrastructure would likely be lower for DNA data storage due to its higher data density. For end-of-life treatment and destruction, we used shredding and incineration as the disposal methods for HDDs and tape, and incineration as the disposal method for DNA. Since water is used as an input for the DNA synthesis process, we also included wastewater treatment for DNA data storage.

Impact categories

For this LCA, we quantified GHG emissions, BWC, and energy as the impact categories. We quantified GHG emissions using the IPCC AR5 characterization factor for GWP100, excluding biogenic carbon ($kgCO_2eq$). Blue water refers only to surface and groundwater and excludes rainwater. Water consumption is the portion of water use that is not returned to its original water source and cannot be reused after withdrawal (e.g., water lost via evaporation or water incorporated into a product or plant). We used the GaBi BWC characterization method to quantify blue water (liters). Primary energy was quantified by net calorific value (MJ) otherwise known as low heating value depending on dataset availability.

Data sources

Primary data sources for DNA production, storage, reading, and end-of-life were projections of future production systems extrapolated from current systems. We sourced primary HDD and tape data from literature and primary product information from online resources as detailed below. We sourced secondary data inputs, or life cycle inventory (LCI) data, from GaBi professional and electronics databases (service pack 39) [21] and the Ecoinvent version 3.5 database (with temporal coverage of 2018-2019) [22].

3.2 HDD and tape storage

We modeled HDD and tape storage from cradle-to-grave to match the system boundary of the DNA archival storage system (Figure 4a) and derived HDD production impacts from an existing manufacturer's study that included materials used, distribution, manufacturing, and packaging [23]. LCI data for data storage tape does not exist, so we modeled tape production impacts by tearing down a commercially available tape product (LTO Ultrium 8 Data Cartridge with a compressed data storage capacity of 30TB) and manually identifying and weighing its components. We determined the HDD-use phase assumptions for writing the data and accessing 10% of it annually using the product's energy specs (with the assumption that the disks are not spun down). The tape use phase included the energy to write the tape and access 10% annually using the energy and the product's performance specs and an assumption that, once written, the tape would need to be rewound 48 times per year. For both, we also considered additional energy consumption for servers and networking equipment and media power usage effectiveness.

3.3 DNA data storage scenarios

Given that DNA data storage has not been implemented in a datacenter and its full deployment requirements cannot be anticipated, we approached the LCA by pinpointing the most significant components of the DNA data storage process (shown in Figure 3). We identified synthesis and sequencing as the major contributors to production impacts (Figure 4b).

DNA synthesis volumes

Total volumes and types of chemical reagents required to store 1 TB of data in DNA vary depending on the exact manufacturing processes (acetonitrile versus

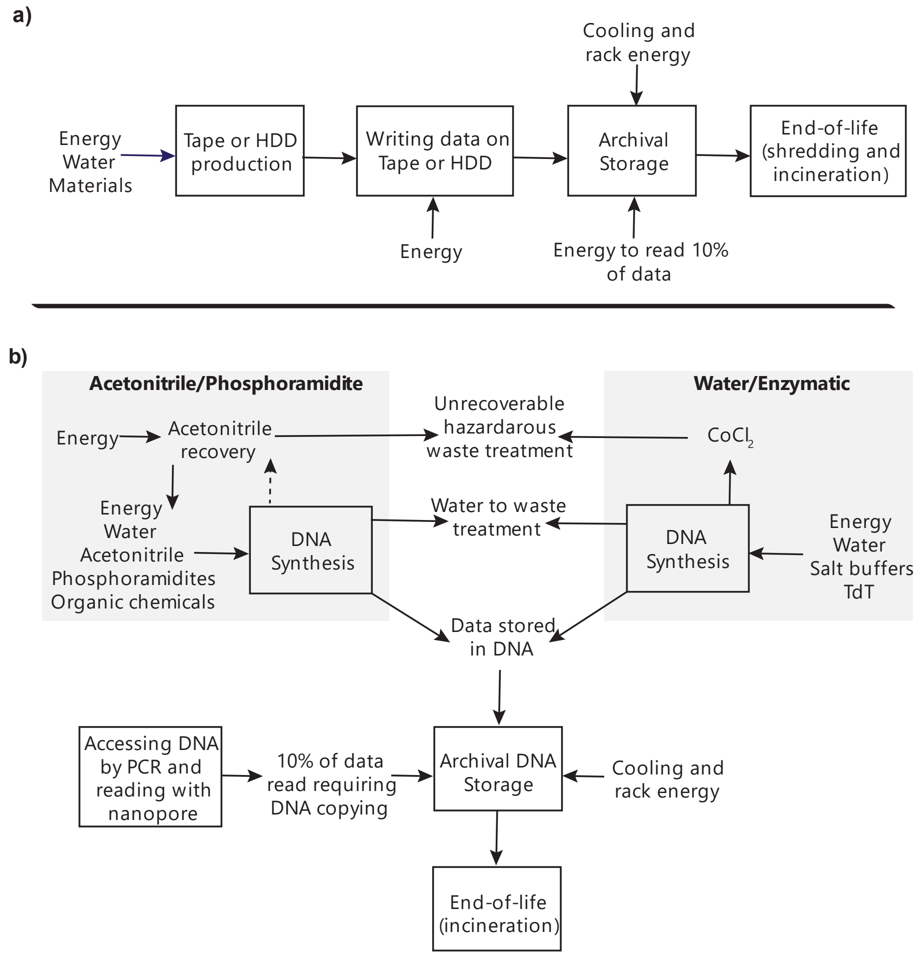

Figure 4. Process flow diagrams for the cradle-to-grave LCA of the different storage media. Boxed text represents. Unboxed text represents inputs. Boxed text represents life-cycle phases. Fig. 4a shows inputs and outputs for storing 1 TB of data and reading 100 GB a year with tape or HDD. Fig. 4b delineates the process of storing 1 TB of data and reading 100 GB a year with DNA. The flow diagram begins with the inputs and outputs for either phosphoramidite/acetonitrile-based DNA synthesis or TdT/enzymatic DNA synthesis and converges once the data has been written into DNA.

enzymatic synthesis) and assumed parameters, so we modeled worst- and best-case scenarios for each DNA synthesis method to account for that. We modeled the worst-case scenario as a synthesis process in which the reagents for each chemical input are used once and then discarded. In the best-case scenario, 90% of reagents could be reused throughout the synthesis run.

For standard DNA synthesis, we incorporated two acetonitrile production methods into the LCA for comparison. We considered acetonitrile derived from propane found in fossil fuels (conventional acetonitrile) and bio-acetonitrile derived from ethanol (bio-acetonitrile). We assumed enzymatic DNA synthesis to be an aqueous system.

Retrieving data in DNA

We assumed the use of the PCR method to selectively amplify the DNA strands encoding the 10% of the data to be read from the 1 TB DNA pool. Once retrieved from the pool, we assumed the strands would be sequenced with a nanopore device.

3.4 LCA results

A tale of two acetonitriles in standard synthesis

Figure 5a shows the cradle-to-grave LCA results from comparing the two types of acetonitrile used for synthesis against the GHG emissions, energy, and water consumption dimensions. The LCA comparison between conventional acetonitrile and bio-acetonitrile production (not shown) did not result in a clear best. We expected bio-acetonitrile would be significantly more sustainable than conventional acetonitrile; however, while bio-acetonitrile production did reduce GHG emissions and energy consumption by 79% and 85% respectively (compared to conventional acetonitrile production), it increased BWC by 84%.

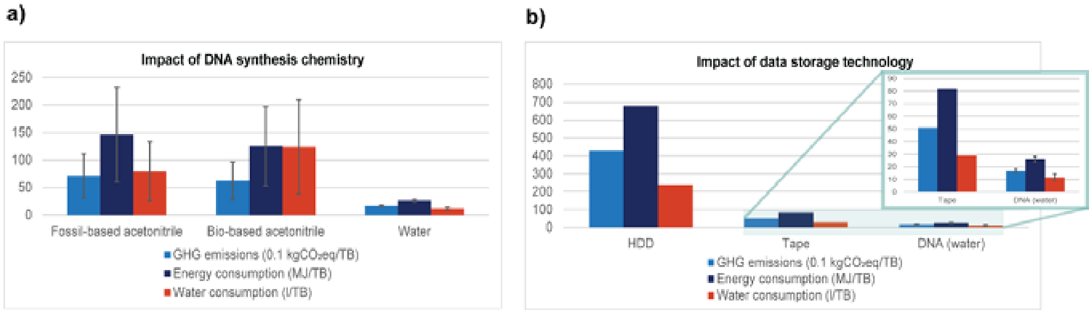

Figure 5. Cradle-to-grave LCA results estimating GHG, energy utilization, and water consumption. Fig. 5a summarizes the impacts of three different DNA synthesis techniques for DNA data storage. Fig. 5b provides an overall comparison of HDD, tape, and DNA data storage (water/enzymatic synthesis).

Unsurprisingly, the primary contributor to water consumption in the LCA for bio-acetonitrile DNA synthesis was bio-acetonitrile production. The water consumption increase was a direct result of higher water inputs for ethanol production from biomass. For conventional acetonitrile, water consumption resulted only from the production of miscellaneous input chemicals to the synthesis process.

For energy consumption, the production of the four base phosphoramidites used to create the oligonucleotides was the main contributor to both conventional and bio-acetonitrile DNA synthesis.

Standard vs. enzymatic synthesis

Enzymatic DNA synthesis utilizes fewer chemicals than phosphoramidite synthesis, and it is performed primarily in aqueous neutral buffered solutions (i.e., saltwater). Since it does not use acetonitrile, enzymatic synthesis has lower GHG emissions, energy consumption, and water usage than either conventional or bio-acetonitrile DNA synthesis.

As expected, direct water consumption during the DNA synthesis process drove the water metric. Breaking down the drivers for GHG emissions and energy consumption, we found the production of the salts (e.g., tris-acetate) used in the buffered water to be the primary contributor.

Overall HDD, Tape, and DNA comparison

Of the storage media evaluated in this study, HDD storage has the highest GHG emissions, energy consumption, and water usage, as shown in Figure 5b. The main driver of the environmental impacts was the use-phase energy demands of storing 1 TB of data with a 10% access rate. This includes the power required for spinning the disks, accessing and reading the data, and cooling the system. Tape, by comparison, has a significantly lower impact than HDDs even though the main contributor to environmental impacts was also use-phase energy demands.

The environmental impacts of DNA data storage are less clear-cut and depend heavily on the method used to manufacture the DNA. DNA data storage using standard synthesis may be more sustainable than existing HDD and tape storage when closer to its best-case scenario. In its worst-case scenario, it falls short of expectations. In contrast, DNA data storage with enzymatic synthesis appears to significantly reduce environmental impacts across all storage types and metrics, regardless of best- or worst-case scenario assumptions.

3.5 Limitations in analysis

While both HDD and tape are commercially available storage technologies, they lack readily available inputs and existing datasets; therefore, we modeled them using literature, product teardowns, and assumptions. GaBi databases lacked a significant number of DNA data storage components and processes. Mini-LCAs had to be completed for each lifecycle phase, including phosphoramidite DNA synthesis and enzymatic DNA synthesis and sequencing. Within these sub-LCAs, many of the inputs lacked LCI data and had to be modeled with proxies serving as functional counterparts or manufactured in similar processes. An example is the use of amylase production as a proxy for TdT in enzymatic synthesis. Both are enzymes, and large-scale enzyme manufacturing generally involves the fermentation of microorganisms engineered to produce the desired enzyme [24]. Since amylase manufacturing is done at scale, we selected the results from an amylase LCA as the most appropriate approximation for TdT in the quantities needed for DNA data storage.

Using data proxies and assumptions limits the results' applicability to future at-scale rollouts of these technologies. Future work will include the modeling of reagents and other important DNA synthesis inputs and consider archival-type HDD storage applications. At the time of this paper's writing, we are actively creating LCAs for each input proxy to incorporate into future assessments.

4 Discussion and Conclusion

We expect that the next few decades will see a great deal of innovation and improvement in datacenter sustainability. As we transition from the digital revolution to the fourth industrial revolution (a fusion of physical, digital, and biological technologies), biotechnology advances promise to have great impact on datacenters.

DNA data storage could both increase the density and durability of archival storage systems and be more environmentally sustainable than existing storage media. Though the future impacts of DNA data storage will largely depend on improvements in DNA synthesis and sequencing technologies, in this paper we demonstrated the potential of DNA storage to improve GHG emissions, energy use, and water consumption.

We foresee that optimizing phosphoramidite chemical reagent consumption for standard DNA synthesis or reaching a mature enzymatic DNA synthesis process will reduce DNA data storage's environmental footprint. The fact that DNA is inherently biological also enable a new end-of-life disposal method: the DNA could be biodegraded.

Beyond DNA data storage, we believe biotechnology has the potential to address other datacenter sustainability needs. New concrete mixtures can reduce the carbon emissions associated with datacenter construction — biomaterials, sand and bacteria compositions, and graphene reinforcement are all solutions under development [25], [26].

Another area of interest is identifying greener methods to power datacenters, such as clean biofuels derived from biomass. The renewable nature of these fuels may help prevent the release of previously sequestered carbon and eliminate the emission of unhealthy, volatile organic compounds and sulfur compounds typical of fossil fuels [27], [28].

With datacenters shifting toward higher levels of circularity, we expect electronic components to be harvested from their original boards for redirection to their highest possible value use. However, the remaining printed circuit board substrates with custom metal tracks are still likely to become physical waste. To address this, we foresee a future in which such boards are biodegraded. In this scenario, biodegradable materials are combined with biological or synthetic biology-based technologies so the metals present in the degraded boards can be easily scavenged. E-waste composting could become a reality.

These examples illustrate that biotechnology may help address the multiple sustainability challenges currently faced by datacenters. Though some of these technologies are not yet fully mature (or have even surpassed proof of concept), it is important to discuss them now so that their development can be nurtured and expedited. Early success in these areas can unlock significant paradigm shifts in datacenter sustainability.

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Analysis on resource reduction effects by ICT usage in Japan

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Abstract

Information and communications technologies (ICTs) can potentially contribute to reduce resource consumption through increased productivity in many industries by enabling total optimisation and dematerialisation. In this research, we tried to build assessment models to grasp the effects on resource reduction and CO_2 emission reduction by using new digital technologies. In case studies of an artificial intelligence-based taxi application and a bicycle sharing service, resource reduction effects and CO_2 emissions reduction effects were analysed by comparing resource consumption and CO_2 emissions when the ICT services are and are not used. In both case studies, reduction effects on CO_2 emission appear in a short time span. However, resource consumption strongly depends on decreased demand for metals, so the reduction effects appear only after a relatively long time lag. Though resource consumption may temporarily increase due to the increase in ICT devices use, long-term resource consumption reductions are found in both case studies.

1 Introduction

The last century saw an unprecedented increase in the use of natural resources and materials with global raw material use rising at almost twice the rate of population growth [1]. In the future, many kinds of metal resources will not be able to be covered by existing reserves, and some metal resources are expected to be used several times as much as their existing reserves by 2050 [2]. Natural resources are certain to be depleted if the current use of resources continues. To reduce resource consumption, countries have been shifting to resource saving production and consumption models, including circular economies. There is an urgent need to shift from resources to a decoupled economy.

Information and communications technologies (ICTs) can potentially contribute to reduce resource consumption and CO_2 emissions through increased productivity in many industries by enabling total optimisation and dematerialisation, even though ICT equipment also consumes resources and produces environmental load. CO_2 emission reduction effects by ICT use have been widely studied [3~6], but few studies have focused on the resource aspect. Even though resource consumption of ICT equipment, such as smartphones and personal computers, has been widely analysed [7], resource consumption reduction by using ICT has rarely been researched.

Furthermore, many emerging digital technologies, such as artificial intelligence (AI) and the Internet of Things (IoT), have been quickly advancing and gradually spreading in various industrial fields and daily life. To collect large amounts of data and optimise the production and consumption activities, more sensors and ICT user devices are needed. Of course, more energy will be consumed to support equipment and network operation. Therefore, there are concerns about how these emerging digital technologies will impact the environment, including CO_2 emissions and resource consumption, and whether they can be used more sustainably.

This research focuses on two kinds of ICT services that are widely used or becoming more common in Japan. To grasp the effects on metal resource reduction and CO_2 emission reduction by using new digital technologies, assessment models are built on the basis of a lifecycle assessment method [8]. Since these new digital technologies will take time to become widely used, two stages of analysis on the time axis, including in the middle of introduction and fully introduction, are considered in this research.

2 Method

The assessment method used in this research is mainly based on the environmental lifecycle assessment (LCA) for ICT goods, networks, and services described in ITU-T recommendation L.1410 [8]. Environment impacts are assessed by comparative analysis/LCA between an ICT use case and a reference case (before using ICT). As shown in Figure 1, the same goal and scope need to be set between the target ICT use case and reference case (before using ICT). Then inventory analysis and impact assessment are done in the ICT use

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case and reference case, respectively. Finally, environmental impacts are calculated as the difference between the ICT use case and reference case.

By using this basic method, two case studies are carried out in this research, that is to say, an AI-based taxi application and a bicycle sharing service. Both target ICT services are used in the transport sector, since it has the second highest CO_2 emissions of all sectors in Japan (Figure 2) and metal resource consumption for vehicles is also large [9]. Furthermore, various ICT services have been introduced in this sector. In the two case studies, environmental impacts of two ICT services are analysed by comparing resource use and CO_2 emissions in the ICT services use case and reference case (before using ICT services).

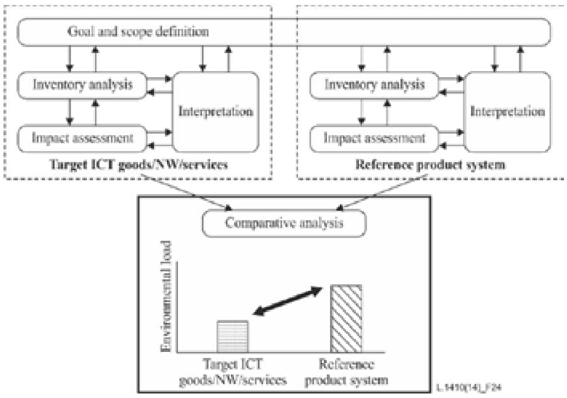

Figure 1: Comparative assessment of a reference product system and an ICT goods, networks, and services product system [8]

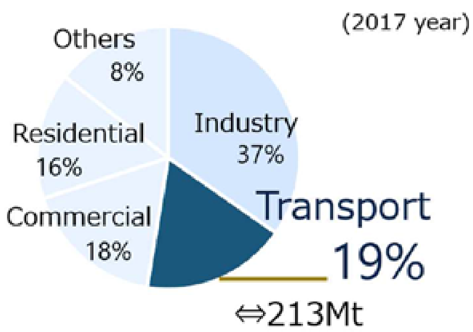

Figure 2: CO_2 emissions by sector (Japan)

3 Case study 1

3.1 Target ICT service: AI Taxi

AI Taxi is an emerging digital technology utilising AI that is being introduced into the taxi industry in Japan. This service uses AI to deliver information on future taxi demand forecasts (30 minutes later) on the basis of mobile space statistics, weather data, event information, train delay information, etc. More efficient taxi operation will contribute to improving driver productivity and reduce operation distance of empty cars. AI Taxi can also optimise the number of taxis, thereby potentially reducing metal resource consumption for vehicles.

In 2018, 19,949 taxis were operating in Tokyo. The average Tokyo taxi conducts 28.2 passenger transportations and covers an average operation distance of 245 km per day [10]. In the introduction demonstration test carried out between December 2016 and March 2017 in Tokyo, the average boarding rate (the percentage of operation distance with passengers) was improved by 3%, and average income per month/driver increased by about ¥1400 for inexperienced drivers [11].

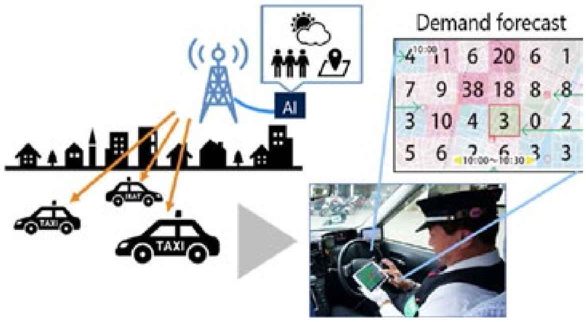

Figure 3: Image of AI Taxi

3.2 Assessment conditions

The comparative analysis is done for 205,647,066 passenger transportations by taxi in the 23 wards of central Tokyo per year. The statistical data comes from the Tokyo Hire-taxi Association [10]. There are two main ways to take a taxi: taking cruising taxi and calling a taxi through a call-centre (taxi dispatch). Compared with the case before using AI Taxi, drivers can take passengers more efficiently when using AI Taxi, depending on the passenger demand forecast. Therefore, AI Taxi enables the same number of passenger transportations with a reduced total operation distance. There are three main changes when using AI Taxi. The first is shorter operation mileage or fewer taxis due to efficient operation. The second is reduced needs for taxi dispatch. The third is additional increased use of ICT devices and networks for AI Taxi. Figure 4 shows the changes when using AI Taxi, and Table 1 lists the details on change factors before and after AI Taxi use.

Now, in Tokyo, AI Taxi has been implemented in 1400 taxis. In this research, as mentioned previously, two stages of analysis on the time axis are considered. In the first and second stages, the impacts of only 1400 taxis and all taxis in Tokyo using AI Taxi are calculated, respectively. The difference between the two stages is that, in the first stage, only operation mileage decrease is considered, but in the second stage, long-term reduction in the number of taxis is also considered. This is because, as a result of the 2008 financial crisis, passenger transportations dropped immediately, whereas the number of taxis decreased gradually over two years.

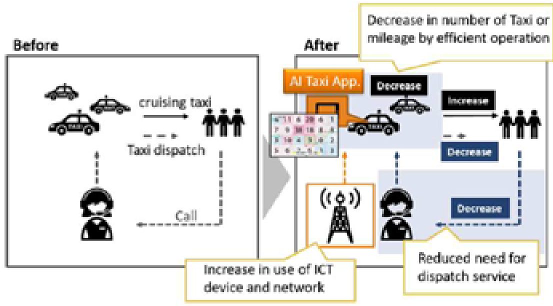

Figure 4: Changes when using AI Taxi

	Before / After			Stage 1	Stage 2	Change
Operation	Car	Use		○	◎	Decrease
		Production/disposal			◎	Decrease
	Driver	Commuting			◎	Decrease
Taxi dispatch centre	ICT equipment (PC)	Production/ Use/disposal		○	◎	Decrease
	ICT equipment (Telephone)					Decrease
	ICT equipment (Server)					Decrease
	Network	Use				Decrease
	Staff	Commuting				Decrease
		Office use				Decrease
Telecommunication equipment (After only)	ICT equipment (Tablet)	Production/ Use/disposal		○	◎	New increase
	ICT equipment (Server)					New increase
	NW	Use				New increase
Software (After only)	Application	Development		○	◎	New increase

■ : Decrease
■ : New increase

Table 1 Change factors before and after using AI Taxi

3.3 Calculation equations and dataset

3.3.1 Calculation equations

For taxis (car), metal resource consumption is calculated by multiplying the number of cars and metal resource consumption per car (equation 1). Then CO_2 emissions from production and disposal are also calculated by multiplying the number of cars and CO_2 emissions per car (equation 2). CO_2 emissions from use are calculated by the product of the number of operating cars and operation distance per day per car and CO_2 emission per km operation and operation days (equation 3).

For ICT equipment, resource consumption and CO_2 emissions from production and disposal are calculated the same as for cars. CO_2 emissions from use are calculated by the product of the amount of ICT equipment and power consumption per equipment and use rate and use time and CO_2 emission factor per kWh (equation 4).

$$R_{(t,i)} = N_{(t)} \times RB_{(t,i)} \quad \text{eq. 1}$$

$$EP_{(t)} = N_{(t)} \times EB_{(t)} \quad \text{eq. 2}$$

$$EU_{(t)} = N_{(t)} \times D_{(t)} \times ED_{(t)} \times Da_{(t)} \quad \text{eq. 3}$$

$$EU_{(e)} = N_{(e)} \times P_{(t)} \times Ra_{(e)} \times T_{(e)} \times EF \quad \text{eq.4}$$

R: metal resource consumption (kg)

N: number of each transpotation

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RB: metal resource consumption per transpotation [metal resource basic unit] (kg)

EP: CO_2 emission in produce and disposal (kg)

EB: CO_2 emission in produce and disposal transpotation [CO_2 emission basic unit] (kg)

EU: CO_2 emission in use (kg)

D: operation distance per day (km)

ED: CO_2 emission per operation distance (kg)

Da: operation days (day)

P: power consumption (kWh)

Ra: utilisation (%)

T: use time (h)

EF: CO_2 emisson factor of power consumption (kg-CO_2/kWh)

t: type of transport

i: type of metal

e: type of ICT equipment

For staff in call-centre, commuting and office use are considered here. For application development, CO_2 emission from the development process are counted in the results.

3.3.2 Dataset

The main data on basic units, such as those of metal resources and CO_2 emissions, and CO_2 emission per km operation distance are collected from IDEA ver. 2 [12]. This database was developed by the National Institute of Advanced Industrial Science and Technology. IDEA contains LCI datasets of non-manufacturing sectors (agriculture, forestry and fisheries, mining, construction and civil engineering) as well as manufacturing sectors (food and beverage, textile, chemical industry, ceramics and building materials, metal and machinery) and also utility sectors (electricity, gas, water, and sewerage). It covers all products that are classified within the scope of the Japan Standard Commodity Classification. Then other data are collected from traffic statistics and related studies. Also some parts of basic units, such as those for CO_2 emissions per yen from application development and for networks (CO_2 emissions per telecommunication traffic bite), are calculated on the basis of our internal data.

The biggest challenge in this research is how to estimate operation distance per taxi after introducing AI Taxi in the first stage and how many taxis can be reduced after introducing AI Taxi in all taxis in the second stage. In this research, decreases in operation distance and the number of taxis are estimated mainly on the basis of the demonstration test values [10] and also include some assumptions. Total operation distance per day for one taxi decreased from 245km to 231km in the first stage, and the number of taxi decreased from 19,949 to 18,862 in the second stage.

3.4 Results and discussions

The results show that CO_2 emission rom taxi operation in Tokyo could be reduced by 5.8 and about 60 thousand-ton by introducing AI Taxi in the first and second stages, respectively (Figure 6). Figure 7 shows CO_2 emission change by item in the second stage. The biggest reduction factor is use (operation) of taxis, which accounts for 95% of the total reduction. On the other hand, the CO_2 emission increase caused by using AI Taxi is about 0.5 thousand-ton, less than 1% of the reduction amount.

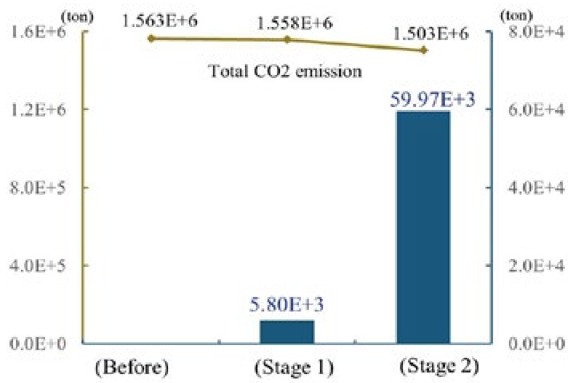

Figure 6: CO_2 emission reduction by using AI Taxi

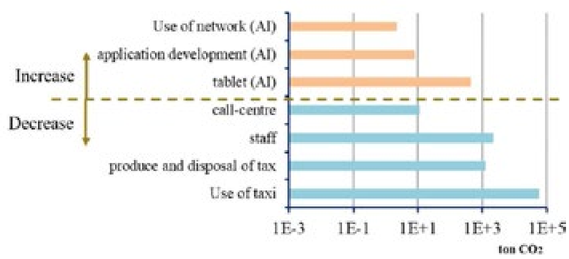

Figure 7: CO_2 emissions change by item

Figures 8 and 9 show the changes in resource consumption in the first and second stages, respectively. In the first stage, increases are mostly caused by the introduction of the new tablets. Then in the second stage, decreases are mostly caused by the reduction in the number of taxis. Most remarkably, the decrease in Fe consumption is almost 1000 times the increase in the first stage. The second biggest reduction is consumption of rare metals.

In this analysis, all taxis are assumed to have a new tablet for obtaining information on passenger demand forecasts. Since most taxis use car navigation systems, if instead of a new tablet, all taxis just install an AI Taxi application onto the existing car navigation system, CO_2 emissions and resource consumption could be further reduced. On the other hand, this analysis is based on the data from the introduction demonstration test carried out in Tokyo. Since population density is high and passengers regularly take cruising taxis, effects may be larger than in rural areas, where almost all taxi use comes via taxi dispatch.

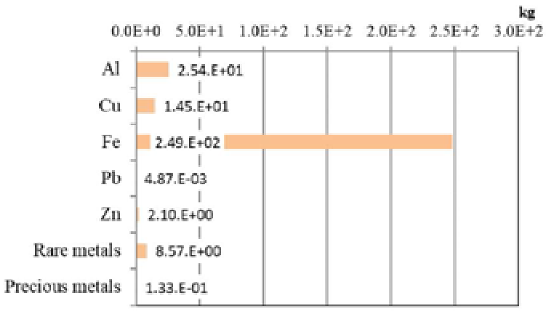

Figure 8: Increases in resource consumption by using AI Taxi in the first stage

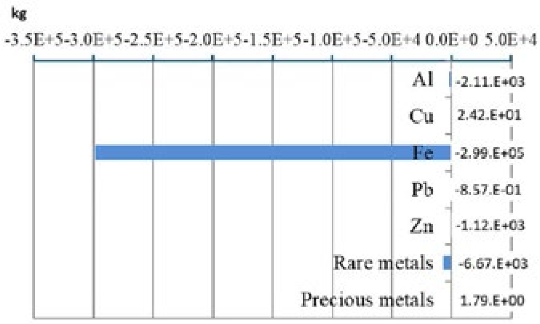

Figure 9: Change in resource consumption by using AI Taxi in the second stage

4 Case study 2

4.1 Target ICT service: Bicycle Sharing

The second case study analysed environment impacts of bicycle sharing. In many big cities in the world, such as Paris, New York, Beijing and Taipei, bicycle sharing is very popular. In Japan, there are several bicycle sharing operators. For example, one operator, Docomo Bike Share, has 8100 electric-assisted bicycles at 780 ports in 10 wards in central Tokyo, with over 390,000 registered members. The same as for almost all bicycle sharing services, users can reserve a shared bicycle through an online website or an application on mobile phone and unlock it by using the mobile application or IC card. Since all the bicycles are setting with GPS, users can be sure that they have the bicycle where they want it. Of course, all payments can be made with your mobile phone or credit card.

4.2 Assessment conditions

This research analysed the impacts in one service area, Minato Ward, which is densely populated and contains 1010 electric-assisted shared bicycles at 63 ports. In the introduction demonstration test carried out from October 2014 to December 2016, shared bicycles were used are about 600,000 times. Average turnover is 2.02 uses per bicycle per day, and average use time is 37 minutes. The comparative analysis in this research was done for 45,364 shared bicycle uses in one month. The models before and after using shared bicycles are shown in Table 2. By introducing shared bicycles, use of personal bicycles, trains, buses, taxis, and personal cars decreased. The reduction rates are based on results of a questionnaire conducted by the Chiyoda Ward Office [13]. If there were no shared bicycles, more than 40% of respondents said they would travel on foot or not at all, more than 40% said they would travel by train or bus, less than 10% said they would travel by their own cars or taxis, and 6% percent said they would travel by their own bicycle. In the reference case, the CO2 emissions and resource consumption were calculated if the abovementioned 45,365 movements were carried out in accordance with the transport percentages in the questionnaire. Even if trains/buses/cars are not used, relocation of shared bicycles will generate new CO_2 emissions and setting up ports will generate both new CO_2 emissions and resource consumption. However, AI technologies have already been applied to optimise relocation paths, since the shared bicycles all have GPS installed.

Before

Bicycle	Production/disposal
	Use
Bus	Production/disposal
	Use
Train	Production/disposal
	Use
Taxi/ Car	Production/disposal
	Use

After

Shared bicycle		production/disposal
		Use
Port setting		production/disposal
Maintenance		staff
Bicycle relocation		Transport of bicycle
		Truck Production/disposal
NW/ System use	Server	Production/disposal
		Use
	Network	Use
Application		Development

Table 2: Changes before and after introducing bicycle sharing

4.3 Calculation equations and dataset

Calculation equations for metal resource consumption and CO_2 emission for transportation including bicycle, trains, buses, taxis, and personal cars and ICT equipment are almost the same as eq. 1 to 4 in 3.3.

The basic units for CO_2 emission and metal resource consumption are also based on IDEA mentioned in 3.3. Data for use of shared bicycles are collected from the introduction demonstration test and some related questionnaires.

4.4 Results and discussions

Figure 10 shows changes in CO_2 emissions between the reference case (before using shared bicycle) and after introducing bicycle sharing. The yellow bars and the blue bars showed CO_2 emissions before and after using shared bicycle, respectively. Total CO_2 emissions are reduced by 12%. The biggest decrease in CO_2 emissions in the reference case is from taxis/cars. Since the percentage of the use of taxis/cars is less than 10%, CO_2 emissions from one use is much larger than for trains or buses. After introducing bicycle sharing, the biggest increase in CO_2 emissions is from relocation of shared bicycles. Therefore, more efficient transportation for bicycles may lead to further CO_2 emission reduction in the future.

Then, for metal resource consumption, according to a related survey, about 13% of shared bicycle users said they no longer needed to own a bicycle thanks to the introduction of shared bicycles [14]. Here, the main resource consumption reduction comes from this change. On the other hand, setting up new bicycle sharing ports and using truck to relocate the shared bicycles generated new resource consumption. As shown in Figure 11, resource consumption of Fe and rare metals slightly increased compared with the reference case before using shared bicycles, and other metals slightly decreased. Even if personal bicycles may be relatively simply substituted for shared bicycle, the operation schedules of trains and buses are difficult to reduce or change in a short time span. The same thing can be said for personal cars, since their main role is for longer distance movement. Therefore, resource consumption reductions of trains/buses/cars are not considered in the results. Of course, for a longer-term analysis, if resource consumption reductions from trains/buses/cars are also considered in the calculation, consumption of most metals could be reduced by about half, which the details are omitted here.

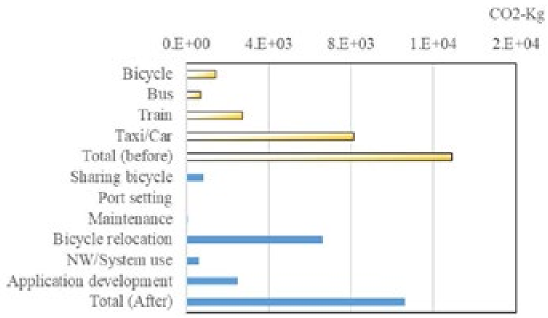

Figure 10: Changes in CO_2 emissions before and after introducing bicycle sharing

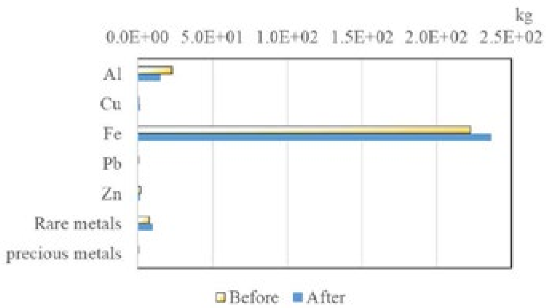

Figure 11: Changes in resource consumption before and after introducing bicycle sharing

5 Conclusions

This research analysed the environmental impacts of two ICT services for taxis and shared bicycles by focusing on not only CO_2 emissions but also metal resource consumptions, based on lifecycle assessment (LCA). In both case studies, CO_2 emission reduction effects appear in a short time span. That is to say, the reduction in the use stage of vehicles with high CO_2 emissions was more effective than the CO_2 emissions from the production/use/disposal of new ICT equipment. However, regarding to resource consumption, in the early stages of the introduction of new ICT, though the use of resources caused by the use of ICT equipment increased, the originally used vehicles would not be reduced immediately, but instead gradually decrease over time. Therefore, it was found that there is a time lag compared to the CO_2 emission reduction effect. Though resource consumption may temporarily increase, long-term resource consumption was found to decrease in both case studies.

In the future, rather than individual ICT services, optimisation by advanced AI for the total transportation system may bring about greater effects in terms of convenience, environmental protection, and health. ICT including new digital technologies is quickly advancing, so to build a sustainable society, usage of ICT in consideration of the environment aspect will be more and more important in the future.

Acknowledgments

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A.3
(ECO)PRODUCTS: MOBILE DEVICES

Sustainability paradoxes for product modularity: the case of smartphones

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Abstract

Pioneering smartphone companies have embarked on ambitious journeys to adopt modular product designs (MPD) as part of their circular economy strategy. MPD refers to the idea of designing products based on grouping related functions in individual modules with standardized interfaces. Previously, MPD has been extensively discussed as an approach to achieve efficient product manufacturing in the upstream supply chain. As part of circular business strategies, MPD is increasingly applied as a design principle for supporting lifecycle management downstream. In a circular economy, modularity could enable replacements and recovery of individual modules to extend product and material lifetimes. However, applying MPD to achieve extended lifetimes could also create design tensions that require trade-off solutions, leading to system-level paradoxes. In particular, these tensions arise with regard to the ambitious sustainability intentions of companies while operating in a conventional linear system. We conduct an in-depth case study on a small-scale European smartphone original equipment manufacturer (OEM) producing modular smartphones. We observe that an OEM's original design intention and its operationalization of MPD for sustainability goals could generate tensions and, eventually, paradoxical outcomes. Our results illustrate that modularity does not automatically contribute to sustainability. Instead, it requires collaboration of suppliers and OEMs as well as adjustments of the regulatory system.

1 Introduction

Recent regulation requires manufacturers to consider material efficiency throughout the entire product lifecycle. In particular, the European Union's Ecodesign Working Plan [1] has been extended from an energy efficiency perspective to considering overall resource and energy efficiencies. As a result, original equipment manufacturers (OEMs) are required to adapt their product designs to facilitate product and material lifetime extensions through "the possibility to repair, remanufacture, or recycle a product and its components and materials" [1, p. 8]. Modular designs are seen as a great potential for facilitating a circular economy (CE) in this regard [2]. However, modularity is no panacea to reduce environmental impacts, especially when use patterns are taken into account [3].

Aside from enabling efficient circular service operations, modular product design (MPD) may also spark innovation potentials and economic performance through increased production efficiencies and mass customization [2, 4, 5]. Generally, modularization refers to the idea of designing products based on grouping related functions in individual modules with standardized interfaces [6]. So far, MPD has been discussed extensively as an approach to achieve efficient product manufacturing and delivery in the upstream supply chain. As part of circular business strategies, MPD is increasingly discussed as a design principle for supporting lifecycle management downstream [5]. The idea is that in a CE, modularity could enable replacements and recovery of individual modules to extend product and material lifetimes. Applying MPD to achieve extended lifetimes, however, could also lead to technical, organizational, environmental, and economic tensions as well as contradictory results. The literature frequently points to practical challenges in implementing modular designs, including rapid technological change, technical complexity due to numerous interfaces, and additional material use for module housing [5, 7, 8]. Using the example of smartphones, this paper aims to elaborate on emerging firm-level tensions and trade-offs for implementing MPD, as well as resulting system-level paradoxes of MPD while the product is in use with the end-user.

Smartphones certainly have become our daily companions. By 2019 there was an estimated total of 3.4 billion smartphones in use worldwide [9], even as their production and consumption create substantial sustainability impacts [10, 11]. Recently, we have seen that the primary (new) smartphone market has stagnated while

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the secondary market has been flourishing [12]. We have also seen that dominant smartphone designs and business models are only partially suitable for prolonging smartphone lifetimes and establishing efficient secondary markets. As smartphones are becoming saturated in major markets [13] and governments are imposing additional sustainability requirements, MPD has become more attractive. MPD could allow OEMs to benefit from prolonged lifetimes through cascading cycles of use with corresponding business models. Pioneering smartphone OEMs have successfully embarked on ambitious journeys to adopt MPD as part of their CE and broader sustainability strategy [4, 14].

While modularity is not a new concept, its contribution to sustainability is not widely researched. Although sustainable MPD is focused on product adaptability in the downstream value chain, the initial design has substantial implications for the up-stream value chain as well [5]. Therefore, our main research question is: *"How are smartphone OEMs dealing with sustainability tensions, trade-offs, and paradoxes when implementing MPD strategies?"*. To investigate this question, we conducted a case study on the pioneering OEM "SmartMod Ltd."We collected qualitative data from interviews and ethnographic observations at the company's European headquarters as well as with assembly and suppliers in China. We borrow concepts from the organizational literature on tensions, trade-offs, and paradoxes to analyse our data from an integrative perspective on these contradictions [15]. In our field study, we observe that an OEM's original design intention and its operationalization of MPD for sustainability goals could generate tensions and eventually paradoxical outcomes while operating in a conventional linear system.

2 Background

In this section, we first introduce key terms, including the modular product design within a CE, and the concept of tensions and paradoxes. We then present our preliminary conceptual framework for our analysis.

2.1 The role of design

One objective of the CE concept is to slow down resource throughput and greenhouse gas emissions by increasing longevity of durable consumer goods such as smartphones. For corresponding technical cycling, circular strategies to increase product and material lifetimes include repair, reuse, upgrade, refurbish, and recycling [16, 17]. OEMs choosing to vertically integrate the resulting circular service operations have considerable incentives to adapt their product design toward the creation of closed-loop systems [18]. In this way, they can decrease material contamination, improve resource efficiency, and bring potential economic gains on technical, systemic, and interaction levels [19]. As a result, their general product architectures play a key role in the transition to a CE [20].

Circular design has been explored by various scholars in recent years [21, 22]. In contrast to eco-design, circular design takes a more strategic approach that allows to fully realize the economic potential of products and capitalize on product longevity [22]. Thereby, product lifetime – that is the sum of consecutive use phases – is determined by a number of factors. On the topic of product lifetime, the literature distinguishes between absolute and relative obsolescence [23]. A product becomes absolutely obsolete through premature technical failure, whereas relative obsolescence describes discarding a functional product for emotional or economic reasons. Frequently discussed design strategies to extend product life of electronics include design for (emotional) durability, for ease of maintenance, for adaptability, and for disassembly [24]. A promising design principle to execute circular design strategies is modularization, as it allows for product changes in the downstream value chain, including repairs, upgrades, and disassembly. These activities allow for prolonging the use time of products and increase the likelihood of realizing their full potential. As a result, circular design can prevent premature obsolescence [22].

2.2 Product architecture and MPD

Product architectures are the central elements of all product concepts. They represent the basic blueprints for both product designs and for managerial strategy, with fundamental impact on manufacturing performance as well as product variety, adaptation, and standardization [25]. Generally, product architectures have both functional and physical properties [26]. In this way the functional elements eventually contribute to a product's performance and are assigned to so called physical building blocks. This design concept is probably also best known from Bauhaus as "form follows function" [27].

In the literature, two basic product architectures are differentiated: Integrated and modular product architectures [6]. In modular architectures, one or a few functional elements are assigned to a single building block with well-defined interactions between them. Thereby, one building block becomes one module that may consist of several components, but can be exchanged with little or no impact on other modules [25]. In contrast, in integrated product architectures, functional elements require more than one physical building block, and a single block is responsible for multiple functions. Thus, the highest degree of modularity is reached when each (sub)function is implemented by exactly one module. However, these types are to be understood as two extremes that rarely fully apply. Modularity is thus a relative property [6].

Historically, MPD served various objectives that have changed over the course of its development from an upstream, efficiency focused model, to the most recent downstream, sustainability-focused model (Table 1).

	Modular Production (upstream focused)		Modularity for Sustainability (downstream focused)
Decade	1970s: Rationalization	1990s: Economies of Scope	2010s: Sustainability and circularity
Aim of MPD	MPD to decrease production lead time and increase efficiencies	MPD to manage variants and enable mass-customization	MPD to enable product lifetime extension and recyclability
Type	Assembly-based modular design and standardization	Design for product variety and management of platform strategies	Design for product change (replacements, upgrades, and recovery)
Benefit (selection)	Optimized manufacturing costs	Meeting customer needs	Leveraging sustainability potential to reduce environmental impact

Table 1: Goals for applying MPD changes over time, based on: [5, 25, 28, 29]

Accordingly, MPD for electronic devices can take various forms [8], depending on a firm's underlying business model. For electronic devices and in particular smartphones, Schischke et al. 2019 distinguish nine modularity types [8]. These range from visible LEGO style approaches for user repairability or customization to non-visible rather integrated designs optimized for professional serviceability.

In the literature, there are discussions about the role of modularity for contributing to environmental sustainability, specifically, that modularity is no panacea [3]. In certain cases, it can increase overall environmental impacts through additional material usage for connectors on the micro level or through creating additional demand on the macro level (e.g. up-to-date modules). To accurately understand the impact of modularity, it is critical to assess the potential environmental impacts on a case by case basis while taking into account underlying business models and use patterns [8]. This follows the insight that design-level improvements for the life-cycle are not independent from business model innovations [30].

Despite the popularity of circularity in business model creation, there are several known challenges of initiating and managing circular models in traditionally linear systems. In fact, there are known challenges in almost every aspect of the business including pricing, branding, inventory management, consumer acceptance, supply chain design, remanufacturing, and manufacturing cycles [20]. MPD can also create several system-level contradictions. In the study of interfirm modularity, a phenomenon where companies working together to produce compatible modular components enabled by a shared product architecture, researchers found system-level constraints in coordinating MPD. These constraints include firms getting frustrated at the lack of control over the definition of their own products, including key decisions on modules and interfaces. Firms also face difficulties in management and resource allocation[31]. The challenges and contradictions create tensions that often require trade-off decisions when firms aspire to achieve sustainable MPD.

2.3 Tensions and trade-offs in operationalization

Firms following an integrative sustainability strategy see themselves confronted with several conflicting interconnected and interdependent goal conflicts and associated tensions [32]. While aiming to improve circularity, e.g. through a modular product, they must (at least partially) operate and obey the rules of the linear economic system [33]. To analyse our observations with regard to these contradictions, we borrow from more general concepts within organizational studies literature on tensions, trade-offs, and paradoxes.

In organizational contexts, tensions arise when opposite concepts or principles clash among different stakeholder groups and thus push and pull on each other [15, 34]. Tensions are often presented as dualities, making it difficult to move forward without preferring one pole over the other. Thus, making an either/or choice may create inconsistencies and contradictions over time [15]. Such trade-offs are also perceived as contradictions or opposing elements negating one another [15]. Trade-offs typically emerge during product development, especially in the eco-design context with conflicting sustainability targets such as reducing weight in passenger cars to increase fuel-efficiency which might also decrease durability and crash safety [35]. Thus, balancing alternative solutions with opposing aspects ultimately leads to trade-offs with compromise situations to "sacrifice [...] in one area to obtain benefits in another" [35, p. 1420]. While trade-offs may be solved through either/or approaches after carefully considering available alternatives, a paradox lens takes an integrative "both/and" perspective [36].

The paradox lens has been proposed as a new way to manage underlying tensions and trade-offs in the context of sustainability [32] and greentech innovation [37] to impede ironic outcomes with opposing results of what was initially intended [15]. Smith and Lewis define paradoxes as "contradictory yet interrelated elements (dualities) that exist simultaneously and persist over time" [38, p. 387]. In particular with regard to sustainability, firms face contradictions on various levels, as most sustainability problems are systems problems with complex dynamics [36]. Paradoxes thus cannot be solved at the individual level, but can be managed by attending to these competing demands simultaneously [38].

Aside from the concepts of tension, trade-off, and paradox, we refer to literature in organizational intelligence to examine the decision making processes of the organization we study, namely whether it makes decisions that are either "choice-based" or "rule-based" [39]. A choice involves selecting among alternatives by evaluating the consequences. A rule involves the logic of appropriateness and following criteria that match the appropriate situation. In our analysis, we examine the choices of a company when facing modularity consequences.

2.4 Preliminary conceptual framework

Based on the above concepts and contradictions, we have developed the following preliminary conceptual framework as the basis for our empirical exploration (Figure 1).

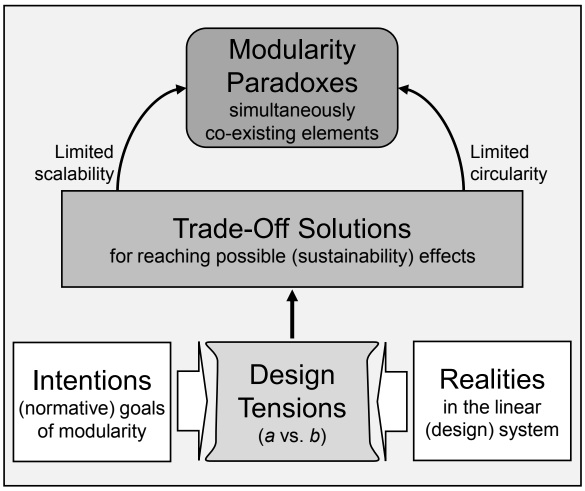

Figure 1: Preliminary conceptual framework

Our framework takes the clash of design principles as the basis for our analysis. Initial design intentions to make devices more modular and thus eco-friendly stand in contradiction to the established economic and design realities. From these design tensions arise trade-off solutions that favour one over the other in an either/or approach. These trade-off solutions create inconsistencies with regard to the original design goal. On the one side they are limited in their scalability, while on the other their circularity potential is limited, too. These elements exist simultaneously, creating overarching paradoxes while the product is in use with the end-user. We discuss paradoxes on a systems level, referring to the entirety of firms working on similar components or products [31].

3 Method

We adopt an exploratory research design because there are a very limited number of companies that have successfully commercialized MPD in the smartphone market [40]. Efforts such as Google's Project Ara, a modular smartphone project that features LEGO-style bricks, was terminated although it had less of a sustainability focus and attracted a lot of media attention [8].

Our qualitative research approach is ethnographic in nature and includes various data sources (Table 2). We combined formal interviews with supplementary site visits and actively seized opportunities for informal ethnographic interviews in a natural context [41]. Some members of the research team set up a professional innovation lab for sustainability in the smartphone industry which included the company we chose for our case study [42].

Data type	Data source and total length	Documents
Semi-structured interviews	2 (CEO + Designer) 1:45h length	Transcripts
Ethnographic observations in China (site visits)	- 2 days @ SmartMod - 2 days @ Suppliers - 1 day @ Industry expert	> 65 pages notes, photographs, 2 research diaries
Archival data	Websites, corporate presentations	PDFs

Table 2: Overview data sources

We conduct an embedded in-depth case study [40] on "SmartMod Ltd.", a small-scale smartphone OEM producing modular smartphones, and their suppliers. Through in-depth interviews with the OEM's owner-managers, designers, line operators, and additional industry experts as well as site visits in final assembly and suppliers in China, we compiled first-hand observational data of the applications and implications of modular design. We analyse MPD impacts regarding firm-level tensions and trade-offs from which we develop the more general modularity paradoxes. We designed a codebook to code each interview with the categories from the preliminary framework. Two interviewers also served as the coders for the analysis. Each coder/interviewer coded the interviews independently following the codebook. Coding discrepancies were resolved through discussions with the research team. We use an inductive approach where the findings are uncovered from the interview and site visit data instead of through hypothesis testing [43].

4 Results

4.1 Case description

SmartMod is a small-scale pioneering OEM (<50 employees) for electronic devices used in particular smartphones. While the company's headquarters, including management and design teams, are located in Europe, manufacturing design, production, and final assembly are based in China. The company follows an integrative sustainability approach and puts economic success second after sustainability. SmartMod can be considered to be following a vertical integration strategy for its circular activities [18]. Accordingly, the company operates its own repair, take-back, and second-hand systems. This allows SmartMod managers to learn from their reverse activities and adapt their product design accordingly. For their recent devices they have adopted a modular architecture mainly for sustainability reasons. This study covers two of SmartMod's recent smartphone models with a modularization type that can be characterized as "DIY repair modularity" without additional module housings [8].

4.2 MPD trade-offs

In the following section, we analyse and summarize the intentions, realities, tensions, trade-off solutions, and resultant system-level paradoxes (see Table 3). For each section, we specify the life cycle phase for these observations. In this paper we only discuss life cycle phases based on direct observations, but acknowledge that there are some phases where we do not have observations relevant to the coding criteria.

1) Modular design vs. integrated design

One goal of SmartMod in the design phase is to bring modular devices to the market. However, in the current production system only integrated designs are available and are the norm – mainly driven by their cost efficiency. SmartMod faces the choice of adapting each component individually and developing its own modular architecture or staying competitive by falling back on up-to-date components with integrated designs. Thus, SmartMod either develops its own specific architecture from scratch or relies on standardized parts from the existing market. The trade-off solutions that SmartMod has identified are to simplify its smartphone design to reduce the number of components, build in-house design capacity and establish strong collaborative relationships with its suppliers. At the systems level, this leads to the paradoxical situation that modular devices are more expensive and to some degree outdated even though the design is simpler. Owing to the proprietary architecture, modular designs in fact become less compatible than linear designs. Because of system lock-in, there is an additional development cost to implement MPD [6].

2) Modular design vs. durability

With their specific modular architecture, SmartMod managers aim to facilitate repair, upgrades, and disassembly in their design. This requires replaceable interfaces mostly implemented by means of mechanical connections. However, in reality, while additional mechanical connections can accommodate increasing functionalities of the products, they may also result in less durable design [14]. This raises a design tension when the SmartMod team faces the choice of increasing the number of exchangeable parts via mechanical connection or minimizing the number of connectors through soldering and use of adhesives. SmartMod has identified a trade-off solution that can be summarized as a *two-level modularity*, which refers to designing parts that determine product lifetime or fail frequently to be easily removeable. Still, this approach has its limits as the main processor units limit lifetime but definitely require soldering. Overall, this raises a paradox at the system level as modularity may decrease reliability during use but also enable reparability and thus durability from a life cycle perspective.

3) Flexibility and adaptability through MPD vs. efficiency

SmartMod intends to increase flexibility and adaptability of production through its modular product architecture. Based on modularization the company was able to set-up its own assembly line and allow workers to rotate around different workstations. This stands in contrast to conventional production setups mainly driven by efficiency rationales. This raises a tension when SmartMod faces the choice of allowing flexibility and adaptability for production employees or increasing efficiency through minimizing lead time. The trade-off solution that SmartMod has identified is to devalue efficiency in favour of improved flexibility and workers' experience by offering two delivery speeds to their customers. Thus, customers can choose to buy immediately from stock, or have their device produced "on-demand," with the latter customer receiving an economic inventive. From an organizational decision-making perspective, SmartMod made a "choice-based" decision to prioritize workers' experience versus the alternative of a "rule-based" decision to prioritize the efficiency of the output. At the system level, the paradox is that modularity incurred additional operational costs but enables workers to gain a sense of autonomy and flexibility.

4) Oversizing vs. increase size of exchangeable block

In order to prolong device lifetimes during use, SmartMod intends to facilitate future upgrades for specific modules during use. In the current market situation, however, component versions (i.e. from new generations of technology) each require new interfaces, which limits inter-generational compatibly and thus the lifetime of the modules. SmartMod faces a tension between adopting an oversize form factor and additional interfaces in anticipation of future versions of components or increasing the size of exchangeable "blocks" (one module or multiple modules) of the phone gradually as new versions of components arrive. To solve this, SmartMod has identified multiple trade-off solutions: 1) design the mainboard to accommodate multiple display interfaces, which facilitates upgradability for the phone; 2) facilitate closed-loop second-hand market and cascading of product use through a deposit scheme and allowing users to trade-in spare parts or the entire phone. At the systems level, this creates another paradox, as modularity in principle allows for module upgrades, but technologies such as software and hardware develop too fast and thus become incompatible with old modules. This makes small-scale module upgrades difficult and often leads to upgrading of the entire device, diminishing the opportunity to minimize waste.

5) Limited support time vs. storing blocks/parts

Another goal of SmartMod is to promote long-term serviceability of the product to around ten years during the use phase. However, in reality, components have a short half-life period and the firmware and software that are used to support the hardware may no longer be supported. Further, component manufacturers stop production when new generations come to the market, even while corresponding devices are still produced. The tension arises when SmartMod faces the choice to increase production sovereignty through supplier collaboration or to stockpile potentially unnecessary and eventually outdated spare parts. Trade-off solutions that SmartMod has identified are to 1) choose suppliers based on "duration of re-procurement time" and 2) harvest from their own returned products with a deposit scheme. At the systems level, the paradox is that modular products cannot realize their full potential because of external technological and economic constraints [6].

5 Discussion and Conclusion

Modularization has the potential to allow for both prolonged product lifetimes through repairs, upgrades, and improved recycling as well as new business opportunities. Yet, there are several conventional trade-offs for modular designs, such as lower weight and smaller size for integrated architectures vs. higher weight and larger size for modular architectures [6]. There are also trade-offs that are sustainability specific.

Two-level modularity as a design strategy

To delve more deeply we identify that modularity may decrease reliability of devices (due to mechanical connectors) while also allowing for increasing durability through repairs and upgrades. This raises the question of whether there is an optimal level of modularity that can be defined. In our case study, SmartMod has developed a *two-level modularity* that distinguishes between parts that determine product lifetime versus parts that are uncritical for product lifetime. For example, this allows for fast and simple user repairs of the battery and display. Additionally, furthering modularity of potential technological bottlenecks, such as the CPU and the main PCBA design, could be considered.

Earlier research already distinguishes between consumer and supplier repairability [44]. Going one step further, research suggests it is useful to split up parts of the phone that are owned and others that are leased as part of a Product-Service System (PSS) [45]. Two-level modularity might contribute to the discussion of the right-to-repair movement and product level CE standards, as it provides a trade-off solution with repair by users and by professionals, depending on the defect.

Flexible assembly line as a choice-based decision

In expanding MPD beyond the upstream of the supply chain, SmartMod follows a choice-based decision-making process in its product design, production, and circular services. Instead of following the rule of profit and efficiency maximization to manufacture its products, SmartMod intentionally chose a social impact-focused path that deviates from the conventional linear production system. Modularization opens up opportunities for the assembly line workers to be part of a more flexible work dynamic as well as for the users to engage in a positive social mission. As benefit corporations and corporate sustainability become more mainstream [46], it is possible that additional companies will move towards a choice-based decision-making scheme when considering their environmental and social impacts through MPD.

System-level MPD paradoxes

System-level paradoxes emerge while the device is in use, leading to shorter lifetimes than expected. Modular architectures have additional system-level implications given the need to define interfaces, standards, and protocols [6]. We have also found evidence for modular smartphone designs optimized for sustainability using proprietary architectures only partially reaching their desired positive environmental effects because of these system implications.

Through optimizing production efficiencies of integrated designs over time, the electronics industry has developed a large variety of models, especially in the Android segment [47, 48]. In order to enable extended repairs, OEMs need to support users or repair facilities with appropriate spare parts [18]. With constant model updates and changes, it is challenging for OEMs to simultaneously continue producing the latest models while keeping up steady streams of spare parts in anticipation of future repair needs. This is particularly difficult to small-scale OEMs with limited production capacity and high pressure to survive the market competition. It is important to acknowledge that a single OEM cannot reshape an entire production and consumption system.

Aside from identifying the specific trade-offs, we notice the processes and dynamics of how SmartMod implemented MPD during design, production, and use phase through ethnographic observations and interviews with SmartMod's teams in Germany and China as well as industry experts. These observations add richness to our understanding of how the trade-offs and paradoxes were shaped. We observe that SmartMod's headquarter in Germany focuses more on slowing down the material use of products through MPD while the China team, including suppliers, focuses more on material recyclability and closing the loop during the operationalization of MPD. Overall, the two teams have developed strong interpersonal and business relationships over time that enabled the increasing number of productions.

Our case study demonstrates that sustainable modular product designs may lead to paradoxical outcomes that are beyond an individual OEM's control. For sustainable MPDs to be successful in economic and environmental terms requires rethinking not only the individual product architecture but also system-level production and consumption. If the entire economy is more circular, the tensions identified in the case study could be lessened. Sustainable modular products interact more intensively with their embedded systems than integrated designs [6], in particular as they require corresponding circular service operations throughout the lifecycle to unfold their sustainability potential. An interfirm modularity with multiple firms jointly developing and controlling the modular architecture could be a promising approach [31]. Aside from management strategies to deal with sustainability paradoxes, further adjustments of the regulatory system are necessary to reduce paradoxical outcomes for MPD in the use space.

Limitations

Our study is subject to several limitations. First, our analysis is based on a single case study of a relatively small pioneering OEM, with the results not directly translatable to OEMs with more resources and industry power. Secondly, detailed analysis of overall environmental implications for specific MPDs throughout the lifecycle (including lifetime extension) are necessary. Thus, further studies are needed to analyse MPD´s effects on a larger scale.

Life cycle stage	Intentions	Realities	Design tensions	Trade-off solution	Modularity Paradox (system level)
Design	Bring modular device to the market	Only integrated designs are available with internal components that enable the design	Creating own modular design and components vs. following integrated design	Simplify smartphone design, develop in-house design capacity and strong collaboration with suppliers	Modular devices are more expensive even though the design is simpler
	Facilitate disassembly and repair	Large number of mechanical connections necessary to accommodate increasing product functionalities	More vs. less exchangeable blocks	Two level modularity	Modularity may decrease reliability in the field, while it enables repairability and thus durability
Production	Increase flexibility and modularity during manufacturing	Production sites driven by efficiency of outputs and specialization of workers	Flexibility and adaptability of MPD vs. efficiency	Devalue efficiency for improved flexibility and worker experience	Modularity may incur additional operational cost, while it enables autonomy and flexibility of workers
Use	Facilitate upgradeability	New component versions require adapted/new interfaces	Oversize from beginning vs. increase size of exchangeable block (up to entire phone)	1) Design to accommodate multiple interfaces 2) Allowing users to trade-in spare parts or the entire phone	Modularity not able to accommodate upgrades due to rapid development of software and hardware.
	Improve long-term serviceability (aim ~10 years)	Components have short half-life period and might not be continuously supported by firmware/software	Limited support time vs. storing potentially unnecessary and eventually outdated spare parts	Choose suppliers based on "duration of re-procurement time"; harvesting from own products with deposit scheme	Modular products cannot realize their full potential due to external effects (technological and economic)

Table 3: Summary of main findings following the conceptual framework along product life cycle stages

6 Literature

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Environmental Impacts of Modular Design - Life Cycle Assessment of the Fairphone 3

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Abstract

The Fairphone 3 is one of the few modular smartphones on the market today. The design approach allows users to easily repair their device and thereby extend its lifetime. Previous life cycle assessments (LCA) of smartphones have shown that lifetime extension is the most effective strategy to reduce their overall impact. As the environmental impacts of smartphones are predominantly associated with the manufacturing phase, repair and continued use after a hardware failure can avoid the environmental burden that would result from manufacturing a new device. However, implementing modular design does produce additional impact. The results of the LCA study presented in this paper show that the initial manufacturing impacts are indeed slightly increased due to the modular design. However, this can easily be outweighed when the use phase is extended through repair. The modularity overhead has also decreased compared to the Fairphone 2 due to a new connector design.

1 Introduction

The main findings of an LCA study of Fairphone 2 carried out in 2016 showed that the modular design slightly increased environmental impacts of the manufacturing phase, mainly due to the large (gold-coated) connectors between the different modules, and the additional printed circuit board area needed for these connectors. However, this initially increased environmental burden can easily be outweighed when the device is repaired after a failure and used longer [1].

The design of the Fairphone 3 (FP3) specifically addressed the connectors and switched from the large pogo pin connectors of the Fairphone 2 to smaller press-fit sockets, resulting in less material use, but also in increased use of flexible boards. Logistical changes have also been introduced, such as transporting devices and modules by train instead of plane to the distribution hub. Data transparency has also been improved in all phases of LCA.

This paper presents results from the LCA study of the FP3 [2], with a focus on reassessing Fairphone's environmental impacts and identifying improvements, opportunities and trends with the hindsight of the aforementioned LCA study for the Fairphone 2.

2 Methodology

An LCA study for the FP3 was carried out, covering the entire life cycle from raw material acquisition, manufacturing, use, transport and end-of-life. Five different impact categories were covered by the full LCA, which are also covered in this paper. The focus here, however, will be on global warming potential (GWP), as it is the most widespread and best-understood indicator for the communication of results.

The functional unit for the LCA is the intensive use of a smartphone over the period of three years. The corresponding reference flow is the Fairphone 3 as delivered to the customer, including sales packaging, manual, screwdriver and bumper, but without charger, which is not part of the standard package. No part or component failures are assumed for this baseline scenario. Additionally, the impact of life time extension through repair is assess via a scenario-based approach.

3 Life cycle inventory

The data inventory is based on the bill of materials (BOM) cross-checked with the material declarations for subparts from suppliers, a teardown of the device, and further analysis of high-impact electronic components. The final assembly process is based on primary data provided by Fairphone.

Processes were modelled with the LCA software package GaBi and the corresponding database, incl. the electronic extension database. This was supplemented with the ecoinvent database v3.6. For integrated circuits (IC), battery and display, additional sources from literature were consulted.

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3.1 Raw material acquisition and manufacturing

The manufacturing phase was modelled according to the bill of materials (BOM) of the Fairphone 3 and material compositions data for several components provided by the suppliers. The analysis was supplemented with a teardown of the phone performed in-house at Fraunhofer IZM.

Life cycle data sets were allocated to all parts based on weight (mechanical parts), number of pieces (electronic components) or size/area (e.g. printed circuit boards, ICs). The main parts of the phone are presented in Table 1.

Module	Main parts	Mass
Fairphone 3		190.4 g
Core module		
	Mainboard with main electronic components, module connectors and connectors to battery and display assembly	18.5 g
	Button assembly	
	Flex boards to module connectors	
	Fingerprint sensor	
	Frame and mid frame	
Top module		5.1 g
	Top module board	
	Front camera	
	Receiver (speaker)	
	Earphone jack	
Camera module		2.9 g
	Camera	
	Camera board	
Bottom module		4.3 g
	Bottom module board	
	Vibration motor	
	USB-C connector	
Speaker module		3.1
	Speaker, microphone	
Display module		63.4 g
	Display frame	
	LCD display	
	Display board	
	Cover glass	
Battery module		50.4 g
	Battery	
Back cover		12.6 g

Table 1: Main parts of the Fairphone 3

3.1.1 Printed circuit boards

Printed circuits boards (PCBs) were modelled based on the production layouts, taking into account the real-life cut-offs. The four module boards with 6 layers are produced on one panel and the mainboard with 12 layers on a different panel. The results for the area allocation show that the offcuts would have been underestimated for the module boards (in total by 13.5 cm^2) and overestimated for the mainboard (in total by 17.8 cm^2) if based on the outer dimensions and not on the actual production layouts.

3.1.2 Integrated circuits

The environmental impact of ICs is determined mainly by the processed die area. Die area was determined with computed tomography (CT) scan images of the boards, and x-rays and vertical grinding of ICs to determine the area of individual packages, particularly for stacked dies. Main drivers in terms of die size are the power management ICs, CPU and the flash/RAM stacked package. Flash storage and RAM are located within one package containing nine stacked dies. The die area of this package is larger than all other ICs combined. The impact of the ICs is modelled according to impact data from [3] for CMOS logic chips and [4] for the memory package.

3.1.3 Display

The display is modelled according to the CSR report from the Taiwanese display manufacturer AUO [5]. The data is scaled by panel size, which is 81.9 cm^2 for the FP3.

AUO data covers scope 1 (direct emissions) and scope 2 (purchased energy). Scope 3 covers product use, business travel, and commuting, but not the impact of upstream suppliers and is therefore not taken into account. Production of input materials is not covered, but addressed via additional data sets from Gabi and ecoinvent. The data covers the panel manufacturing without backlight and electronics (display board). The display board is modelled based on the BOM and teardown. Die size of LEDs per screen area is modelled based on [6] for a comparable tablet display. This results in a die area of 0.0077 cm^2 for the FP3 display. The LEDs are modelled per die area as CMOS logic as it is also described by [7].

3.1.4 Connectors

The board-to-board connectors have been changed from pogo pin type in the FP2 to press-fit connectors in the FP3. Those mainly consist of the following materials:

- Copper, nickel and gold for the contacts,
- steel or bronze for metal fittings, and
- glass fibre-supported plastic for the housing.

All modules are connected to the mainboard through flex cables with a male/female connector pair on each side. The connector between mainboard (core module) and display board is the only pogo pin connector with

32 pins on the mainboard and contact areas on the display board. The pogo pins are modelled, as the press-fit connectors, based on the material composition given by the supplier. The flex cables are modelled as one-layer PCBs. For the contact area, the additional amount of nickel and gold on the PCB is accounted for.

3.2 Use phase

In order to model the use phase, the following use pattern was applied:

- 3 years use without repair
- One charging cycle consumes 19.21 Wh, which results in 7.01 kWh annually

The power consumption per charging cycle is based on measurements carried out at Fraunhofer IZM with new and aged (80 % state of health) batteries. For the number of replacement batteries, laboratory cycle life testing of the battery was carried out, showing that the batteries can theoretically endure 1000 full charge/discharge cycles while retaining a capacity (SOH) of 80 %.

Previous LCA studies of smartphones have worked with the conservative assumption that the battery is fully charged and discharged once every day, resulting in 365 charge/discharge cycles per year. Empirical data suggests that the actual number may be closer to 230 cycles on average annually [8]. For the FP3 LCA it was assumed that the battery durability is sufficient to last for 3 years of use, after which it needs to be replaced with a fresh battery. However, to calculate the use phase energy consumption, the study adopts the conservative assumption that the battery is fully charged once every day.

Electricity use is assigned according to the distribution of sales within Europe, assigning national electricity grid mixes.

3.3 Transport

The following transport phases and conditions are taken into account:

- Transport of parts from tier 2 suppliers to final assembly in China (truck delivery within China, air freight for international transportation)
- Transport of the entire phone to the distribution hub in Europe (freight train)
- Transport to customer from distribution hub within Europe (truck delivery within Europe with average distances weighted according to the distribution of sales)

The transportation is modelled as tonne kilometres (tkm), taking into account transported weight of the part/product including packaging and distance.

3.4 End-of-life (EOL)

The FP3 is assumed to be discarded as electronic waste to join the wider WEEE recycling stream. Following the Umicore recycling process [9], the device is set to have the battery removed first (depollution) and then the rest is sent to the material recovery streamline as scrap. The main processes included in the model are copper smelting, electro-winning and precious metal recovery.

In the depollution step, 95 % of the batteries were assumed to be separated correctly [10] and a recovery rate of 95 % for the copper and cobalt contained was estimated. In the electro-winning step, copper is recovered with a rate of 95 %. Finally, in the precious metal recovery step, three elements are yielded: gold, silver and palladium, all with a rate of 95 % based on [11]. All burdens as well as credits of the material recovery were allocated to the life cycle of the FP3.

3.5 Repair scenario

For the assessment of potential lifetime extension through repair, repair through module replacement (A) as well as direct module repair (B) were analysed. It was assumed that over the course of 5 years, each phone is repaired once and the battery is replaced once as well. A mix of repairs is assumed reflecting data from repair statistics:

- 63 % display
- 16 % connectors resulting in 9 % top module (earphone jack) and 7 % bottom module (USB-C connector)
- 10 % camera module
- 5 % speaker
- 3 % back cover and bumper
- 3 % mainboard

For module repair (B) it is assumed that mainboard, camera, top and bottom module can potentially be repaired through board-level repair. A return rate of 75 % of broken modules was assumed, 50 % of which were assumed to be reparable for the scenario, leading to 63 new modules needed per 100 replacements.

4 Results

The assessment results in a total life cycle GWP of 39.5 kg CO_2-equivalents (CO_2e). The main impact for all impact categories is caused by the production phase. Transport and use phase have a comparatively smaller impact. EOL activities have a negative impact value, meaning a positive potential for the environment due to recovered materials (Figure 1). Transport is driven mainly by air freight from suppliers to final assembly.

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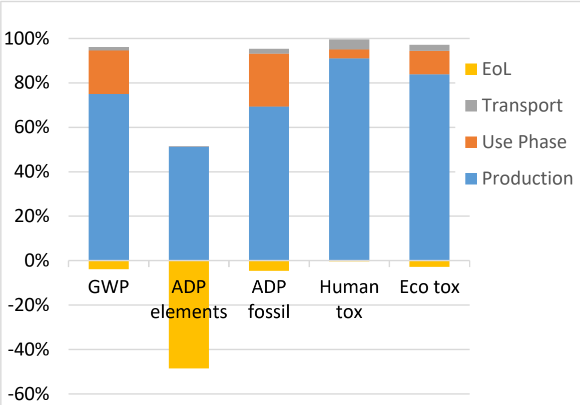

Figure 1: Impact per life cycle phase

Within the production phase, the production of the core module and therein particularly the mainboard causes the highest impact for all impact categories (Figure 2). The final assembly has a GWP impact of 6.8 % of the total production impact, the display module contributes 7 %. The back cover, bumper and screwdriver cause a combined impact of less than 1 %.

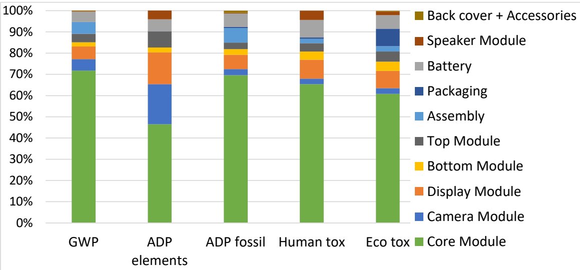

Figure 2: Production impacts per module

Broken down per type of component, the major impact share is caused by the production of the ICs, followed by the PCBs. Connectors have the highest relative impact in the category ADP elements (14.7 %) due to the amount of gold used (Figure 3).

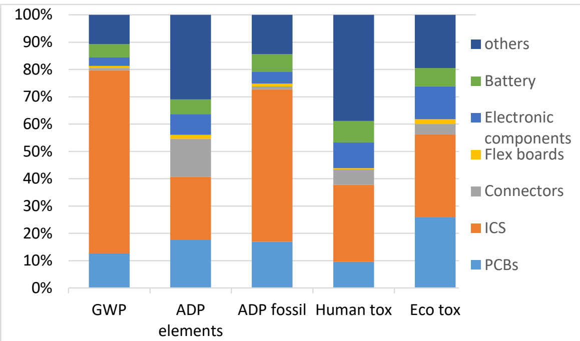

Figure 3: Production impacts per type of component

4.1 Modularity

The impact of the modularity overhead (as it was shown also for the Fairphone 2 in [1]) is driven by additional module housing, module connectors and the connecting flex boards as well as the additional PCB area for the board-to-board connector between display and mainboard. Additional PCB area, flex cables and connectors each cause about one third of the modularity GWP overhead. ADP elements and human toxicity are driven more strongly by gold, leading to the connectors causing a stronger impact. Module housing causes a minor relative impact (Figure 4). Overall, the modularity overhead causes about 2.3 % of the total production GWP impact.

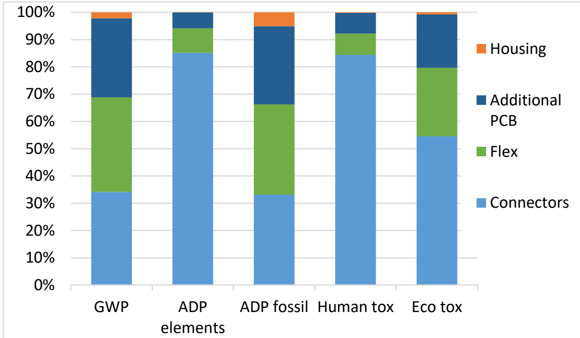

Figure 4: Impacts connected to modularity

4.2 Repair scenarios

The impact of the repair itself is rather small and pays off when it leads to longer use of the phone. The difference between module replacement (scenario A) and module repair (scenario B) is too small to be visible per year of use (Figure 7). The additional benefit of module repair differs significantly between the repaired modules.

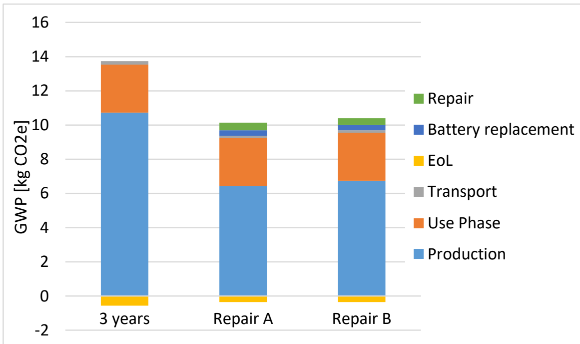

Figure 5: Impact of repair per year of use

Results show that repair in both its forms indeed results in lower associated impacts per year. This is however dependant on several factors, such as the mode of transportation to ship replacement parts, which has been switched recently by Fairphone from air freight to train freight, reducing drastically the overhead it imposed on repair.

5 Interpretation and discussion

The absolute impact of 39.5 kg CO_2e, as well as the distribution across life cycle stages, are comparable

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with other smartphone LCAs, which differ in detail but have several similarities as shown by [12].

5.1 Display

The FP3 display was – similar to the FP2 display – modelled based on AUO environmental data as no data set was available in GaBi. The 2018 AUO material and energy consumption per produced panel area was lower compared to the year 2016, leading to lower emissions per display area. Although the display size increased from FP2 to FP3, the calculated impact decreased due to new IC data, lowering the impact of the backlight LEDs as well as the display driver IC (one controller chip compared to two for the FP2). The overall impact of the display unit is influenced more by the IC data set than by the display panel.

Compared with other smartphone LCAs, the result for the display is quite low. [13] state a value for 3.6 kg CO_2e for a 74 cm^2 display, a much higher per-area value than the 1.9 kg CO_2e for 81.9 cm^2 FP3 display. [13] state a higher electricity consumption for display manufacturing at about 0.1 kWh/cm^2, compared to 0.008 kWh/cm^2 from AUO [5]. However, the electricity value from AUO does not include the production of upstream materials or display electronics, which is addressed with GaBi data sets.

5.2 Integrated circuits

ICs have a very strong impact on the overall result, however, up-to-date life cycle data is scarce and technology advances fast. Therefore, the results for ICs are associated with higher uncertainties than other aspects of the phone.

All ICs are modelled based on silicon die data, although at least one chip (WiFi) in the FP3 contains a die based on gallium-arsenide. However, no life cycle data is available for this semiconductor material.

Production process impacts of ICs are more strongly linked to die area than to the weight of the dies or chip packages. External data sources were used as described in section 3.1.2, as GaBi data on ICs can only be scaled per piece of packaged chip, which does not contain detailed information on the die size. However, the die-to-package ratio can vary significantly. Ecoinvent data on the other hand is scaled per weight, which is not deemed a reliable factor, particularly as stacked dies are thinned, leading to lower silicon mass but increased production impact.

The impact of 3.4 kg CO_2e/cm^2 for logic chips and 2.5 for DRAM and flash memory used in the study are within the range of 2.2 to 4.3 kg CO_2e/cm^2 as used by [1] and [13] according to [12]. The absolute results for the ICs of the Fairphone 3, as well as the resulting share, are within the range reported by [12] for other smartphone LCAs. The relative impact of the RAM/flash package are quite high, which is caused by the very large die area identified in the IC analysis (x-ray and grinding of the package).

5.3 Final assembly

Final assembly causes an impact of 1.7 kg CO_2e per device or a share of 5.5 % of the GWP impact. This is caused mainly by the electricity consumption of 2.2 kWh per phone. There is not much data on energy consumption of assembly processes of smartphones available in literature, however, the number is considerably lower than for the FP2, for which the manufacturer stated an electricity consumption of 4.7 kWh per phone.

Huawei publishes carbon footprints for their smartphones [14]. The short reports do not state the energy consumption of the final assembly, but the corresponding GWP impact. They range between 2.1 and 3.2 kg CO_2e per Huawei smartphone, thereby being a little higher, but in the same range as the Fairphone assembly.

5.4 Phone and module repair scenario

The results for the repair scenarios A and B showed little difference between simple module replacement and module repair. This is due to the assumed share of repairs, with more than 63 % being display repairs, where the display modules themselves cannot be repaired, but only replaced as a unit. For the repairable modules, the variations between scenario A and B differ, as is shown in Figure 6. The absolute benefit of module repair is significant for the repair of the mainboard, which also causes the major share of the initial production impact. Keeping as many of the ICs in use as possible is therefore beneficial from an environmental perspective. For the camera module, the repair of the module only leads to a very small impact reduction, as the submodule with the highest environmental impact (the camera itself, including the CMOS sensor) needs to be replaced in the process.

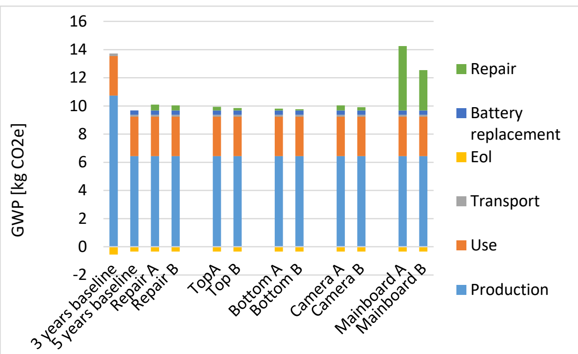

Figure 6: Variation of different repairs – per year of use compared to baseline scenarios

Looking at the entire life cycle and the pay-off of smartphone repair, the results show that the environmental impact strongly depends on the module that is being replaced. As shown in Figure 7, repair leads to reduced emissions per year of use for all parts except the mainboard. As the mainboard causes the major share of the absolute impact, replacing it to extend the time of active use by two years is not beneficial. However, if on-board repair is carried out, it becomes beneficial – even under the assumption that only 37 % of the modules can be re-used, based on the assumed return and repair rates (compare section 3.5).

5.5 Modularity

The "impact of modularity" is described in section 4.1 to allow for a comparison with the FP2 modularity overhead, quantifying the effect of the new connectors in the FP3.

One of the main design changes from the Fairphone 2 to the Fairphone 3 were the connectors, which substituted the larger pogo pin connectors to smaller press-fit connectors, using flex-cables to connect the mainboard with the module boards.

As can be seen in Figure 7, a noticeable reduction has been achieved through this change in design. The main reason for this is the reduced amount of gold in the new connectors and reduced rigid PCB area due to their considerably smaller size. The flex cables required for the new connectors add to the impact, but the overall result is still net positive.

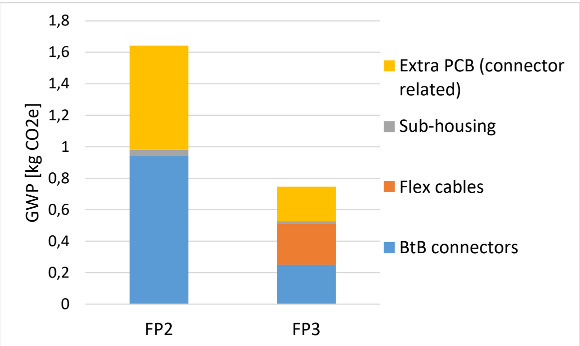

Figure 7: "Modularity overhead" of FP2 and FP3

It should be noted that assignin these connectors solely to the feature "modularity" is not entirely correct, as it neglects the fact that conventional smartphones also have more and more connectors on the mainboard, including attached flex cables to connect sub-parts and sub-boards (see [15]). Therefore, the real hardware differences to achieve modularity is lower than the impact shown there. The only parts really differing from conventional smartphones are the display connector, which, however was also reduced in size compared to the FP2 equivalents, as well as the module housing parts, which do not have any significant impact on the overall phone.

It can be discussed whether the modular design leads to higher PCB area besides the connectors. The individual module boards do not exist in many other smartphone designs. The impact of the module boards combined make up one third of the mainboard PCB, due to lower PCB area and fewer PCB layers.

The PCB areas differ across smartphone designs and the total FP3 PCB area is within the range of conventional smartphone designs. The PCB area depends strongly on the shape of the PCB: L- and especially U-shaped PCBs lead to more produced PCB area compared to rectangular PCBs. PCB layout placing on the production panel by the PCB manufacturer also has an impact.

6 Conclusions

As has been shown by previous LCA studies of smartphones, the manufacturing phase, and therein the manufacturing of PCB assemblies, and therein the manufacturing of integrated circuits, is associated with the largest share of environmental impacts. From an eco-design perspective, this is a difficult issue to tackle, as the ICs are integral to the functionality of any modern electronics. Possible points of attack are the amount of RAM and flash memory included in the phone – this, however, may present designers with a delicate balancing act between functionality and environmental concern. "Over-engineering", such as integrating more flash memory than needed by most users, may result in larger-than-necessary environmental burden, while "under-engineering", on the contrary, may lead to a system that becomes obsolete prematurely, as it cannot satisfy customer needs in terms of performance (e.g. in case of too little RAM or storage space). Future 5G connectivity and associated cloud services may present additional questions around the environmental impacts of local file storage versus cloud-based solutions.

Changing the connector design from the large pogo pin type employed in the FP2 to more common press-fit sockets has resulted in net benefits in ecological terms. The "modularity overhead" has thereby been notably reduced. Whether this type of connector will be able to withstand repeated repair processes throughout the lifetime of the phone was not yet known to the authors at the time of writing.

Another change, the switch from air transport to freight trains to the distribution hub has had a considerable reduction in impact in both the "standard scenario" life cycle impact of the device, as well as in the footprint of repairs, in which a module is replaced, where air transport was the main driver.

Similarly to the Fairphone 2, the modularity of the FP3 provides the user with the choice to extend its lifetime through a highly reparable design. Whether environmental benefits associated with lifetime extension are realized therefore ultimately depends on the user.

In conclusion it can be stated that the consistent application of life cycle assessment to subsequent iterations of the Fairphone has over time facilitated data-based optimization decisions in its life cycle design, thereby supporting eco-innovations in the area of modular electronics. Accompanying changes in user behaviour enabled by such innovations will need to be observed and possibly addressed in further work to be done.

7 Acknowledgments

Fraunhofer IZM conducted the full LCA of the Fairphone 3 in 2020, as well as the LCA of the Fairphone 2 in 2016, on behalf of Fairphone B.V..

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The smartphone evolution - an analysis of the design evolution and environmental impact of smartphones

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Abstract

The smartphone industry has always been characterized by rapid technical change and new product proliferation. Although the smartphone has a relatively small environmental footprint compared to other IT products, it has one of the shortest use cycles and at the same time the widest dissemination of any electronic product, making it a product of high environmental concern. In this paper we will provide a market based analysis on smartphone designs for a period from 2000 to mid-2019 showing that smartphones changed towards "bigger and better" (bigger displays and batteries, more storage, memory, cameras, faster and better processors, cameras and sensors), with only little variability between models, brands and market segments. Thereby, this product development is mirrored with changing environmental data (e.g. maturing technology, more efficient production) showing how the absolute environmental impact changed.

1 Introduction

The smartphone industry has always been characterized by rapid technical change and new product proliferation. Although the smartphone has a relatively small environmental footprint compared to other IT products, it has one of the shortest usage cycles and at the same time the widest dissemination of any electronic product, making it a product of high environmental concern. The dynamic nature of the smartphone market and the persistent short useful lives of smartphones increasing the necessity for the evolution towards a more sustainable design. In this paper we will provide a market based analysis on smartphone designs for a period from 2000 to mid-2019 and address three questions: (1) How (fast) did technology features change regarding smartphone, (2) when do "flagship features" reach the centre of the market, (3) how does this correspond with changing environmental data (e.g. maturing technology, more efficient production)?

Research on the design evolution of cell- and smartphones dates back to the early 2000s and has always been driven by the question of dominant design strategies, but environmental issues are often missing. For the analyses we gather market data of smartphones with an internet-based data mining approach where we combine different internet sources. We will show that the market will reach a peak in product proliferation by 2014, followed by a steady decline in annual new product releases, indicating a transition to a mature industry. Despite this, various surveys indicate that the smartphone market continues to be characterized by short market cycles (e.g. time in markets, release cycles) and persistently short usage cycles (section 2). This will be compared and combined with life cycle data on smartphones as a whole and on individual features (section 3).

2 Technological evolution of the smartphone

This section gives a brief outline on the historical development of mobile communication, particularly concentrating on the design developments.

2.1 The evolution of a new technology (1861 - 1990)

The first telephone and much later its mobile version were not an instant success. "Alexander Graham Bell was so convinced his pioneering telephone would be such an unwanted intrusion that he initially promoted his invention in the 1880s at expositions and fairs as an entertainment system that conveyed music and theatrical performances over headphones to those who couldn't afford to buy tickets to the real thing" [21]. The example shows an inherent characteristic observable in all emerging technological fields: products do not appear out of the blue and always evolve in the interplay between innovators (producer) and lead users. While the "knowing-how" creates the basis for certain technologies, the "knowing-what" is about the successful identification and testing of possible operational domains [7].

The restraint towards the telephone and its application proved only temporary and spread quickly throughout

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the business world. Once the proof of usefulness was given and due to new successes in radio transmissions, soon first ideas of mobile phones emerged. In his essay „Das drahtlose Jahrzehnt" [The Wireless Century] from 1910, Robert Stoss anticipates some features of a modern smartphone as "Citizens of the wireless age will walk around everywhere with their "receiver" placed somewhere in the hat or elsewhere"[29]. Stoss even goes beyond simple communication as he predicted the "gesprochene Zeitung" [spoken newspaper], "Telharmonie" [Multimedia Streaming] and envisioned a kind of mobile online shopping [29].

The prognosis of Stoss was surprisingly close to reality, but there was still a long way to go: At the beginning and increasingly from the middle of the 19th century onwards the first mobile car telephones were developed by Ericsson and others. The first-generation devices still had to connect to the local network, thus making it impossible to make phone calls while driving. Later in 1920, large two-way car radios came on the market. An improved version for the mass market was introduced by Galvin in 1931. "Galvin linked ''motion'' and ''radio'' and gave the radio the trade name Motorola" [12]. Second World War revealed smaller backpack mounted devices that were nicknamed "walki talki" [18]. Over time, radio technology further advanced but could not overcome its main limitation for a broader commercial use: „each radio would have to work on a separate frequency from its neighbours, otherwise calls would be interfered with, confused, or worse, eavesdropped" [1].

In 1973, Motorola revealed its game changing portable telephone, the shoe-sized and 800 grams heavy DynaTac. However, not until 1983 a commercial version came available in the market. Yet the actual system level innovation took place in the background. To allow several devices to communicate without interfering with each other in a network, larger cells were divided into smaller cells. To enable mobile conversation, a massive fixed infrastructure of wires, transmitters and receivers had to be in place [1]. Thus, the set-up of the first commercial cellular radio systems (1G) took several years to evolve and was first introduced 1979 in Japan and 1983 in the United States [12]. Until today, the principle of cellular radio is the most effective version of mobile radio and is still the principle for all network generations that have followed so far.

2.2 Optimization and consumerization (1991 – 1995)

Despite the launch of early cellphone networks form 1979 upwards [12], the commercialization for mobile communication was still on hold. The first-generation networks (1G) were based on analog signal transmission and therefore limited in the capacity of network participants and bandwidth. Each country had its own specification that were often incompatible with each other. This changed slowly with the introduction of the first full-digital networks (2G) and especially the GSM network (Global System for Mobile Communications) in Europe in the early 1990s [15]. The GSM and its technical specifications were a result of a pan-European collaboration in standardization [30]. In hindsight, GSM was a great commercial success, but initially network vendors registered low subscriptions of less than 5% of the total population in Europe [15]. It was not until 2002 that the number of mobile subscribers overtook the number of fixed-line subscribers on a global scale [28]. Nevertheless, it was the standardization efforts for a shared network that led to further consumerization and market growth, as manufacturers could now produce for a global scale rather than for niche markets.

The first GSM approved phone was brought to the market by Orbitel in 1991, had a weight of 2 kg and was more a bulky transportable phone than a mobile. Motorola and Nokia followed little later with much smaller, cost-efficient consumer handsets [7]. In general, in the first half of the mid-1990s manufacturers where characterized by technical improvements and constraints: "The design choices were governed by the tradeoffs between production costs, size and weight, and battery run-time" [17].

2.3 Segmentation and product differentiation (1996 – 2007)

In the early market phase, manufacturers focused on vertical innovation, e.g. by increasingly integrating components along the supply chain, improving quality and upscaling production to reduce costs. Throughout the 1990s there was a clear convergence towards light, compact mobile phones with improved technical performance, "a trend towards vertical product homogenization" [17].

The pioneering advantage of early innovators diminished over time as demand grew and others were attracted to the market. Started as niche manufacturers, brands such as Nokia, Ericsson and Motorola quickly became global players and where accompanied by other large electronic equipment manufacturers such as Mitsubishi, Samsung and Siemens. The increasing competition forced manufacturers and brands to differentiate their products. How to attract new or existing customers to new products? There are various examples that can be illustrated:

- Gamification: The Nokia 6110 (1997) got a pre-installed game called "Snake".

- Individual customization: The Nokia 5110 (1998) offered the possibility to change the appearance individually with exchangeable covers.
- Improved interface: Siemens S10 (1998) had the first color screen
- Changing form factor: Nokia 3210 (1999) had a fully internal antenna.
- Add hardware features: The Kyocera Visual Phone VP-210 (1999) was the first commercial mobile with an integrated digital camera.
- Internet: The Nokia 7110 (1999) was the first mobile with wireless application protocol to browse the Internet
- Customer segmentation: The Samsung Lady Phone (2004) had a mirror and menstruation calendar

The product differentiation phase created a variety of new designs, form factors (e.g. flip phones, sliders, clamshell) and dozens of new features that extend the core function of a simple telephone [7]. Such devices are also called „feature phones", although the term was not so common back then.

In tandem with the development of feature phones, there was another decisive development and important prerequisite for the development of smartphone. Thanks to further advances in microelectronics, a completely new generation of devices was introduced at the beginning of the 1990s with the Personal Digital Assistants (PDA). PDA or handhelds were portable devices and downsized pocket Personal Computer's (PC) [31]. They combine a number of features for Personal Information Management (PIM) such as calendars, notes, phone book and wireless data transmission (email, Internet).

Regarding the parallel development of mobile phones and PDA's it seems naturally that both products began to converge. Already in 1997, Ericsson came up with a prototype for a new device it named „Smart Phone" (Ericsson GS 88). In contrast to a feature phone with its bundle of integrated and unchangeable special-purpose features, a smartphone is a multipurpose device with: „ (…) the ability to run software programs, later called 'apps,' that enabled them to perform tasks that had not been envisaged when the phone was manufactured" [19]. The development of smartphones as universal computers was already in use before Apple released the iPhone in 2007 and even anticipated by some experts [31].

Although technological development progressed steadily until 2000, manufacturers were faced with bandwidth limitations, limiting the operating range to simple applications with low data usage. RIM had great success with the introduction of its two-way pager the BlackBerry 850 in 1999, which supported email – but was lacking other features when there were already other product with more features in the market: „Early wireless inventors failed because they crammed multiple office tools into book-sized devices. The product were battery and bandwidth hogs and a headache to operate [21]". The example illustrates the importance of convenience and ease of use when it comes to product design. Looking back, one would think that the devices were easy to use in the past, but in many cases, they were not. However, manufacturers often violate this rule by increasingly integrating features that are not fully mature and are often only a response to the competition (also known as „featuritis") [22].

At the beginning of the 21st century, product designs began to proliferate in all directions, colours, sizes, features, different user interfaces and navigation concepts. From a theoretical point of view, experimenting with different designs and configurations is a necessary part of any product evolution, which often end in a dominant design: "After that selection takes place as an interactive process by different forces (buying behaviours of consumers, competing manufacturers, legislation, etc.), leading to the survival of the best-adapted product variants, of which the most prolific are also referred to as dominant design. Then retention of know-what (product characteristics, items) and know-how (manufacturing technology) is achieved as best-adapted variants are reproduced" [7].

2.4 Dominance of the multi-purpose Smartphone (2007-2019)

The introduction of the iPhone by Apple in 2007 marked a turning point for the smartphone industry. „Even it was not the first model of smartphone in the market, it soon became a point of reference for all producers in the coming years in terms of design and user interface" [6]. The iPhone had an integrated Operating System (OS), a web browser and the iTunes Store for downloading audio and video. It had a touch screen (instead of a keyboard) with a software-based keyboard. One year later, the iPhone 3G was launched, along with a virtual marketplace (Appstore) for downloading additional software applications.

According to Giachetty, Apple was able to redefine the market boundaries in two ways: „First, it was able to look across substitute industries: the smartphone industry, the portable music industry, and the Internet communication device industry – three product categories that shared similar functionalities. Apple was the first handset vendor to perfectly integrate the core functions of these three product categories into a single device. Second, Apple looked across complementary product and service offerings by relying on a platform mounted on its other devices that brought together a broad ecosystem of app developers for its iPhone" [9]. Instead of inventing completely new technologies, Apple has consistently converged what was already there or in other words: „Smartphones were not invented by Apple, but they were defined by Apple" [1]. However, this development was not detached from external political circumstances.

Apple used an advantage that no other manufacturer had ever had before and that was leading to another system level innovation. Although mobile data could previously be used over networks, and in particular with the introduction of 3G in 2003, its capacity was rather limited. For this reason, the network operators have specific requirements for the manufacturers regarding the amount of data that may be moved in the network at all. Network operators used to make money from phone calls and SMS, so how should one make money from email and internet videos? For a long time, carriers not only run their networks, but also sold handsets and content. In order to use their networks effective and gain profits, carriers set up technical requirements which OEMs implemented accordingly. Apple was the exception, as it made a unique deal with the U.S. carrier AT&T to design its iPhone the way it wanted without intervention [14], [9]. In return, Apple gave the carrier a share of the profits and agreed to an exclusive partnership. The iPhone was designed for multimedia applications and thus strained the networks of AT&T and its battery, which lasted less than eight hours. Apple changed the mobile game: Bandwidth conservation and battery lifetime was long time the priority of the mobile industry – now the new battleground was mobile computing [21]. Because of the popularity of the iPhone other carrier also wanted to have comparable smartphones for their customers and the old principles of bandwidth conservation were abandoned. By this, Apple not only introduced a dominant design, but also changed the paradigms in the market.

After initial hesitation, major manufacturers later followed and adapted their smartphone designs: Physical keyboards gradually disappeared, form factors became uniform and all manufacturers relied on flexible operating systems that could be extended with third-party apps. Google released Android, an OS that can be used free of charge on devices by other manufacturers and is still one of the most widely used systems.

The historical development of mobile phones shows that performance densities and integration of parts and features have intensified enormously within the market. Moreover, novel use patterns have been 'integrated' into mobile phones (e.g. clocks and diaries). Over time, phases of dominant designs seem to be followed by product differentiations in order to gain market advantage. For most devices, not even the battery can easily be swapped. Displays, which are often damaged when dropped, are also not easy to repair. The architectural innovation of the smartphone (as a converged system of different technologies) was accompanied by an increasing integration of single components that are glued to the phone.

3 Feature development in context of environmental impact

As shown by the historical analysis, the outer design as well as the feature spectrum of mobile phones changed, but aligned towards "bigger and better" since the development of the first iPhone in 2007: bigger displays and batteries, more cameras and sensors, more storage and memory capacity, but (at least until the foldable displays in 2019) the whole market developing in the same direction.

As several life cycle assessments (LCAs) of smartphones show, the main impact is caused by the electronic components. Printed circuit board PCB and the main ICs processor, memory and storage can cause more than half of the whole manufacturing GHG emissions, followed by battery and display with a significantly lower share (see Figure 1, [8], [23], [27]).

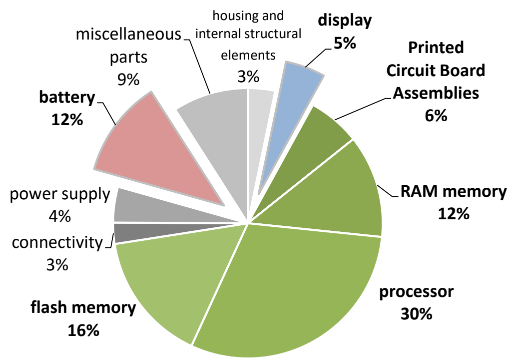

Figure 1: Share of GHG emissions caused by smartphone manufacturing, picture from [27]

In the following, we analyse the feature development in the context of the environmental impact (specifically the GHG emissions). Thereby, LCAs are always one-off assessments based on a data with specific time and technology relevance. To assess the changing environmental impact of feature development also needs to take into account changing manufacturing efficiency or even different manufacturing processes and technology nodes. However, reliable data for the manufacturing of electronics is already scarce and partly out-dated. Changes over time in the manufacturing data can therefore be shown only for a small range of parts.

For the design and feature analysis a data set from the online product database GSMArena was gathered, capturing product specifications for 9,430 smartphones from the year 2000 upwards. The data shows an increase in number of models and manufacturers on the market from late 1990 to 2014, with more than 900 models released from almost 60 manufacturers. Since then, the number of models and manufacturers decreased slightly. The GSMArena data shows that phones became bigger in the last years, containing more display area, bigger batteries, better and more cameras, more storage capacity, and more sensors ([10], detailed analysis of this data is published in [24]).

3.1 Display and form factor

The form factor of the phones changed, the devices became larger, but thinner. At the same time, the weight increased only slightly. The thinnest smartphones are about 5 mm thick, most high-end and middle-class devices are below 1 cm currently. The average display size changed from 2 inches in 2005 for mobile phones and 3.5 inches of the first iPhone in 2007 to about 6 inches in 2019 with screen-to-body ratio increasing from 20% to 80% (Figure 2). Thereby, not only the shift from feature phones to smartphones increased the screen-to-body ratio. The ratio still increases for smartphones, leading to camera notches and fingerprint sensors under the display class. Display resolution increased as well in absolute pixels and pixels per inch (PPI) with currently 360 PPI on average [4] [10].

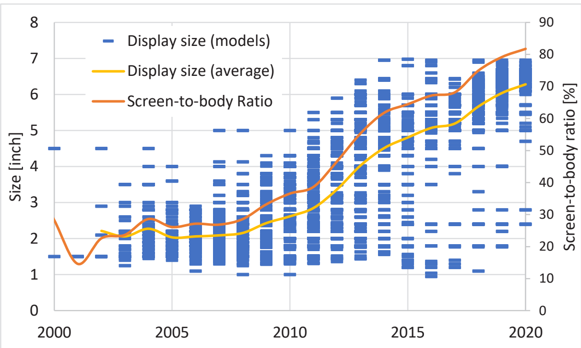

Figure 2: Display size and screen-to-body ratio, based on [10]

Thereby current carbon footprints by Huawei from 2016 to 2019 smartphones show, that although displays do not cause the main share of the overall impact, the total footprints correlates with the display size (see Figure 3).

Figure 3: Carbon footprint of Huawei smartphones and their display size, based on [11]

The impact of the production and the energy consumption in use have likely increased with larger displays over the years. On the other hand, production efficiency increased as well. Environmental reporting from the Taiwanese display manufacturer AUO shows decreasing GHG emissions per produced panel area since 2008 (Figure 4).

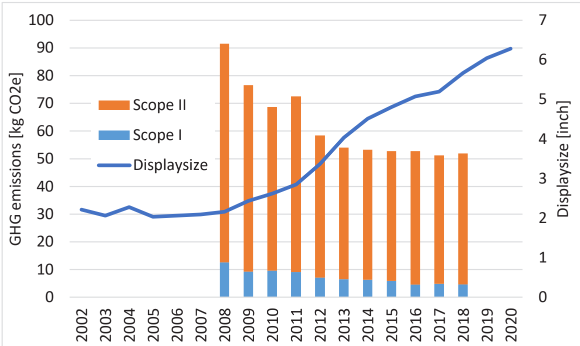

Figure 4: GHG emissions per produced panel area and average display size of smartphones, based on [4], [10]

This shows that GHG impact from display manufacturing decreased significantly between 2008 and 2012, and stabilized on the same level since then. Use of chemicals stayed more or less stable, with the limitation that with more processes being covered in the detailed accounting by the manufacturer, the higher the numbers became. This led to several recalculations for past years [4].

Besides growing display size, there are also different display technologies in use: LCD and (AM)OLED displays, with the latter growing in numbers over the last year. From environmental perspective, the production impact of both technologies is similar according to [2] with OLEDs having a slightly lower impact by 8%.

3.2 Battery technology

The environmental impact from battery manufacturing depends on the weight and capacity of the battery. Average battery capacity increased from ~700 mAh in 2000 to ~3,700 mAh in 2019. In the same time, a technology shift from nickel-metal hydride (NiMH) over lithium-ion (Li-Ion) to lithium-polymer (Li-Polymer) batteries took place. NiMH batteries were phased-out, Li-Ion and Li-Polymer batteries are still used in the marked with a stronger shift towards Li-Polymer. According to an LCA by [13], this trend towards Li-Polymer is favourable from environmental impact as the Li-Polymer batteries have a lower production impact per capacity. No LCA data on production efficiency over time is available.

3.3 Storage and memory

The storage capacity of the smartphone has a strong impact on the total GHG emissions of the phone. Data on iPhones shows the difference between the lowest and highest storage configuration does have an impact between 10 and 30% of the total phone (see Figure 5) and are on average between 70 and 80 g CO2e/GB [3].

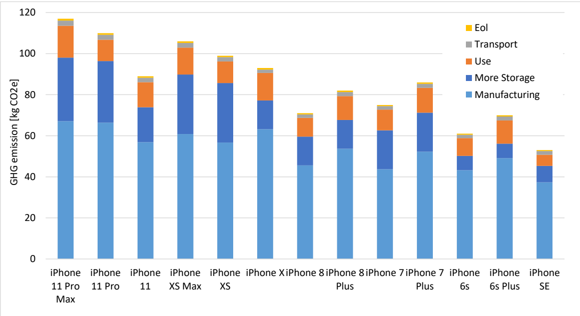

Figure 5: GHG emissions of iPhones, based on [3]

As shown in Figure 6 and Figure 7, the GHG emissions per GB dropped significantly over the last years due to technology improvements. Older data from Boyd also showed that, the impact per die area increased, but needed die area per GB decreased, leading overall to an improvement of the impact [5]. The absolute number shown in Figure 6 and Figure 7 are however significantly lower than presented by other sources such as Boyd [5] or indirectly by Apple [3].

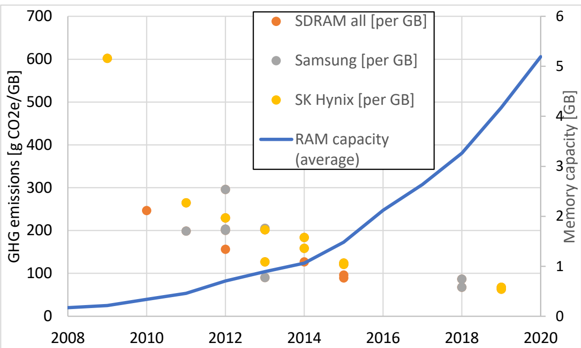

Figure 6: GHG emissions per GB storage capacity of DRAM chips and average memory capacity of smartphones, based on [16], [10]

From the first iPhone in 2007 and today's average according to data by GSMArena, there was an increase in storage capacity by factor ~20. Based on the shown improvement of GHG emissions data, this would only result in an increase by factor ~3. Similar for RAM, which increased from 128 MB to 4 GB, the GHG emissions increased by factor ~7.

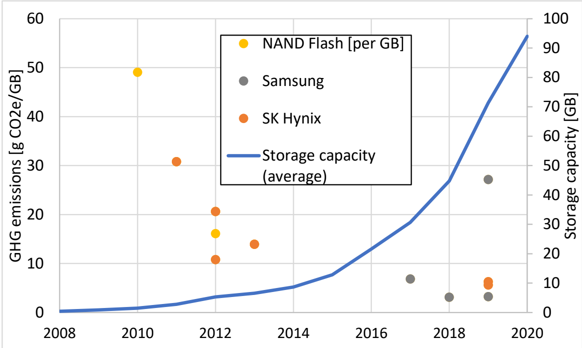

Figure 7: GHG emission per GB storage capacity of Flash chips and average storage capacity of smartphone, based on [16], [10]

3.4 Feature spectrum

Besides the performance level of the integrated features, the feature spectrum increased as well. The first iPhone had one rear camera, the current iPhone 11 Pro has one front and three rear cameras, each of them coming with an individual CMOS sensor.

The average number of sensors increased, fingerprint sensor, face recognition and NFC are more and more common in today's phone as shown in Figure 8. All of these features need additional control chips.

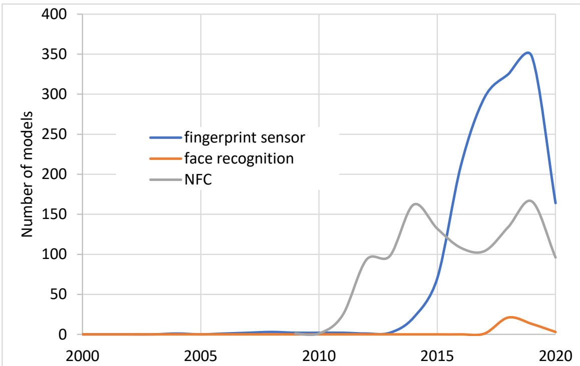

Figure 8: Availability of smartphone models with fingerprint sensor, face recognition and NFC, based on [10]

Aspects such as PCB area and number of layers stayed more or less the same across several generations according to [20], but the density, in which electronic components are placed on the board, increased as the total number of ICs increased with the growing feature spectrum.

Housing material changed from plastic frames and back covers to metal frames with aluminum and glass back covers. With the growing number of devices with wireless charging capabilities, glass and plastic back covers increase at the expanse of aluminum back covers which are not suitable for that feature. According to [26], the wireless charging feature comes with an impact 0.25 kg CO_2e within the phone and lower charging efficiency which would reduce in higher use phase emissions. Additionally, the different housing materials also leads to differences in the environmental impact as glass and metal have a higher GWP and higher weight for the same size of phones. However, the overall impact on the smartphones GWP is small as shown in Figure 1.

3.5 Impact of an "average" smartphone

Based on the before described feature development, the "average" smartphone for 2008 and 2019 could be defined as shown in Table 1: display size, battery capacity, storage and memory capacity increased, housing material changed from plastic to glass.

Features	2008	2019
RAM [GB]	0.128	4
Flash [GB]	4	70
Battery capacity [mAh]	700	3,700
Battery type	Lithium-Ion	Lithium-Polymer
Display size	3	6.2
Housing material	plastic	glass
Cameras	1 rear	1 front, 3 rear
Wireless charging	no	yes

Table 1: Features of the "average" smartphone 2008 and 2019

For an estimation of the environmental impact this functional development is connected with evolving environmental data as shown in section 3.1 to 3.3. For other aspects similar environmental data is used, neglecting the fact that several features like additional fingerprint sensor, more network capabilities come with additional ICs. The basic numbers are extrapolated from a smartphone LCA according to [25]. This estimation of life cycle impact leads to an increase of GWP by roughly one third as seen in Figure 9.

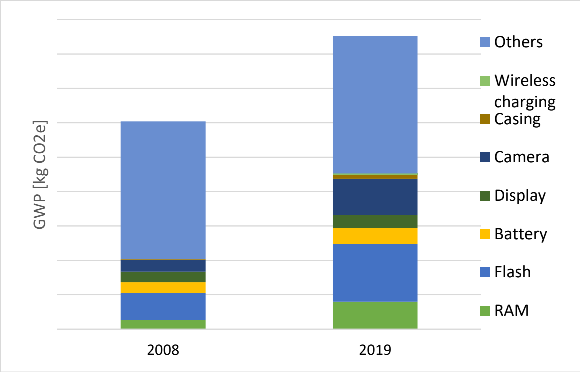

Figure 9: GHG emissions of the "average" phone 2008 and 2019

4 Summary and conclusion

The analysis showed that "the smartphone" is currently connected to a very specific look and feature spectrum with only little variation. Functional performance has significantly increased with technology evolution on several levels, which was often connected with efficiency gains in production. Where environmental data is available not as an on-off data point, but as timeline, we showed that the environmental impact decreased per functional parameter (e.g. per display area or per GB storage) and also technology changes can be connected to more efficient production (as shown for the change of battery technology). However, these efficiency gains cannot outweigh the rapid functional increase, leading overall not to a decrease of environmental impact.

Currently, with foldable displays coming to the market, it remains to be seen how that will impact the relevant form factors of the smartphone market, the environmental impact of display manufacturing as well as the lifetime of the products.

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Understanding Asian consumer acceptance toward a refurbished smartphone

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Abstract

Refurbishment is a circular strategy where the goal is to transform the end-of-use product into a product to the original specification via cleaning, replacing, and/or repairing major components that have a defect. Refurbishment is of interest to academia and firms as a cost-effective and environmentally advantageous strategy, but an Asian consumer perspective on refurbished products has received far less attention. This article aims at breaking down Asian respondents' intentions and related perceptions for purchasing a refurbished smartphone. We examine the effect of underlying factors, such as perceived risk, price consciousness, environmental consciousness, and innovativeness on the behavioural intentions of consumers towards a refurbished smartphone. Our results also represent that not surprisingly, Asian consumers prefer to buy new (latest expensive, low priced, or durable) smartphones rather than refurbished ones provided by either OEM or third-party. The findings can yield insights for business managers seeking to promote the refurbishment business in Asian countries.

1 Introduction

The circular economy is an issue of interest in academia and industry, an attractive idea in response to the waste and resource consumption problems. Refurbishment is a circular strategy where the goal is to transform the end-of-use product into a product to the original specification via cleaning, replacing, and/or repairing major components that have a defect [1]. By giving a product its second life, refurbishment leads us to save significant raw materials and energy [2]. It can also be a commercially viable strategy for companies [3].

Examples of refurbished consumer products are refurbished mobile phones, laptops, tablets, etc. Due to its characteristics that they are replaced and thrown away often while being kept with residual values, smartphones represent the opportunities for refurbishment. Indeed, many firms including original equipment manufacturers (OEMs) and electronic distributors are interested in refurbished smartphones.

In Asian economies, closed-loop production patterns have been shaped with regulatory initiatives. For instance, Japan enacted the basic law for a sound material-cycle society in 2000 and the Act on Promotion of Recycling of Small Waste Electrical and Electronic Equipment in 2013. The Resource Sustainability Act (2019) in Singapore and the Korean's Extended Producer Responsibility (EPR) system (2003) and the basic law on resource circulation (2018) can be understood in the same vein. Under the current CE-driven pressure, companies are facing challenges in understanding and enhancing their consumers' acceptance of second-life products including refurbished products. However, a consumer or market perspective on refurbished products in Asia has received far less attention.

This article aims at breaking down Asian, more specifically, Japanese, Singaporean, and Indonesian respondents' intentions and related perceptions for purchasing a refurbished smartphone. Besides two different refurbished smartphone options, we suggested three more options for buying a new smartphone and asked consumers' responses to each option. The options are i) the latest expensive new smartphone, ii) low-price new smartphone, iii) durable new smartphone, iv) refurbished smartphone provided by the OEM, v) refurbished smartphone provided by the third party. This study also focused on underlying factors addressed previously in the extant literature such as the perceived risk of a refurbished smartphone and an individual's price consciousness, environmental consciousness, and innovativeness so that explain consumers' decision to purchase each smartphone option in three Asian countries. The findings can yield insights for business managers seeking to promote the refurbishment business in Asian countries.

2 Method

2.1 Conceptual model structure of smartphone purchasing intention

An attempt was made to frame a conceptual model that relates to respondents' buying intention of a refurbished smartphone to underlying factors using pictorial representation (see Figure 1).

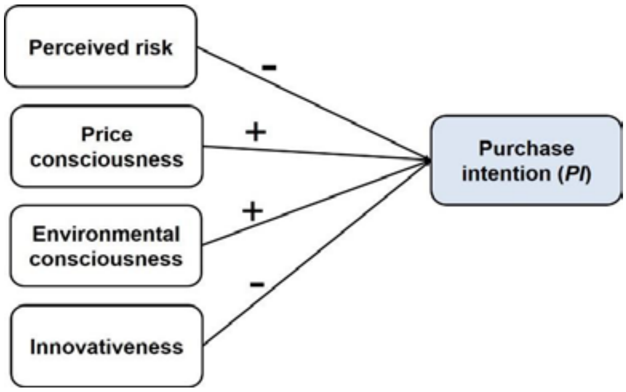

Figure 1: Hypothesized model

This conceptual model indicates the hypothesized model of examining how perceived risk, price consciousness, environmental consciousness, and innovativeness affect Asian consumer's intention to purchase a refurbished smartphone. We set the hypotheses as follows:

H1. Perceived risk of a refurbished smartphone negatively influences the purchase intention of a refurbished smartphone.

H2. Price consciousness positively influences the purchase intention of a refurbished smartphone.

H3. Environmental consciousness positively influences the purchase intention of a refurbished smartphone.

H4. Innovativeness negatively influences the purchase intention of a refurbished smartphone.

2.2 Survey design

Online surveys were conducted with 600 respondents for each country of Japan, Singapore, and Indonesia in November 2019. Each survey was controlled to obtain randomly stratified samples by age and gender (7 segments from 15 years old), providing better coverage of the population. All respondents also own one mobile phone at least. In the surveys, respondents were asked to suppose that they have had five options to buy a smartphone when replacing their current mobile phones. Toward each option, questions to ask their purchase/recommendation intentions were posed on a 7-point Likert scale with verbally defined endpoints (strongly disagree – strongly agree). The options were described as follows: (i) latest model smartphone of a famous manufacturer with expensive price but equipped with the latest features and services; (ii) low price new smartphone with simple functions; (iii) durable type smartphone which is hard to break and designed for longer usage with good repair service; (iv) OEM's refurbished smartphone which consists of a user device with the battery, outer casing, and main components re-placed by new ones; (v) refurbished smartphone provided by the third-party manufacturer. Respondents were finally asked 18 questions about their attitudes or perceptions toward four underlying factors; the perceived risk of a refurbished smartphone and an individual's price consciousness, environmental consciousness, and innovativeness.

2.3 Statistical analysis model

This study used ordinary least squares estimation (OLS) for a statistical method as shown as

$$PI_i = \alpha + C_i\beta + X_i\gamma + e_i.$$

where PI_i is purchasing intention index of a respondent i, C_i is the vector of perceptions (the underlying factors in this study) related to the purchase of a refurbished smartphone, X_i is the vector of respondent i's personal characteristics (i.e., demographic attributes) adopted as control variables, and e_i is the error term. Calculations and estimations were performed using IBM SPSS Statistics version 26, a software package for econometrics and statistics.

3 Consumers' intentions and perceptions related to smartphone purchasing behaviour

3.1 Purchase intentions toward a smartphone

Our surveys consist of two questions on purchase intention toward each smartphone option: "If I need to buy a smartphone, I am willing to buy the [latest/low-priced/durable/OEM's/third-party's] smartphone" and "If my relatives and friends need to buy a smartphone,

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I will encourage them to buy the [latest/low-priced/durable/OEM's/third-party's] smartphone."

Looking at their responses to those questions for five different smartphone options, Asian consumers in Japan (JP), Singapore (SGP), and Indonesia (IDN) are more inclined to purchase new smartphones than refurbished smartphones. This is the same when they need to recommend it for family or friends. Table 1 represents the priority in purchasing intention of consumers for each country based on the median value of the response to each question toward five different smartphones.

	Priority
JP	Durable>>Low-priced>Latest> OEM's refurbished>Third-party's refurbished
SGP	Durable>Latest>Low-priced>OEM's refurbished>Third-party's refurbished
IDN	Durable>Latest>>Low-priced>OEM's refurbished>>Third-party's refurbished

Table 1: Purchasing priority in smartphones

As shown in Table 1, Asian consumers in all three countries express strong agreement with purchasing a durable new smartphone. This suggests that even though they still prefer a new smartphone than a refurbished one, Asian consumers, more specifically Japanese consumers may value the durability, long life span, and reparability more than the latest features or high-end image for a smartphone. Toward refurbished options, all Asian consumers are less likely to choose the third-party's refurbished smartphone.

3.2 Perceptions related to purchasing behaviour

Respondents' perceptions are measured by their responses to 18 questions that might affect purchasing intention of a refurbished smartphone. The 18 questions cover four constructs: risk of a refurbished smartphone, price consciousness, environmental consciousness, and innovativeness. These constructs were taken from the existing literature [4-7] and partially adapted.

3.2.1 Perceived risk of a refurbished smartphone

Four statements were asked to respondents for understanding their perceptions related to the perceived risk of a refurbished smartphone. A statement was: "I don't think the quality of the refurbished smartphone is as good as newly manufactured one". Our descriptive analysis found that consumers in Singapore and Indonesia were more afraid of the risk aspect of refurbished smartphones compared to Japanese consumers.

3.2.2 Price consciousness

If people are more sensitive about the price as a factor in purchasing, they are more likely to consider a refurbished smartphone as alternatives in the decision-making process [8]. To measure the price consciousness of consumers, we asked four statements. One of the statements was: "The time it takes to find low prices is usually worth the effort". More than 50% of consumers in Singapore and Indonesia showed positive responses to the statements, representing their price consciousness. On the other hand, Japanese respondents less agreed with the statements and this revealed that they are less sensitive to the price at least than Indonesian and Singaporean respondents.

3.2.3 Environmental consciousness

To capture consumers' environmental consciousness in each country, five statements were provided. A statement was: "I prefer to use environmentally friendly products". The descriptive statistics suggest that Indonesian respondents are most environmentally conscious, followed by Indonesian, and Japanese consumers.

3.2.4 Innovativeness

Consumer innovativeness may refer to his/her desire to use the latest technology or a new product earlier than others [9], which can be a barrier for adoption toward refurbished products [10]. The construct of innovativeness includes the five statements. One of the statements was: "Using latest type products makes me feel proud and comfortable". Based on the responses to the five statements, we found that Indonesian consumers would prefer to adopt the latest technology/product earlier. Japanese consumers were least likely to be sensitive to the latest and technologically innovative products.

4 Purchasing intention model of a refurbished smartphone

4.1 Estimation results

Table 2 presents the estimation results of the regression model relating the purchasing intention of a refurbished smartphone to the underlying factors: perceived risk (PR), perception of price (PC), environmental consciousness (EC), and innovativeness (IN) and age attribute.

	Country	OEM's refurbished	Third party's refurbished
	JP	$-.079^{**}$	$-.081^{**}$
PR	SGP	$-.191^{***}$	$-.244^{***}$
	IDN	$-.255^{***}$	$-.260^{***}$
	JP	$.190^{***}$	$.166^{***}$
PC	SGP	$.177^{***}$	$.124^{***}$
	IDN	$.146^{***}$	$.176^{***}$

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	JP	.255***	.172***
EC	SGP	.215***	.025
	IDN	.162***	-.017
	JP	.342***	.384***
IN	SGP	.172***	.146***
	IDN	.252***	.185***
	JP	-.038	-.090**
Age	SGP	-.098**	-.093**
	IDN	-.072*	.039

* p < .1, ** p < .05, *** p < .01

Table 2: Results of regression analysis: purchasing intention of a refurbished smartphone

4.1.1 Japan

The model in Table 2 suggests that perception of price and environmental consciousness ($p < .01$) has the main positive effect on purchasing intention toward refurbished smartphones provided by either OEM or third-party companies in Japan, supporting Hypotheses 2 and 3. The perceived risk of a refurbished smartphone ($p < .05$) has a negative effect on consumers' purchase intention of refurbished smartphones regardless of the manufacturer. Thus, H1 is supported. Age has a negative effect on the purchase intention of a refurbished smartphone by the third-party manufacturer with a significant level of 5%.

4.1.2 Singapore

The result for Singapore shows that the purchasing intention of refurbished smartphones decreases with age at a significance level of 5%. The effect of the perceived risk of consumers toward a refurbished smartphone and price consciousness on their purchasing intention is statistically significant in Singapore, thus supporting H1 and H2. However, their environmental consciousness positively influences the purchase intention only toward the OEM's refurbished smartphone.

4.1.3 Indonesia

The regression result for Indonesia represents that Indonesian consumers with high price consciousness are more likely to purchase a refurbished smartphone. If they have a higher perception of the risk toward a refurbished smartphone, they inclined to reject buying it. The findings support our hypotheses, H1, and H2. When they considering a refurbished smartphone by the OEM as an option, younger people are more likely to adopt a refurbished one ($p < .1$). Consumers' environmental consciousness has an effect on the purchase intention toward only the OEM's re-furbished smartphone in Indonesia.

The results of the regression models do not support our hypothesis H4 that consumer innovativeness negatively influences the purchase intention of a refurbished smartphone. Our regression results rather show the contrary in all three countries.

5 Discussion and conclusions

Our regression model shows that consumers' intentions to purchase a refurbished smartphone can be strongly influenced by the perceived risk of a refurbished smartphone in three countries. The business providers who target the Asian market need to take the measure to enhance consumer's trust in the quality of a refurbished smartphone. In addition, it should be noted that refurbishing smartphone marketing strategies and pricing schemes focused on the cost-saving aspects of a refurbished smartphone may increase the probability of refurbished smartphone adoption and use. The regression results suggest that for those who are environmentally conscious in Asian countries, a refurbished smartphone by the OEM would appeal. Though it shows the contrary to our hypothesis, consumer innovativeness and related characteristics may be a factor in the purchase behaviour of a refurbished smartphone.

In this article, we treated ordinal variables as continuous for the regression model and Liker with five or more categories can often be used as continuous. However, an additional econometric model needs to be further developed to confirm whether statistical relationships identified by the regression model between the underlying factors and the purchasing intention are consistent in other models as well. Thus, future research will use a structural equation model for the analysis of the data.

6 Acknowledgments

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Understanding Obsolescence in Smartphones; An exploration of smartphone life expectancy and maximum lifespans through online repair manual web-traffic

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Abstract

A dominant narrative surrounding smartphone lifespans suggests that if devices were more repairable consumers would use them longer and the production of new devices and generation of e-waste would subsequently decline. Using a 'big-data' approach, we utilize novel datasets to explore consumer interest in smartphone performance and repair over time, and whether they are affected by objective performance and repairability. Examining over 3.5 million iPhone benchmarking test scores we reveal that the objective performance of devices remains very constant over time and does not deteriorate as common wisdom might suggest. Testing frequency however, varies substantially suggesting that factors other than objective performance affects consumers' perceptions of product functionality and obsolescence. Relatedly, our analysis of 22 million visits to a website offering free repair manuals revels that while objective performance remains stable, interest in repair declines exponentially over time. In addition, our findings indicate that repairability does not increase interest in repair. Together these results suggest that mental depreciation and perceived obsolescence play a critical role in determining smartphone lifespans and the potential to prolong them via technical solutions. As such, we propose that sustainability advocates increase the emphasis on the exceptional stability in performance of devices and try to avoid narratives of planned obsolescence which might encourage a sense of pointlessness about repairing older devices.

1 Introduction

The fast pace at which consumer goods are currently replaced seems to conflict with sustainability and remaining within planetary boundaries. The environmental implications of what is often referred to as the 'throwaway society' are particularly evident in the case of consumer electronics. Due to their short lifespans, high penetration rates and significant environmental impact relative to their size, smartphones make for a particularly interesting case study in the context of sustainability.

Yet despite consumers' professed interest in repair, and wide advocacy from academics, policy makers, and activists, currently, most leading smartphone models are notoriously challenging or costly to repair. This discrepancy is taken by many as an indication that manufacturers are actively engaging in planned obsolescence.

This strong narrative around planned obsolescence in smartphones could similarly provide consumers with a rational explanation for why they upgrade so frequently. However, repair can do very little to address perceived obsolescence. After all it won't make an older device more fashionable and its potential to enhance devices' compatibility with the broader eco-system of evolving apps and services is at best, limited.

As policymakers around the world debate the adoption of right to repair laws, gaining a better understanding of the relationship between repairability, obsolescence and product lifespans is both timely and imperative to support informed policy making.

While previously, data on people's attributes was limited to what researchers could collect via experiments or surveys, the wide spread adoption of the internet and smartphone apps has transformed the types and amounts of data through which researchers can observe and analyse human behaviour. In this paper we examine visitor traffic to free smartphone repair manuals available on iFixit.com to measure consumer's interest in repair over time and shed light on mental depreciation.

It is important to note that our investigation of interest in repair does not espier to provide robust evidence on casual mechanisms. Rather, our analysis is an attempt to highlight the potential of using novel datasets through which consumer behavior can be observed to

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dig deeper and improve our general understanding of issues such as planned obsolescence and repair.

2 Consumers & Product Replacement

While the environmental implications of product obsolescence and replacement have mostly been studied from an engineering perspective, the field of consumer behavior offers insights into consumers' decision-making process and the ways in which they reason about product replacement. Using lab and field experiments, researchers in consumer behavior typically rely not only on peoples stated preferences (as gather via surveys or focus groups), but also on revealed preferences teased out via experiments and observations. These revealed preferences, when examined under different experimental conditions allow researchers to investigate the underlining psychological mechanisms driving peoples' decision making and consumption choices.

Building on the idea of mental accounting [1], Okada [2] conducted a series of experiments indicating that when purchasing a product, consumers create a mental account-book in which they log the initial purchase price. Over time, as the product is used consumers slowly depreciate the amount of utility gained against the initial cost until they feel that they got their 'full money's, at which point, the products' value in the mental accounting book if fully depreciated and reaches zero. Since a replacement purchase, typically involves two intertwined decisions- the purchase of a new product as well as the retirement of an older one, consumers consider not only the cost of the new product, but also the mental cost associated with retiring the product they already own [3]. When the incumbent product (i.e. the one consumers currently own) has a low residual value in the mental accounting book, it is easier to justify its replacement. In contrast, replacing a product before it has been fully depreciated mentally, is harder since it forces the consumer to write off the residual value as a loss in the mental accounting book.

Examining replacement purchases of watches, for example, Jacoby et al. demonstrate that consumers often use minor signs of wear and tear to justify the need for replacement [4]. These results indicate that consumers inflate the importance of minor functional or cosmetic issues in order to ease the mental pain associated with prematurely retiring a functioning product. Focusing on upgrades, Belleza et al show that consumers tend to be more careless with their possessions when they know a newer, more desirable version is available [5]. For example, they reveal that consumers are less likely to search for a lost phone when a new model comes out, or safeguard a coffee mug so it does not break when an upgrade is available. This "upgrade effect" stems from consumers' need to justify the purchase of a replacement product when they haven't gotten all 'their money's worth' out of what they already own.

More recently, Shani et al (2020) used smartphones as a case study to demonstrate that consumers find it easier to justify an upgrade purchase when the new model offers functional improvements over their current device compared to when the new model offers only stylistic or aesthetic improvements [6]. They suggest that differences in functional performance between the incumbent and newer model, give consumers just cause, or a "functional alibi," to purchase a smartphone they desire yet feel wastefully guilty to buy [7]. Considering that consumers prefer to justify replacement purchases on the basis of objective, utilitarian reasons, an alternative explanation to the survey results presented earlier could be offered. Specifically, consumers might be motivated to report that they replaced their smartphones following technical or functional issues because it helps them justify their decision to retire their old device.

3 Interest in Repair

To investigate if and how interest in smartphone repair changes over time, we examined web traffic to pages providing free repair manuals on the iFixit.com website. iFixit is one of the leading independent repair outlets, and is well known for its free and easily accessible repair manuals, product teardowns, and repairability rankings. Since there is no cost associated with browsing the website, examining traffic data provides a useful setting to investigate interest in repair without the need to control for other factors such as the availability of spare parts or the cost of repair. As such, examining web traffic to websites such as iFixit offers a somewhat unique opportunity to observe actual, real life behavior reflecting interest in repair, instead of relying solely on consumer surveys.

Focusing on a set of pre-defined Apple and Samsung Galaxy S series smartphone models, we used the iFixit Google analytics plug-in to directly log the number of daily visits to each model's repair manual landing page. To remove some of the noise originating from daily variability and reveal the underlying trend, for each model's repair manual webpage, we then calculated the 30-day moving average for traffic to each and used it to measure interest in repair overtime. A preliminary analysis revealed that for each smartphone model, the trend is characterized as starting from a low base from the time of the launch, followed by a continuous rise in interest in repair before peaking and entering a period of more gradual decline with a long tail off. To illustrate, Figure 1 shows the daily site visits to the iPhone 5 repair guide landing page, from its launch lade in September 2012 through to January 2020. The trend line is the 30-day moving average. For each smartphone model, we then defined and calculated (a) time between launch and peak interest, (b) the time taken for repair interest to drop to 50% of peak and (c) the time taken for repair interest to drop to 10% of peak interest.

While time till peak can help examine the effects of changing service contracts or warranty package terms, given our interest in product lifespan we focused on the post peak period, and specifically period c which we refer to as interest decay.

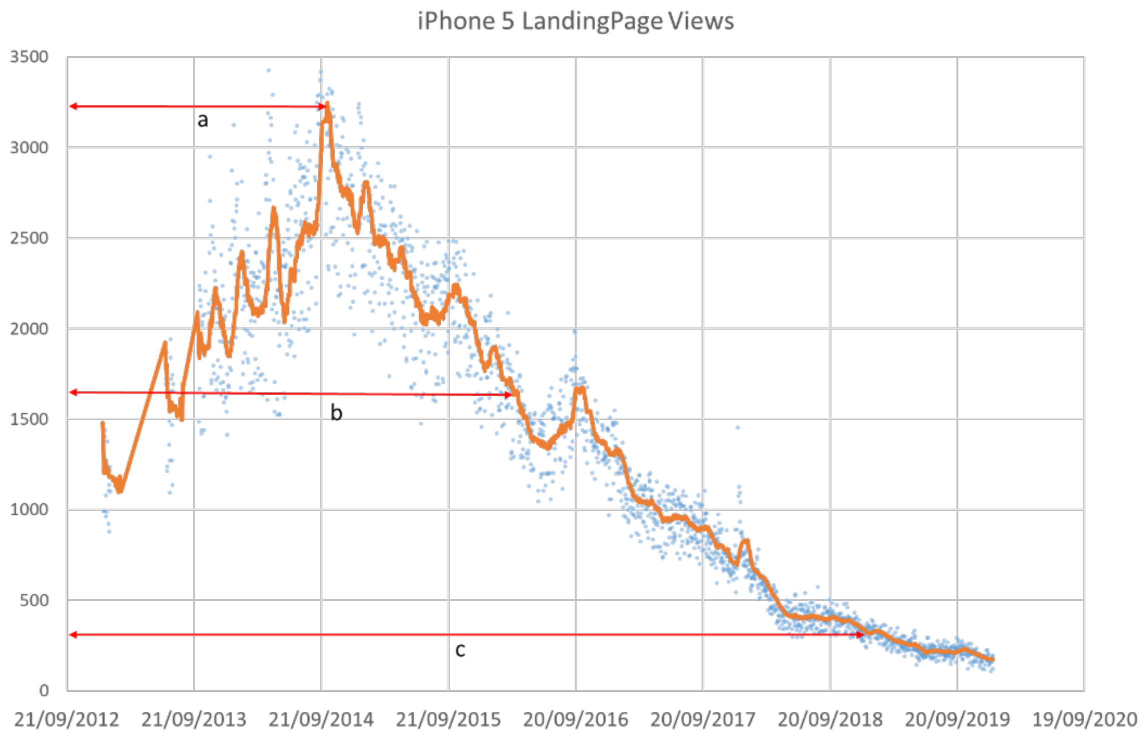

Figure1 iPhone 5 Landing Page Views

We posit that peak interest reflects a tipping point, after which users gradually lose interest in repairing their devices until interest in repair dissipates completely. In other words, the decline can be viewed as a reflection of the rate at which the population of owners as a whole judge their devices to be obsolete when faced with a repair/replace choice. Since site traffic is asymptotic, we defined the mental lifespan of devices as the time between model launch and the point at which interest in repair drops to 10% of peak interest.

In older models, where traffic had already reached 10% of its peak, we calculated the rate at which interest in repair had decayed. Confirming that decay followed an exponential curve we then predicted future decay for all remaining iPhone models for which data on period c was not yet available accordingly. Decay rate is thus a proxy for the speed in which a smartphone model becomes obsolete and the faster the obsolescence the higher the decay rate. Only devices which had reached their peak and had declined sufficiently to make reliable projections were included in our analysis (hence the more recent devices, e.g. iPhone SE 1st Generation were excluded).

In addition to our examination of repair interest over time we also specifically explored the potential impacts easy to replace batteries might have on product lifespan. Since battery depletion is one of the main reasons consumers supposedly replace their devices, having a user-replaceable battery is widely considered as key to enabling product lifetime extensions. Using interest in repair as a proxy for service life we use a natural experiment, namely Samsung's design decision to switch from a user replaceable battery in its Galaxy S5 model (launched April 11th 2014) to an integrated (and therefore challenging to replace) battery in its subsequent models the Galaxy S6 (launched April 10th 2015) .

According to the iFixit repair guides the design changed the battery replacement process from being a two-step process not requiring any tools, taking 1-2 minutes and rated as bring "Very Easy" to a 17-step process with 7 recommended tools, requiring 40 minutes – 1 hour and being rated as “Difficult”. Since the S6 is far less repairable than the S5, we would expect to see a faster decay in repair interest in the S6 model compare to the S5.

3. Results

Table 1 shows the parameters of interest and also includes the decay rate in visits as %age per month and the iFixit Repairability Score.

Model	Launch Year	Page Visits	Months to Peak (a)	Months to 50% (b)	Months to 10% (c)	Decay Rate (%age per month)	iFixit Score
Galaxy S7	2016	328,592	18	34	72	4.411	3
Galaxy S6	2015	641,007	12	26	56	5.250	4
Galaxy S8	2017	275,533	5	31	92	2.655	4
Galaxy S5	2014	948,711	11	31	56	5.116	5
iPhone 4	2010	4,420,538	27	54	84	4.067	6
iPhone 5s	2013	2,516,937	25	55	95	3.212	6
iPhone 4s	2011	2,471,229	36	46	78	5.417	6
iPhone 5	2012	2,688,494	25	43	77	4.419	7
iPhone 6	2014	3,447,491	25	43	78	4.149	7
iPhone 6s	2015	1,533,223	28	45	83	4.118	7
iPhone 7	2016	1,253,521	13	42.	104	2.494	7
Galaxy S4	2013	818,872	17	32	64	4.929	8
Galaxy S3	2012	852,231	20	35	66	5.003	8
Total Site Visits		22,196,379					

Table 1 Key Parameters of Interest in Repair Site Traffic

This data can be examined to explore a number of relationships and test whether and how repair score and launch year affect smartphone lifespan. A regression analysis revels that, for the smartphone models examined, repairability is not a good predictor of lifespan (adj. R^2 = 0.01). While the sample used is not sufficiently large to support a robust analysis, these finding are well aligned with previous empirical work showing that repairability does not prolong the service life of smartphones [8]. Consistent with market research, our analysis of repair interest also suggests that smartphone lifespans are getting longer, that is newer models seem to outlast older ones. Comparing across brands however, our results indicate that the decay in repair interest tends to be faster for Samsung devices compared to Apple ones. For example, the iPhone 7 is expected to reach full mental depreciation in 104 months (8.6 years), while the Galaxy S7 is expected to do the same within 72 months (6 years). In line with previous work our findings indicate that that smartphone lifespans are not homogenies but vary across brands [8].

We have found no discernible difference in repair interest between the Samsung Galaxy S5 which has a user replaceable battery and the Samsung Galaxy S6 which has an integrated battery according to our analysis. Indeed, the profile of their repair interest is strikingly similar with the Galaxy S5 having a decay rate of 5.1% per month and the Galaxy S6 having a decay rate of 5.2% with both reaching 10% of peak after 56 months. This is shown graphically in Figure 2. While repairability gives consumers the opportunity to repair their devices, they still need to be sufficiently interested in repair to act on it.

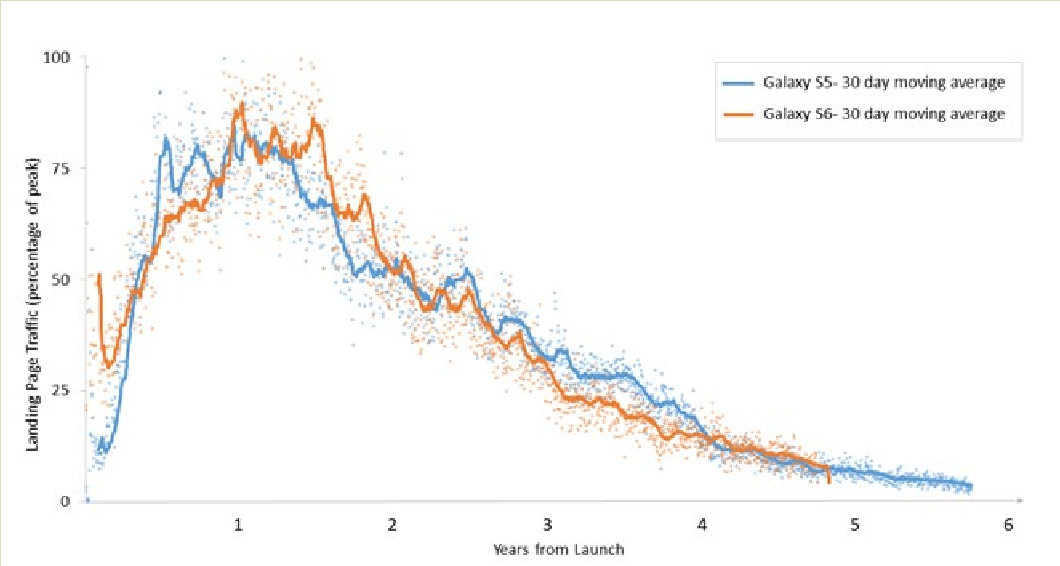

Figure 2 Comparison of Repair Interest for Samungs Galaxy S5 & Samsung Galaxy S6

4. Discussion

The nature and quantity of data increasingly available in this new age can radically change our understanding of consumer perceptions, preference, and behavior. Here we analyze test scores and testing frequency on a leading benchmarking app, as well as visitor traffic to online repair manuals to gain insight into smartphone obsolescence and the potential impacts of repairability. Contrary to common knowledge, we find that smartphone functionality does not deteriorate substantially over time. Interest in repair however, declines as time goes by regardless of how easy or hard it is to repair a specific device. Collectively, our analyses suggest that mental depreciation plays a critical role in determining smartphone lifespan.

To date, efforts to prolong product lifespan and postpone obsolescence in smartphones have mostly focused on technical aspects, especially device repairability, the logic being that when the occasion arises, users will willingly repair them themselves or have them repaired locally. Yet this analysis indicates that psychological obsolescence and mental depreciation play a critical, yet seldom addressed role in shaping the point at which products are deemed obsolete.

For example, while the objective performance of an iPhone is highly stable over a long period, the use of benchmarking tools reveals a compulsion to check it which seems, on the surface, to be especially acute at key moments such as new product and operating system launches and updates. Why is there a baseline of about 7,000 people per week testing the performance of their iPhone with significant spikes at and around times of major publicity for iPhones? Perhaps because they are being constantly communicated with messages that their phones are being deliberately degraded?

Additionally, and perhaps counter-intuitively, the objective repairability of a device does not seem to influence the longevity of the interest in repair with brand being of much greater significance. Likewise, in the limited case of the design change from the Samsung Galaxy S5 to the Samsung Galaxy S6 which removed the user-replaceable battery we have not found any evidence that this change in objective repairability made any difference to the interest in repair for that model.

Based on these findings we argue that measures to improve the repairability of devices may not be enough in isolation to support lifetime extension and resource efficiency. While there is little doubt that companies such as Apple and Samsung have a vested interest in increasing product sales, it is also likely that to some extent, consumers use the planned obsolescence narrative as a ‘functional alibi’ to justify purchases of new products they desire yet feel guilty buying. Public discourse around planned obsolescence is likely exacerbating the problem and hastening mental depreciation of older devices such that if they are damaged repair doesn’t register as a real possibility for the user. Repair advocates should seek to create a new narrative which highlights how good smartphones are performing over the long term, working to inflate, or at least dampen the depreciation of, the mental book value and employ the language of loss which emphasizes the lost utility of a broken screen or degraded battery. This is not to challenge the aim of devices being more repairable but guidance on how to augment the campaign.

Notably, our analysis is subject to some limitations and caveats. As it is based on real-world traffic to a commercial website and uses of commercial software the underlying data is subject to questioning about the impact of advertising campaigns, search rankings, multiple visits to the site by the same user and web-crawling by bots (Google Analytics does take measures against this). While the large numbers and consistency in trends gives a degree of confidence in the data we have at all times been moderate in the claims presented and advise that they should be considered in the context of the wider literature and evidence about this topic.

Ultimately, it is clear that there are limits to repair and the marketing of new devices will continue to drive psychological obsolescence. New features will continue to provide functional alibis enabling the justification for replacement and thus early/premature product replacements. As such we propose that sustainability advocates focus more on the exceptional stability in performance of devices rather than narratives of planned obsolescence which might in fact convince consumers that repairing older devices is pointless. Similarly, service contracts might also give consumers a faulty reference point, which then serves as an anchor for the time after which a device should be replaced.

The strength of our novel approach to studying planned obsolescence and repair is not the size of our datasets but that they allow to examine expressions of consumer interest in smartphone performance and repair, which are not tainted by social desirability bias or people's aspirational, more sustainable selves. While we fully acknowledge that interest differs from action, we argue that by utilizing newly available forms of "big-data" offers the opportunity to push forward theory and policy making on issues such as repair, planned obsolescence, and circular economy more generally.

5. Acknowledgements

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Methodology to Assess the Circularity of Product Design for Mobile Electronics

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Abstract
Circular product design refers to different design measures which aim to extend the use time of products and components for as long as possible, thereby preserving materials and minimising environmental impacts over the whole product life cycle.
The objective of this research was to develop a method to assess the circularity of different product designs of mobile electronic products (such as smartphones, tablets, etc.) and to guide the user towards a more circular product. As a result, this method was integrated into a web-tool that is simple in its application and widely applicable to assess and evaluate mobile electronic products, and determine strengths and weaknesses of the product design.

1. Introduction
This work represents the development of an assessment method that is able to evaluate the fulfilment of the circularity of electronic products. Particularly, the focus in this work is on mobile electronics like smartphones and tablets. “More than 80% of the environmental impact of a product is determined in the design stage.” [1]. Therefore the leverage to reduce the environmental impact in the design stage is very high. Since mobile electronics are very fast-moving products and are often broken by daily use [2], an extension of their life time by applying circularity measures seems to be promising.

The developed method served as the basis for the web tool “D4R PILOT” [3] similar to the known “ECODESIGN PILOT” [4]. The "D4" from the acronym D4R-PILOT, stands for "Designed for". The "R" represents the different End-of-Life strategies, which among other things form the basis for a CE model. These basic strategies are "Repair", "Reuse", "Remanufacturing" and "Recycling". The fulfilment of these strategies form the basis for a circular product.

2. Method
In a first step there was a need to define the so-called “D4R strategies”. Although there are many definitions already available [5], [6], [7] due to a significant change in the product technologies (smart mobile devices), and some innovative developments in 4R processes, such as robotics for disassembly, a new definition of the different strategies and the related design criteria was required.

In addition to the D4R strategies a criteria catalogue, with a set of specific design measures related to the 4Rs and specifically relevant for mobile electronics was defined (e.g. the housing can be easily removed in order to access the internal components). This catalogue, in combination with the degree of fulfilment of each question and the relative importance for each strategy, form the basis for the assessment method. Further the developed method was tested on several devices (smartphone, digital voice recorder…), to adjust the assessment scales and test the method with its underlying criteria according to its usability.

2.1.Definition of D4R strategies
2.1.1. Product Repair
Repair is defined as: Returning a faulty of broken product back to its usable state. If a product is easy to repair, the life of the product may be extended. Once it gets broken, defective components are either repaired or replaced instead of being disposed. Features of a product which enable and facilitate repair strategies are therefore considered as important requirements to determine the environmental performance of a product.

Design criteria that have an impact on whether a product is easy to repair are for example:
- detachability of connections,
- use of common fasteners,
- number and variety of fasteners,
- possibility to exchange individual components,
- availability of repair instructions and tech. documents,
- good accessibility,
- easy opening of the housing,
- non-destructive removal of parts,
- good identifiability of the components,
- simple method of failure analysis,
- little expertise required,
- large availability of spare parts,

- low spare parts prices,
- short repair time,
- low product complexity,
- low risk of injury, etc,

2.1.2. Product/Component Reuse

Reuse is defined as: Returning a used product to a satisfactory working condition by rebuilding or repairing major components that are close to failure, even when there are no faults in those components. If a product is no longer used by its user for its actual purpose, it or at least as many components as possible should be reused. In other words, new customers are provided with used products.

Relevant design criteria for reuse are:

- detachability of the connections,
- good accessibility,
- easy opening of the housing,
- longevity of the components,
- aging-resistant materials,
- modular design,
- non-destructive removal of parts,
- independence of individual components,
- similarity of the components to previous and subsequent models,
- uniform, product-independent components (e.g. the same charging system for smartphones and MP3 players),
- test procedures for functionality checks to assure faultless products,
- possibility to check the functionality of single components,
- possibility of data erasure, etc.

2.1.3. Product/Part Remanufacturing

Remanufacturing is defined as: Any operation, in which the products' components that have become waste are processed in such a way that they can be used again. Remanufacturing returns a used product to a “like-new condition”.

Relevant design criteria for remanufacturing are:

- detachability of the connections,
- good accessibility,
- easy opening of the housing,
- modular design,
- aging-resistant materials,
- product design that enables future product updates or improvements, etc.

2.1.4. Product Recycling

Recycling is defined as: Extracting and re-introducing materials into new products: Recycling represents the fourth Circular Economy strategy. It is applied when a product or/and its components cannot be reused in any other way. By recycling as much of the materials as possible, they are returned into the production cycle and used for various other products.

Design criteria are:

- use of recyclable materials,
- good separability of the materials,
- good identifiability of the materials used, avoidance of hazardous substances,
- low variety of materials used,
- good accessibility,
- easy opening of the housing, etc.

2.2. Assessment Questions & D4R performance

2.2.1. Assessment Questions

In the course of selecting the relevant design criteria from the product properties listed above, it was shown that many of the properties have an impact on several of the four areas, "Repair", "Reuse", Remanufacturing" or "Recycling".

However no trade-offs between the different criteria have been identified, meaning that none of the product properties listed are in direct contradiction to one another, since repair, reuse and remanufacturing criteria generally have the same design requirements [8]. If a single criteria is improved, there is no need to fear that other areas of CE suitability will automatically deteriorate. In order to avoid multiple assessments, for each design criteria one assessment question is formulated and the questions are than related to the relevant strategies via a “relative importance [%]”. In total 24 assessment questions are defined.
The assessment questions are defined take into account the design criteria (listed above) for each strategy as well as the "main components" of the mobile electronic products. These main components represent the most important components of common mobile electronic products. The idea behind is to distinguish between important and less important components and thus to enable a more granular assessment. For example this allows that if the main components (and not all components) only are replaceable the product still can achieve a positive result. The following main components with a significant impact on the circularity were derived:

- housing
- energy source (battery)
- display
- PCB
- controls elements
- speaker
- microphone
- display
- cameras

All relevant design criteria are aligned to these main components and merged to 24 (see Table 1.) final assessment questions. If a product does not have at least one of these main components, the related assessment questions are left out to achieve a correct result.

Nr.	Assessment Question	*Relative importance for each D4R Strategy*
1.	The housing can be easily removed in order to access the internal components.	*RP-10%, RU-5%, RM-5%, RC-5%*
2.	The battery can be easily removed.	*RP-12,5%, RU-5%, RM-5% ,RC-5%*
3.	The display can be easily removed.	*RP-12,5%, RU-5% ,RM-10%*
4.	The camera can be easily removed.	*RP-5%, RU-5%, RM-10%*
5.	The microphone can be easily removed.	*RP-5%, RU-5%, RM-5%*
6.	The speaker can be easily removed.	*RP-5%, RU-5%, RM-5%*
7.	The circuit board can be easily removed.	*RP-5%, RU-5%, RM-10%*
8.	The control elements can be easily removed.	*RP-5%, RU-2,5% , RM-2,5%*
9.	There are other important components that are not mentioned in this questionnaire, which can be easily removed.	*RP-5%, RU-2,5%, RM-2,5%*
10.	The device can be completely disassembled without using any or only standardized tools.	*RP-10%*
11.	Standard elements are used to connect the different components.	*RP-10%*
12.	Modules or electronic components built into the device are marked and easy to detect.	*RP-10%, RU-5%, RM-5%*
13.	The components and materials have the same lifetime.	*RU-7,5%, RM-7,5%*
14.	A modular design is applied.	*RU-22,5%, RM-22,5%*
15.	There are software updates available to upgrade the device.	*RM-10%*
16.	A functionality check of the product, its components or modules, is possible.	*RP-5%, RU-10%*
17.	There are reliable data erasure options available.	*RU-5%*
18.	The manufacturer uses the same components or modules for a wide range of products.	*RU-7,5%*
19.	Instead of hazardous substances, eco-friendly materials are used.	*RC-10%*
20	Recyclable materials and material combinations are used.	*RC-40%*
21.	The product design supports the semi-manual detection, disassembly and sorting of components and materials.	*RU-2,5%, RC-10%*
22.	The recyclable materials, particularly rare-earth elements are marked.	*RC-15%*
23.	Avoid a high material diversity in order to facilitate recycling.	*RC-20%*
24	The materials used are easy to separate with conventional recycling methods.	*RC-5%*

Table 1: Assessment Questions

2.2.2. Assessment of questions

The assessment questions were formulated specifically as a decision question. In addition to the answer options "yes" and "no", there are also the options "rather yes" and "rather no" to allow gradation and thus partial points if a criterion is not completely fulfilled. The “degree of fulfilment” (Assessment Scale) corresponds to 100% for "yes", 60% for "rather yes", 30% for "rather no" and 0% for "no".

2.2.3. D4R Performance

Each question is related to one or more D4R strategies with a higher or lower importance for each of the strategies. This importance is considered by a relative importance [%] of each question for each strategy. For example, for the assessment question “Is the camera easy to remove?“ the defined “relative importance” for each CE-strategies are Repair-5%, Reuse-5%, Remanufacturing-10% and Recycling-0%. Meaning this question is not relevant for recycling but rather important for Remanufacturing. The “relative importance” of each assessment question for the 4Rs is listed in table 1.

Now the products performance regarding the four CE-strategies ("4R's") can be determined. The *Strategy performance* is given as a percentage between 0-100% and is calculated by the sum of the fulfilment of each question multiplied by the relative importance (example CE-strategy repair):

$$Strategy\ performance\ RP = \sum Fulfilment\ of\ questions\ x\ \text{Relative importance}\ (RP)$$

In the next step an *Overall D4R Score* is calculated based on the four individual *Strategy performances*. For each strategy an absolute importance [%] is predefined, representing its importance for an overall D4R Score see table 2.For example it is of high importance that products are designed to be repaired as the product life time can be prolonged easily using only a low amount of resources. On the other hand design for recycling is less important, as the potential of resource savings is significantly smaller.
Therefore the *absolute importance* is defined as:

Repair (RP)	*Reuse (RU)*	*Remanufacturing (RM)*	*Recycling (RC)*
40%	*25%*	*25%*	*10%*

Table 2: absolute perfomance depending on the CE strategy

And the Overall D4R-Score of the product results from:

$$Overall\ D4R\ Score = \sum Strategy\ performance\ (RP, RU, RM, RC)\ x\ Absolute\ importance$$

2.3.Tool Workflow

To apply the tool, a certain level of specialist knowledge about the assessed product is needed, otherwise questions cannot be answered accordingly and the results are not meaningful. However, the tools' workflow is designed to be easy and flexible to use, and can be used by product developers.

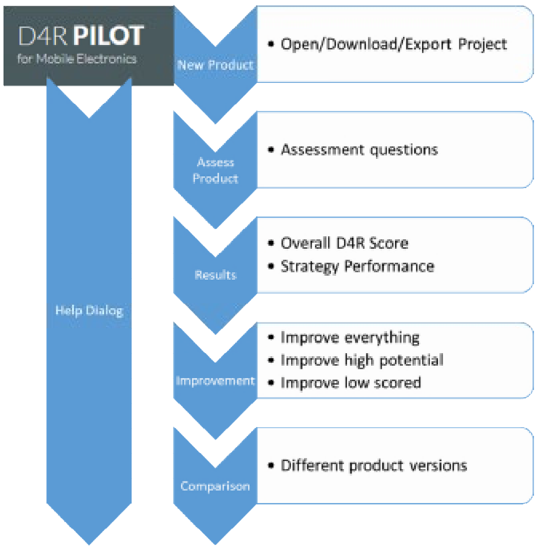

Figure 1: Workflow Webtool D4R PILOT

As a first step for every new product assessment a new project must be created. The tool is designed in a way that it is possible to save one's projects and edit them again later. The assessment itself is carried out by answering the 24 assessment questions (Figure 2) and selecting the most appropriate answer. The next step shows already the results (Figure 3). The "Overall D4R Score" gives a rough summary, while the "Strategy Performance" shows a detailed indepth view related to the individual D4R-strategies. In a third step a new product version to be improved can be created, and the tool gives different filter options to highlight improvement potentials from the reference product. In the next step the improved product can be compared with the reference product. A comparison of different projects is also possible. This way, the product can be compared with its successor or a competitors' product.

3. Results

The developed assessment method was translated into a freely available web-tool, the D4R PILOT: https://d4r-pilot.ecodesign.at. In summary, the following was achieved:

1) The questionnaire (Assessment Questions) of the PILOT is based on the defined design criteria.

2) The questionnaire can be evaluated with different degrees of fulfilment.

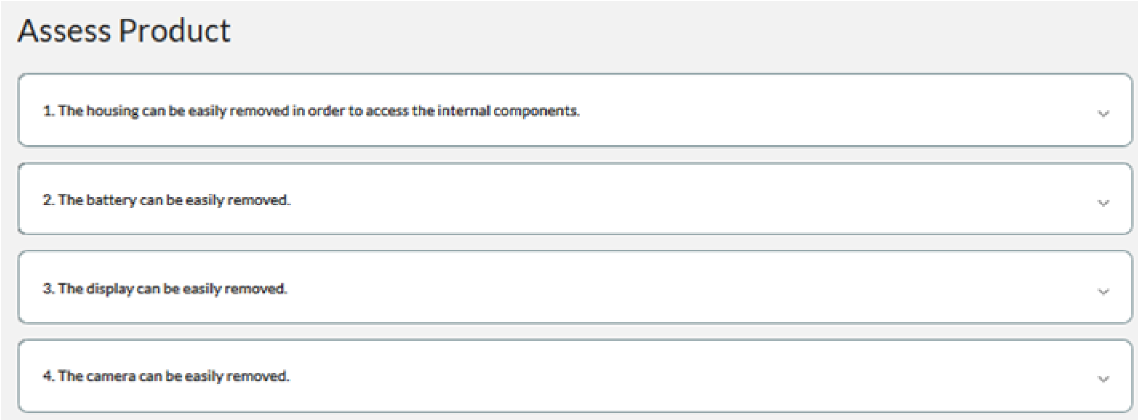

Figure 2: D4R PILOT – Assessment Step

3) Each assessment question is assigned with a relative importance related to the particular CE-strategy (Repair, Reuse, Remanufacturing and Recycling).

4) As a result of the questionnaire, the Overall D4R Score as well as the detailed performance regarding the D4R-strategies are displayed (Figure 3).

Figure 3: D4R PILOT - Result Window Overall D4R Score

5) The tool highlights also the improvement potential (Figure 4). For each identified and low rated assessment question a description and a best practise example is given in order to derive relevant design measures and possible improvement ideas (see figure 5). Additionally the tool lists potential circular business strategies, which could also be relevant for improvement. The intended improvements are saved as an additional product version, the new CE-performance is shown immediately.

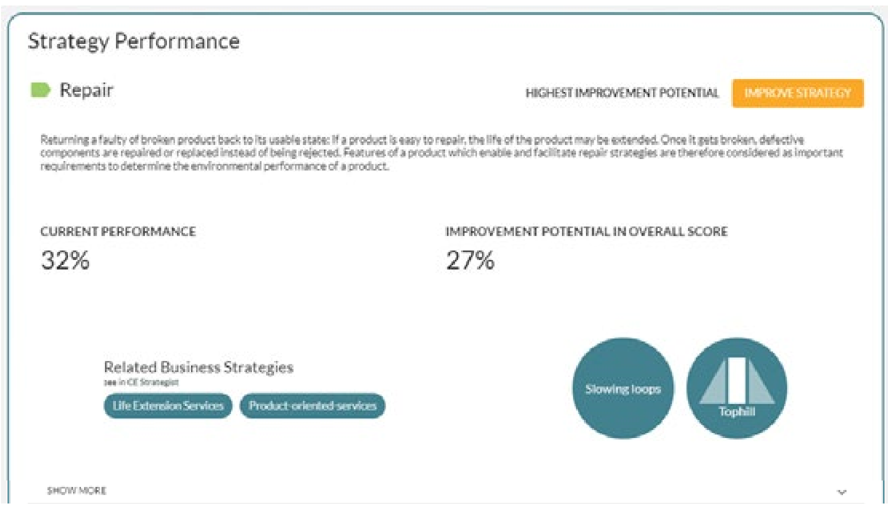

Figure 4: D4R PILOT - Result Window Strategy Performance

6) The tool highlights best practice examples which help during the improvement step (Figure 5)

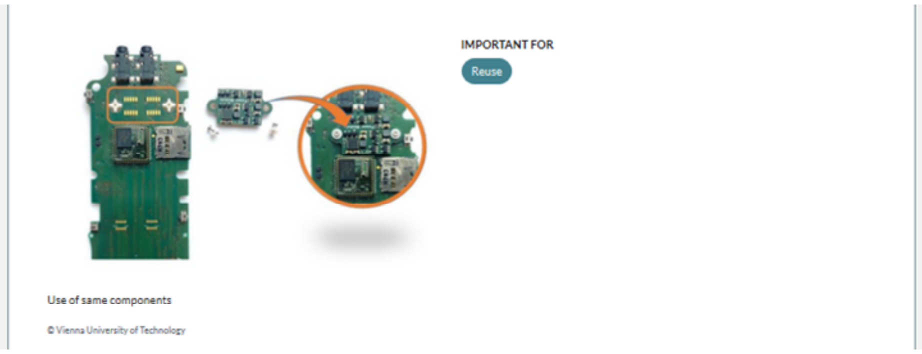

Figure 5: D4R PILOT – Improvement window

4. Conclusions

With the help of the D4R PILOT, it is possible to assess the product design performance in mobile electronic products in order to determine potentials for improvement. Appropriate measures can be taken during the product development process to improve the identified weaknesses. Similar products can also be compared with each other, as the method shows both advantages and disadvantages and the result can also serve to make transparent decisions regarding potential product design changes. The tool can be used already at the beginning of the product concept development. For certain aspects like dismantling

Generally the tool should be used in the very early stages of PD, in order to have more flexibility to change the design towards more circularity. In such early stages needed information is often not available. To overcome this, a predecessor product or otherwise a similar product on the marked should be used in this stare as reference. Then most of the questions e.g. those focusing on the product architecture, like on dismantling of the battery, can be easily answered. Just for some questions focusing on the materials used, like the one on rare earth materials, more knowledge and maybe some background research is needed.

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Environmental Implications of Service Life Extension of Mobile Devices

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Abstract

The number of mobile Internet-enabled devices (MIEDs) is growing. Producing MIEDs requires resources, energy and causes considerable emissions. Extending the service life MIEDs could significantly reduce the demand for new devices and associated environmental impacts. However, whether service life extension actually reduces environmental impacts associated with MIEDs is still uncertain. First, available life cycle assessments of MIEDs suggest that the production of integrated circuits (ICs) accounts for the majority of GHG emissions during the production phase and that greenhouse gas emissions increase with the size of the device and, more importantly, with its storage capacity. However, there is only little information available on MIED specific components such as logic or memory type integrated circuits. In order to quantify environmental impacts of service life extension of MIEDs new approaches for life cycle inventory modelling (e.g. modular modelling) are required. Second, service life-extending measures are subject to rebound effects, which occur if the number of devices being produced does not fall as expected. Such effects depend on consumer behaviour (e.g. re-spending effects) and the rationalities of involved economic actors. Thus, environmental, behavioural and economic aspects have to be taken into account in order to develop service life-extending measures that entail environmental benefits while being both economically viable and appealing to consumers.

1 Introduction

Mobile Internet-enabled devices (MIEDs) such as smartphones, laptops, and tablets have become an integral part of our everyday life, which is reflected in the large increase in the number of devices sold in recent years [1]. These devices require a considerable amount of resources and energy for their production, during their use and must be disposed at their end-of-life [2].

To date, information and communication technology (ICT) end user devices (including MIEDs) cause more greenhouse gas (GHG) emissions than data centres and telecommunication networks together [3]. Most of the environmental impact throughout the life cycle of MIEDs occurs during production [4]. In particular, their material composition contains more than 50 chemical elements, including several scarce metals [5], whose mining and disposal has toxic impacts on humans and ecosystems.

While specific data on the service life of MIEDs are scarce, it is a common practice to replace MIEDs within a few years, despite the fact they are still functional. Thus, extending the service life of MIEDs is technically feasible and can reduce the demand for newly produced devices and environmental impacts associated with MIED production. However, the service life of MIEDs depends on the actions of many actors, including consumers, producers and retailers. In turn, their actions depend on technological development and the economic and regulatory context (e.g. instalment plans offered by device retailers, availability of secondary markets for used devices, warranty requirements, etc.), and between the actors themselves.

Hence, in order to identify and implement effective measures to extend the service life of MIEDs, it is necessary to systematically investigate related issues from an environmental, behavioural and economic perspective. This paper aims at providing an overview of the current state of knowledge with respect to these perspectives and at exploring approaches and further research needed to tackle them. It is structured as follows: In chapter 2, we provide an overview of the status quo with respect to environmental impacts of MIEDs as well as measures to extend their service life. In order to improve the environmental assessment of measures to extend the service life of MIEDs, we introduce an approach to update life cycle inventory data of mobile devices and discuss environmental impacts of a repair scenario as well as potential indirect effects of service life-extending measures (chapter 3). Finally, we summarize and discuss main findings and provide an overview of challenges that must be addressed in future research (chapter 4).

2 Status Quo

2.1 Assessing the Impacts of MIEDS

Life cycle assessment (LCA) allows to assess the environmental impact of MIEDs and – more specifically – to identify environmental hotspots throughout their life cycle [6]. Several existing LCA studies have focused on specific MIED devices. These include devices such as smartphones (e.g. Sony Ericsson W890 [6], Fairphone 1 [7], Fairphone 2 [8] and Sony Xperia Z5 [9]) and notebooks (e.g. Dell Latitude E6400 [10] and ASUS UL50Ag [11]). Some device manufacturers, such as Apple and HP, also provide information on the GHGs caused throughout the life cycle of their devices [12], [13]. In addition, some articles [14]–[16] provide a comparison of the environmental impacts of different devices.

Figure 1 depicts life cycle-related GHG emissions of various devices. On average, the notebooks cause GHG emissions of 309 kg CO_2 equivalents, the tablets 127 kg CO_2 equivalents, and the smartphones 54 kg CO_2 equivalents. There is considerable variability in the data provided by different studies, which differ in scope and system boundaries. For example, the assumed service life of an MIED has significant influence on the environmental impact per year of use. The results of the LCA studies are therefore not directly comparable. Manhart et al. [15] assume that some studies underestimate total GHG emissions (e.g. Fairphone 1) or those of the manufacturing phase (e.g. iPhone 3G). Similarly, Suckling and Lee [14] assume that the effects of Fairphone 1 are underestimated due to differing assumptions.

Nevertheless, the data suggests that GHG emissions increase with the size of the device and, more importantly, with its storage capacity. This is in line with the observation that GHG emissions per device increase over time due to the increasing complexity and storage capacity of the devices. E.g., a comparison of an Ericsson LCA study from 1995 with a study from 2015 shows that even though the gold content of mobile phones has fallen and batteries have changed from nickel-cadmium batteries to more environmentally friendly lithium batteries, GHG emissions have increased due to the higher complexity and storage capacity [9].

Furthermore, all studies come to the common conclusion that the dominant life cycle phase is the production phase. For this reason, extending the service life of the devices and thus decreasing the need for new devices is most relevant for the reduction of environmental impacts of devices.

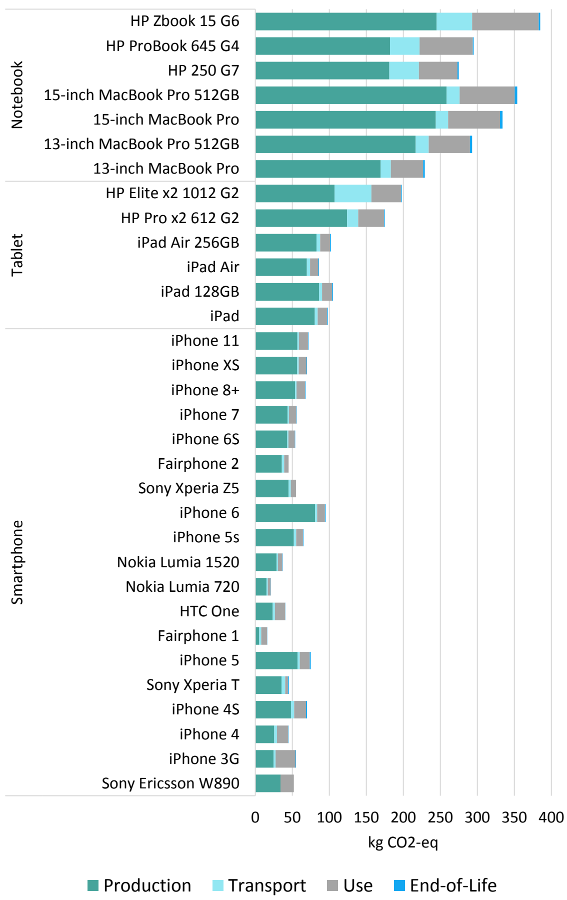

Figure 1: Greenhouse gas emissions (assessed with IPCC 2013 [17]) by life cycle stage of various devices.

Figure 2 shows the GHG emissions caused by the production of main components for three mobile phones (Sony Ericsson W890 [6], Fairphone 2 [8] and Sony Xperia Z5 [9]). The production of the integrated circuits (ICs) accounts for the majority of GHG emissions during the production phase. This effect is mainly due to the use of fossil-based electricity in the manufacturing countries in Asia, because the manufacturing of ICs is a highly energy-intensive process. The ICs consist of processor and memory chips. According to Ercan et al. [9], the GHG emissions caused by the production of the processors (about 4 kg CO_2-eq per cm^2) is higher than for the memory chips (about 3 kg CO_2-eq per cm^2) because the memory production consumes less electricity and has higher yields.

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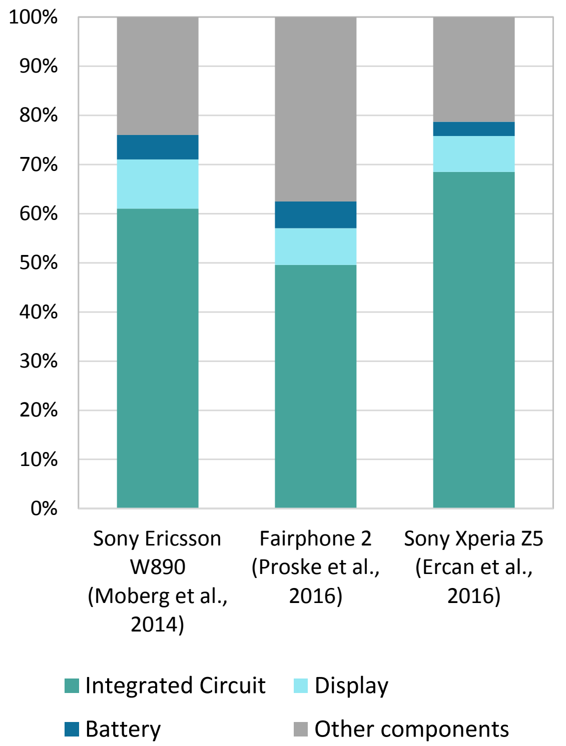

Figure 2: Contribution of different components to the total greenhouse gas emissions caused during production of smartphones (assessed with IPCC 2013 [17]).

Moberg et al. [6] assess the effects of different components in terms of different environmental impact categories for the mobile phone Sony Ericsson W890. For all impact categories, the ICs cause the largest impacts. Again, the effects are mainly due to electricity generation, which is needed for the energy-intensive production of ICs. Ercan et al. [9] also investigate the effects in different impact categories of the Sony Xperia Z5 smartphone. The production stage dominates the impacts in terms of GHG emissions, particulate matter, photo-oxidant creation potential, acidification potential and fresh water eutrophication. The raw material acquisition, in particular gold and copper, cause most of the toxic impacts and the resource depletion.

2.2 Measures for Lifetime Extension of MIEDs

As the production phase dominates the environmental impacts caused throughout the life cycle of MIEDs, extending the average service life of MIEDs (and thus reducing the number of devices produced) seems to be a promising approach to reduce environmental impacts caused by MIEDs. Measures to extend the service life of MIEDs can be clustered into three target categories [18]: The first target is to (1) increase longevity of devices through improved hardware or software. The second is to (2) encourage retention, i.e. increasing the time a device is used by the same user. The third is to (3) promote recirculation, i.e. passing on a device to a different user. A number of different measures can help contributing to one or several of these targets. Table 1 provides an overview of selected measures.

Category	Measure
Improve device design	Avoid software- or hardware-induced obsolescence
	Improve reparability and upgradability
	Improve durability
Retention	Increase awareness for environmental impact of device production
	Increase user attachment to device
	Provide possibilities to repair device
Recirculation	Re-sell device
	Pass on device (e.g. to a family member)
	Device-as-a-service business models
	Repurpose device in different context (e.g. for educational purposes at schools)

Table 1: Selected measures to extend the service life of MIEDs clustered into three categories.

These measures differ in the involvement of and impact on a variety of actors. For example, device design measures lie mainly in the responsibility of organizations involved in the production of MIED hardware and software; however, these face trade-offs when adopting these measures because their revenues correlate with the number of devices produced. Thus, business models, which decouple revenues from the number of devices produced (e.g. renting out instead of selling devices), and policies to incentivize manufacturers to increase service life of devices are required. For example, the EU is considering an initiative to force device manufacturers to use universal mobile phone chargers with a standardized interface [19].

Device retention is mainly shaped by consumer decisions (e.g. when and whether to purchase a new device, repair a broken one, etc.). However, device manufacturers and retailers can also increase device retention, e.g. by offering affordable and convenient repair services or by increasing user attachment to devices through design measures (e.g. engravings). The launch of new device generations and associated marketing activities can have a reducing effect on device retention. Eventually, also the legal framework is important here (e.g. warranty requirements, etc.).

Recirculation measures are again shaped to a large extent by consumer decisions. There must be both a supply of attractive secondary devices as well as a demand for them. Apart from financial considerations and privacy concerns, recirculation is influenced by the availability of convenient ways to pass on a device that is no longer used, e.g. through conveniently located drop-off points [20]) or attractive platforms for re-selling devices.

In many cases, organizations trying to operationalize approaches face challenges. For example, durable and modular smartphones are often larger and heavier than their non-modular counterparts, which is a conflict with demand for compact and lightweight devices [21]. Finding creative solutions requires collaboration of various actors along the MIED value chain, which partly compete with each other. For example, improving modularity of a smartphone can allow new companies to produce spare parts, which were originally only sold and replaced by original equipment manufacturers. Thus, more systematic research allowing to compare the feasibility of various measures is required.

3 Exploring Approaches to Assess Service Life Extension

In the following, we discuss possibilities for assessing environmental impacts of service life-extending measures. This can be seen as a starting point for future research in the field.

3.1 Updated Life Cycle Inventory (LCI) Model for a Smartphone

The availability of life cycle inventory models of MIED specific components is limited. Hischier et al. [22] modelled a smartphone based on data from the ecoinvent database. The production effort for a smartphone is estimated based on available data of production impacts of a laptop computer. In comparison, recently published LCA studies of the production of smartphones show a significant difference in the environmental impact per device. Therefore, we adapted the modular LCI model of Hischier et al. [22] with more recent information on specific components.

3.1.1 Approach

Based on the dataset of Hischier et al. [22], we adjusted the wafer size of the ICs; the weight of the battery, the display, the circuit boards; and also the energy consumption during the production phase. We have modelled the iPhone 6s because Apple has published an environmental report for it [12] and because a teardown report [23] by Chipworks for this device is publicly available. Background data was gathered from the database ecoinvent [24], version 3.5 using the system model "allocation, cut-off by classification".

Since ICs are responsible for the majority of the environmental impact in the production of MIEDs, we paid particular attention to the modelling of ICs. For modelling the ICs of a smartphone, Hischier et al. [22] scaled the weight of a laptop chip to the weight of a mobile chip. However, there are significant differences in the design of ICs used in laptops compared to those used in smartphones. Laptop in contrast to smartphone logic type IC chips, consist of much more IC packaging, which has a lower environmental impact. A smartphone logic type IC chip usually has very little IC packaging, i.e., the chip has almost the same size as the wafer. This is due to the demand for smaller devices with higher performance. Therefore, we increased the surface area of the wafer so that it corresponds to the surface are of a smartphone chip.

In order to adjust the wafer size, we have used the information [23] about the ICs contained in the iPhone 6s. The sum of all logic type IC chips is 6.43 cm^2 [23] per 11 g circuit board [12]. Since smartphone logic type IC chips hardly require any IC packaging, we have made the simplified assumption that the specified area corresponds to the wafer area. The weight of the logic type IC chips and memory type IC chips per circuit board has not been changed. With this information, a wafer area of 0.403 m^2 per kg logic type IC was calculated. This corresponds to an increase of the area by a factor of 22.4, resulting in GHG emissions of 3.45 kg CO_2-eq per cm^2 IC logic type. Manufacturers state that the GHG emissions for processed wafers is in the range of 2.7–4.3 kg CO_2-eq per cm^2 [9]. Thus, our result is within the expected range.

For adjusting the wafer size of the IC of memory type chips, a different approach was chosen. Apple states that the life cycle of the iPhone 6s with 32 GB memory has GHG emissions of 54 kg CO_2-eq and with 128 GB a GHG emissions of 61 kg CO_2-eq. Thus, extending the memory capacity by 96 GB increases the GHG emissions by 7 kg CO_2-eq. Therefore, we assume that manufacturing an IC of memory type with 32 GB memory capacity causes 2.33 kg CO_2-eq. Consequently, we increased the wafer area of the memory type IC until this target value was reached. This resulted in a wafer area of 0.042 m^2 per kg IC of memory type.

In the Environmental Report of the iPhone 6s, the weight of the components circuit boards is stated as 11 g, the display as 29 g and the battery as 26 g [12]. Furthermore, it is stated that the iPhone 6s contains 25 g aluminium, 24 g stainless steel, 18 g glass and 7 g plastic [12]. We adapted the LCI model of Hischier et al. [22] according to these specifications.

For reflecting the target GHG emissions of 43.2 kg CO_2-eq for the production of an iPhone 6s (with 32 GB) [12], we assumed that the remaining difference to the target value of 43.2 kg CO_2-eq is caused by electricity use. This resulted in additional electricity use of 14.3 kWh. This simplification is intended to cover the effects of other aspects that have not been taken into account yet, such as the amount of gold used. In our future work, we will look into these aspects and gradually replace this additional consumption of electricity.

3.1.2 Result and Interpretation

Existing studies (see Section 2.1) suggest that the environmental impact of MIEDs increases with higher device complexity. This is because the memory chip, the CPU, and the graphics chip have the greatest effect on the GHG emissions in the production of the device. For this reason, we have put our focus on updating the LCI for ICs used in smartphones.

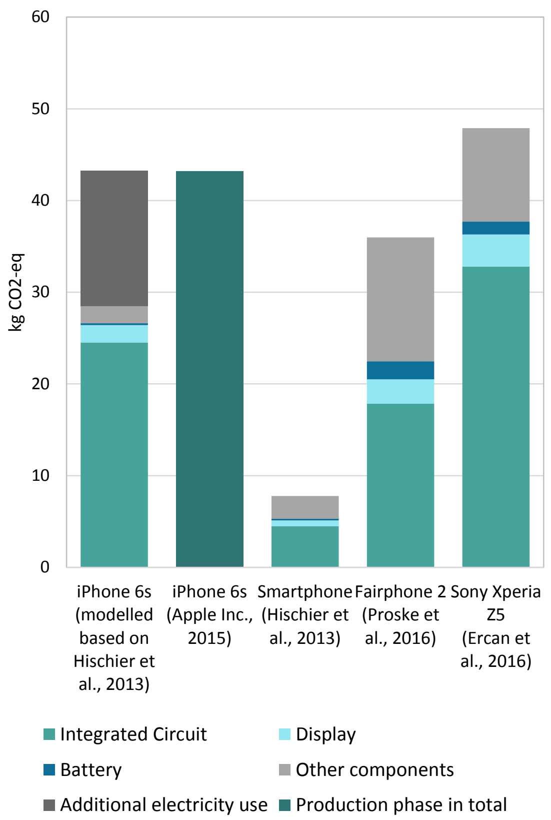

Figure 3: Updated iPhone 6s model in comparison with results from published LCA studies: Greenhouse gas emissions (according to IPCC 2013 [17]) of the production phase per module.

Figure 3 shows the GHG emissions of the production phase per module of the updated model of the iPhone 6s in comparison with the original iPhone 6s [12], the initial model according to Hischier et al. [22] and other results from published LCA studies [8], [9]. It can be seen that the share of the production of the ICs of the total device is within an expected range. The GHG emissions of the IC production of published LCA studies is between 50% and 68% of the total production phase, in the case of the modelled iPhone 6s it is 57%. It can be concluded that adjusting the wafer area is a reasonable approach for updating the LCI of smartphones. The GHG emissions of the displays are also within the expected range.

In future work the modelling of memory ICs has to be examined more closely. Up to now, the wafer size has been adjusted, but other parameters of the memory chips should also be considered. Besides, the GHG emissions of the battery of the modelled iPhone 6s are below the expected proportion. It is therefore required to examine the battery production in more detail. The electricity used in the production of the individual components and the amount of gold built in the components must be investigated, as these are the primary sources of GHG emissions. In this way, the additionally added electricity consumption could be replaced or allocated to the individual components.

It should also be noted that the approach for updating the LCI model presented in section 3.1.1 describes a starting point for updating LCI models for smartphones. Therefore, this approach contains uncertainties and has to be further improved in future work. For example, information on the IC package area was used to adjust the wafer area, instead of considering the actual die dimensions. Therefore, the next step is to model a recent smartphone for which a detailed teardown report, including the die area, is available.

3.2 Assessment of a Repair Scenario

In order to quantify the environmental impacts caused by the service life-extending measure “repair”, we calculated a repair scenario of an exemplary smartphone, which was in this case the iPhone 8 [23].

Since the display and battery are often replaced during a repair, we have considered a replacement of the battery and the display in our repair scenario. As shown in section 2.1, GHG emissions from battery production account for up to 5% of total emissions of the production phase. The production of the display accounts for up to 10 % of the total emissions of the production phase.

For investigating the impact of the transport required for the smartphone’s repair, we calculated the environmental impacts using a lorry process from the ecoinvent database version 3.5 using the system model “allocation, cut-off by classification” [24]. A transport from Switzerland to Poland with a distance of 1,000 km (2’000 km in total including the return trip) was assumed. The calculated GHG emissions for the transport to Poland only account for about 1% of the GHG emissions of the production of a new display.

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Figure 4 compares the GHG emissions of the repair scenario with GHG savings due to a possible avoided production of a new device. In both cases, the use phase is assumed to be 2 years.

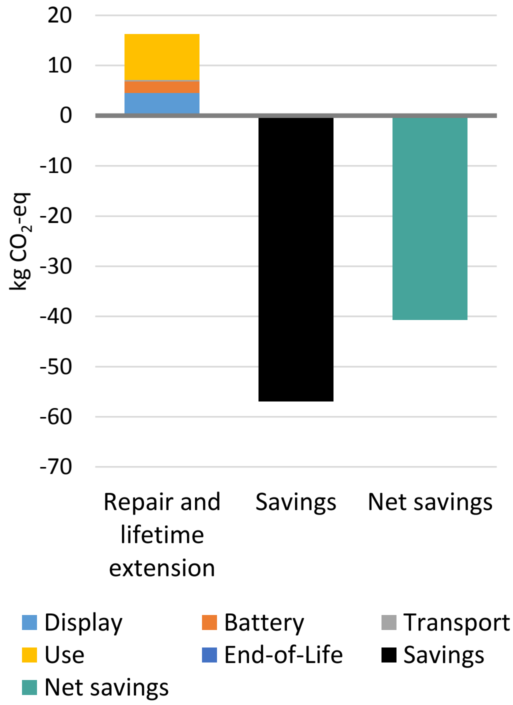

Figure 4: Greenhouse gas emissions (assessed with IPCC 2013 [17]) of a new device in comparison to the repair scenario.

Assuming the service life is extended from 2 years to 4 years and the display and the battery are replaced after 2 years, 72% of the GHG emissions of a new device can be saved compared to buying a new device every two years. This is because the main environmental impacts are caused by the ICs that are not replaced in the repair scenario.

Therefore, we can conclude that the extension of the service life by replacing a battery or a display is worthwhile in terms of GHG emissions, despite the additional emissions from the production of new components and transportation.

3.3 Indirect Effects of Service Life-extending Measures

The main target of measures to extend the service life of MIEDs is to reduce the number of devices produced and associated environmental impacts. However, indirect effects (e.g. rebound effects) can counterbalance environmental gains from service life-extending measures.

Tamar and Makov [26] discuss two rebound mechanisms of service life-extending measures of smartphone: *Imperfect substitution* occurs when extending the service life of a used device "does not avoid demand and production of new product units on a 1:1 basis" [26, p. 2]. *Re-spending effects* occur if used devices, parts or materials are cheaper than their new counterparts, leading to an increase in effective income of consumers who purchase other goods or services, which are also associated with environmental impacts. A flourishing market for used MIEDs can even stimulate market growth, e.g. because consumers can easily sell their devices and invest the income into new devices [26], [27]. Some users, who would not have purchased a new device at all, might purchase a used device because it costs less [26]. The results of the analysis of Makov and Font Vivanco shows that in the US imperfect substitution and the re-spending effect lead to rebound effect between 27% and 46% for specific smartphone models and can even exceed 100% (backfire) in specific regions and under different consumer behaviour.

Service life-extending measures can also lead to induction effects, which occur if adopting the measures induces activities, which are associated with environmental impacts (e.g. consumers traveling to repair facilities or additional connectors required in modular smartphones). Exporting devices for re-use in developing countries can also cause environmental impacts beyond energy consumption and GHG emissions, because these devices, at their end-of-life, are often informally recycled with toxic impacts on the environment and humans [28].

Thus, whether or not a service-life-extending measure leads to reduction of environmental impacts of MIEDs depends largely on the extent to which a measure increases the service life of a device or its components, and thereby avoids additional production, as well as associated rebound and induction effects.

4 Discussion and Conclusion

As the production of ICs causes the highest environmental impacts throughout the service life of an MIED, extending the service life of an MIED is a promising approach to reduce environmental impacts caused by MIEDs. Several measures to extend the service life have been explored in academia and industry practice, which can be clustered into measures, which aim at improving the device design, at device retention and device recirculation. We assessed environmental impacts of a repair measure and showed that the production of new devices causes more than two times more GHG emissions than extending the service life of an existing device by replacing the display and the battery.

However, indirect effects (such as rebound effects) can compensate for environmental gains from lifetime extending measures. For example, it is unclear to what extent the extension of the service life of an MIED actually avoids the production of a new device. Also, re-using devices might trigger additional consumption (e.g. for accessories) or the availability more affordable – used – devices can induce consumers to replace their existing device earlier than later. These effects depend on the behaviour of individual consumers and complex supply and demand relationships in the MIED market.

Thus, environmental, behavioural and economic aspects have to be taken into account in order to develop service life-extending measures that entail environmental benefits while being both economically viable and appealing to consumers. To successfully implement measures to achieve service life extension, economically viable business models, which have environmental benefits and are socially accepted, are required in order to incentivise a more sustainable use of MIEDs.

5 Acknowledgement

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Market Trends in Smartphone Design and Reliability Testing

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Abstract

Over the past decade, smartphones have become ubiquitous. Annual shipments have increased from 305 million units in 2010 to 1.37 billion units in 2019. This makes smartphones a highly relevant product group from a sustainability point of view. This paper firstly investigates market trends in smartphone design features over the past decade, both in terms of the evolution of technical specifications and design aspects that are relevant for material efficiency, particularly reparability and dismantlability. Secondly, reliability testing carried out by ICRT on 108 smartphone models are analysed. Both analysis combined provide a factual data base on which the development of the product group in present, past, and future, can be evaluated in the framework of a sustainable development.

1 Introduction

Over the past decade, smartphones have become ubiquitous. Annual global shipments have increased from 305 million units in 2010 to 1.37 billion units in 2019 [1]. This makes smartphones a highly relevant product group from a sustainability point of view. Reflecting this, the European Commission has launched a preparatory study to investigate the need and potential options for regularity measures under the Ecodesign Directive (2009/125/EC) in April of 2020.

A mounting number of studies investigates the environmental impact of smartphones, such as through life cycle assessment, and attempt to identify measures to mitigate environmental burdens. The consensus is that the majority of environmental impacts of smartphones is caused during the manufacturing stage, largely due to the energy intensive production processes associated with electronics [2].

Environmental impacts are influenced by many factors, a major aspect being hardware design. Therein, relevant questions are: How much RAM and flash memory are incorporated? Can the housing be opened for repairs? Is the battery user-replaceable? Is the smartphone protected from water and dust ingress? Does the device survive an accidental drop?

The first part of this paper analyses the evolution of technical specifications and major design trends that influence the environmental performance of smartphones over the past decade. Market data on the best-selling smartphones between 2010 and 2019 are complemented with specifications and design aspects to generate an array of diagrams that illustrate where this fast-evolving product group has moved towards.

In the second part of the paper, these design trends are linked to laboratory testing results from an international testing laboratory, investigating a range of reliability aspects such as ingress protection and resistance to mechanical abrasion and accidental drops.

Both analysis combined provide a factual data base on which the development of the product group in present, past, and future, can be evaluated in the framework of a sustainable development. The insights may be used to gain an understanding of the design of smartphones currently in use and in the urban mine. They may also serve to support the discussion around policy processes aiming to enhance the environmental performance of the product group smartphones.

This work is part of the H2020 project PROMPT, funded by the EU. The data and information described in this paper are partially based on a deliverable produced within the PROMPT project [3].

2 Methods

2.1 Market trends in smartphone design

The basis for the analysis of trends in smartphone design features is market data retrieved from Counterpoint Technology Market Research [4]. The data comprises sales volumes and market shares for the best-selling smartphone models in wider Europe (countries located in geographical Europe) for the years 2010 to 2019. The number of individual smartphone models and their share of the overall smartphone market varies for each year: 16 models are listed for 2010, 20 for 2011 and 2012, 22 for 2013, and 25 for the years 2014 to 2019, respectively. The total sales volume of

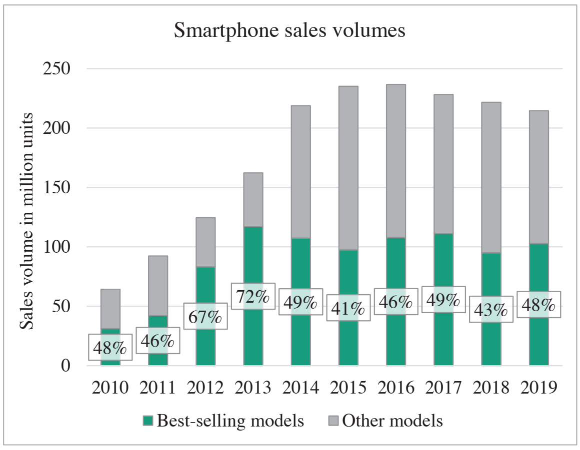

Figure 1: Sales volume of smartphones in wider Europe and market share of the smartphone models covered by the data from Counterpoint Technology Market Research [4]

smartphones and the market share covered by the listed models are illustrated in Figure 1.

The market data for listed smartphone models were complemented with technical specifications from a range of sources such as the GSM arena website [5]. To retrieve information on design and construction-related aspects of each phone model, a range of sources was consulted, including teardowns and repair instructions from iFixit [6].

2.2 Reliability testing of smartphones

Data was provided by the International Consumer Research & Testing (ICRT) within the framework of the Horizon 2020 PROMPT project for 108 smartphones from their 2018 testing programme [7]. The sample consists of low, middle and high-end devices. Several durability tests such as tumble tests, scratch tests (cover and camera) as well as rain (water spray) and water immersion (dive) tests were performed with all devices under test.

Durability against mechanical shocks (e.g. accidental drops) was tested with a tumbling barrel simulating a random fall from 80 cm height against a stone surface, as described in standard IEC 60068-2-31 [8]. For this test, devices are set in operational mode (e.g. active call), put into a tumbling drum for 50 and 100 drops and checked regularly. In case of damages during the test, the results are verified with a second and, if necessary, a third device.

Scratch hardness tests were performed to test how scratch-resistant displays and cameras are. The scratch resistance of the phones' displays and housing is commonly examined using a hardness test pencil (e.g. ERICHSEN, Model 318 S).

For the rain test, the devices were switched on and connected to a network. Following the standard IEC 60529 [9], a raining appliance provides an even rain distribution according to Ipx1 (7.2 l/h). The phones are placed horizontally on a turning table and are irrigated by the appliance for 5 minutes. The functions of the phone are checked directly after the test and several days after. When it comes to the immersion test, only those devices were tested that are certified to be ingress protected from water (at least IPX7) according to IEC 60529 [9]. Following this standard, the devices are submerged into a water tube at a defined maximum depth for 30 min. The correct functioning is checked directly after the test and several days later.

All tests results are reported on a five-point scale from 1 (poor) to 5 (very good).

3 Results and discussion

The results are presented in the following three subchapters, firstly on the evolution of technical specifications, secondly on the smartphone design features with relevancy to material efficiency, and thirdly on reliability testing results.

3.1 Market trends in technical specifications of smartphones

The development of technical specifications in the market is illustrated in a range of diagrams that comprise the market average among the best-selling smartphones for each year in addition to the minimum and maximum value to illustrate the variance of specifications in each year.

The average display size of smartphones, measured as the diagonal in inches, has roughly doubled over the past decade, from 3.2 in 2010 to 6 inches in 2019 (Figure 2). Among the best-selling smartphones in 2019, the largest display measured 6.7 and the smallest 4.7 inches.

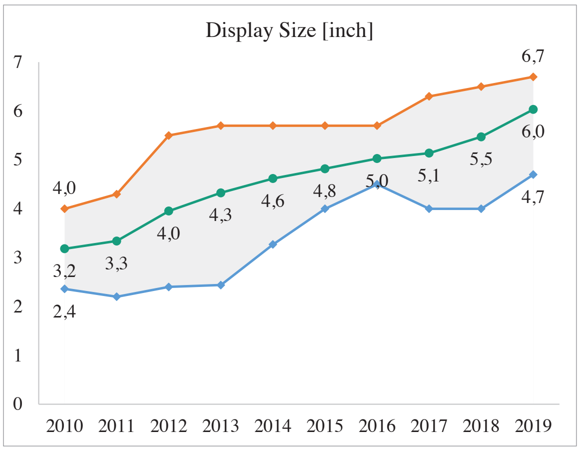

Figure 2: Increase in smartphone display size

The screen-to-body ratio signifies the area of the display relative to the front-facing area of the smartphone.

With increasing screen-to-body ratio, the bezels around the display becomes slimmer, with the display of some devices extending from one side to the other entirely.

The average screen-to-body ratio has been steadily increased over the last decade, from 46 % in 2010 to 81 % in 2019 (Figure 3). The extremes in 2019 among the best-selling smartphones were at 65 % and at 89 %.

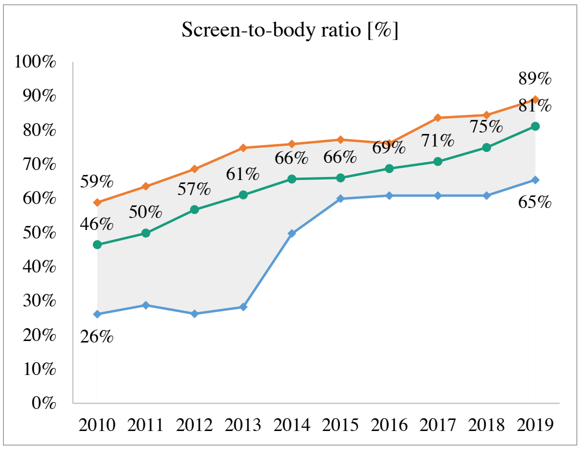

Figure 3: Increase in the screen-to-body ratio

Random access memory (RAM) is an essential component determining the performance of computing devices. The amount of RAM has been increased over time to match increasing performance requirements posed by operative systems and applications. Some smartphone models offer several configurations of RAM. In those cases, the largest available configuration was chosen for the analysis.

The average amount of RAM in the best-selling smartphones in Europe has increased sixteen-fold from 0.3 gigabytes (GB) in 2010 to 4.8 GB in 2019 (Figure 4). The phone model with the least amount of RAM features 2 GB, while the phone model with the highest configuration features 12 GB.

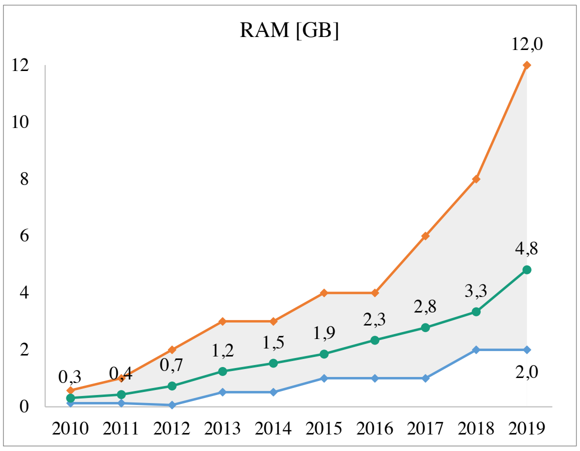

Figure 4: Increase in RAM in smartphones

Internal storage in smartphones is required to store the operating system, apps, and personal data such as photos and music. Commonly, flash memory integrated circuits are used for this purpose. The amount of storage space available has steadily increased over time to meet the need of users to store more and larger files. Some smartphone models offer several configurations of internal storage. In those cases, the largest available configuration was chosen for the analysis.

The average amount of internal storage in the best-selling smartphones has increased from 11 GB in 2010 to 248 GB in 2019. The phone model with the least amount of internal storage features 32 GB internal memory, while the model with the highest configuration features 1.000 GB or 1 terabyte (TB).

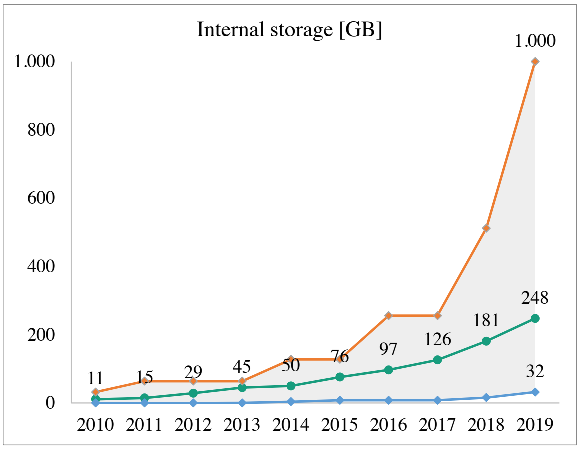

Figure 5: Increase in internal storage

Battery life is an essential parameter of personal mobile equipment. This, in addition to increasing computing power and display sizes, is a considerable driver to increase the battery capacity of smartphones.

The average battery capacity of smartphones, commonly specified in miliampere hours (a measure for electric charge), has increased from approximately 1.300 mAh to approximately 3.300 mAh within the last decade, effectively a 2.5-fold increase. Battery capacity is therefore the feature with the least growth within the last decade among assessed features.

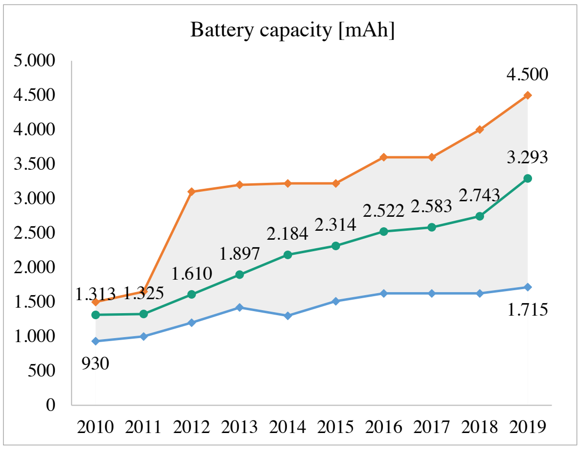

Figure 6: Increase in battery capacity

3.2 Smartphone design features with relevance to material efficiency

One of the most controversial design trends in the product group smartphone in the past decade has been the shift from designs that allow users to easily remove and replace batteries to designs that integrate batteries into the device. This often goes along with sealed housing of the phones to enable elevated ingress protection (IP) from water and dust, commonly communicated by original equipment manufacturers (OEM) with an IP rating according to IEC 60529. Smartphone manufacturers have also increasingly moved from plastic housing to metal and glass housing, particularly in the high-end smartphone market. Glass has become particularly common in recent years, at least in part due to its favourable radio frequency characteristics and compatibility with wireless charging, the latter of which has also been a trend in recent years.

Figure 7 combines the market trend regarding all mentioned aspects. Among the most popular smartphones in Europe, the market share of devices with an embedded battery in the years 2010 to 2012 was between 18 and 33 %. The share of smartphones sold in Europe with an embedded battery then sharply increases every following year until reaching 100 % in the year 2019. This means that all of the 25 best-selling smartphones in Europe in 2019, covering around 48 % of the entire smartphone market in Europe, featured an embedded battery, not easily removable or replaceable without the use of tools and/or thermal energy.

The other design features illustrated in Figure 7, being glass back covers, IP ratings, and wireless charging, have co-developed over the past decade, all sharply increasing between the years 2015 and 2017/2018. There appears to be a reversal in the trend towards the year 2019. This can be explained by the relatively high market share gained by a group of mid-range phones from one of the market-leading OEMs that do not feature many of the designs shared by the phones in the high-end market, including glass back covers, IP ratings, and wireless charging.

Opening the housing is the first step in repair or dismantling, for instance for depollution before recycling. In the past decade, there have been two major design paradigms:

(1) the phone has a back cover that is to be separated in order to gain access to internal components, and

(2) the display unit is separated in order to gain access to internal components ("sandwich type")

The first design commonly enables access to the battery immediately after removing the back cover. Further components are commonly only accessible after removal of a midframe. The display unit and logic boards are therefore commonly not immediately accessible. The second design paradigm provides access to the display unit as well as internal components, including PCBAs and battery, upon opening the sandwich-type housing.

The disassembly pathway for the best-selling smartphones in Europe has shifted in the last decade from predominantly featuring type (1) for approximately 90 % of phones entering the market between 2010 and 2012, while type (2) makes up approximately 50 % in the years 2015 to 2019. The year 2018 saw particularly high market share of phones based on the type (2) design.

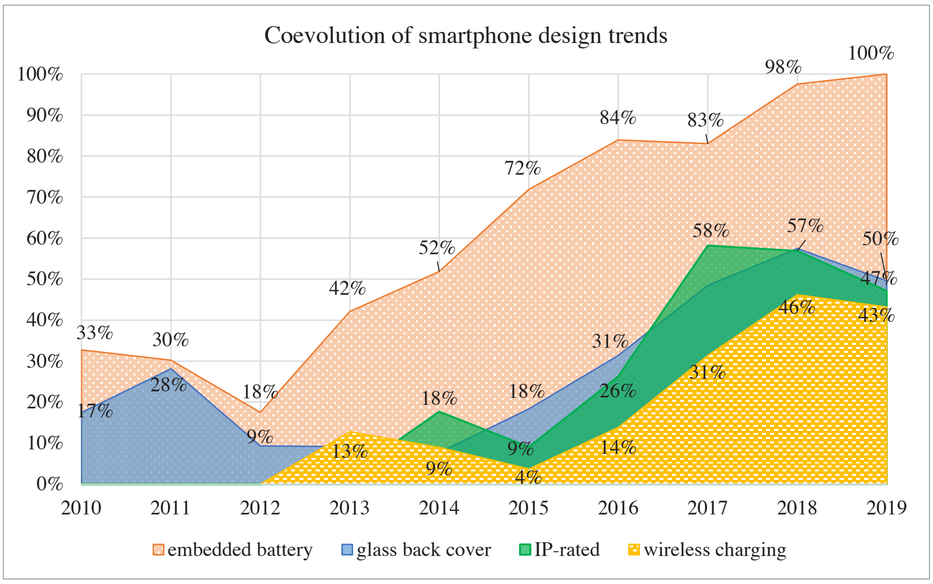

Figure 7: Development of the market share of smartphones featuring embedded batteries, glass housing, IP-rating and wireless charging over the last decade (adapted from Berwald et al. 2020)

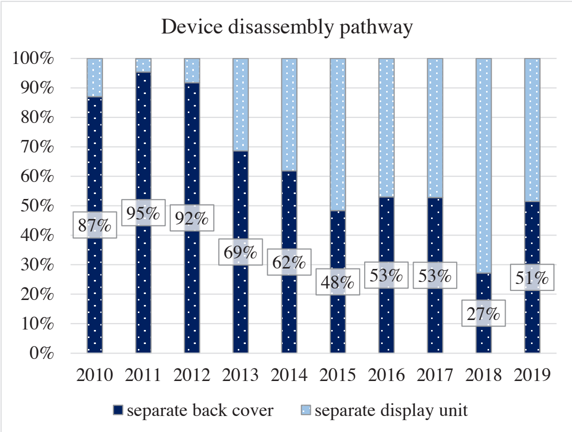

Figure 8: Market share of smartphones following different design paradigms affecting their disassembly pathway

Besides the disassembly pathway, the joining techniques applied to join the housing together are a considerable factor influencing the reparability and dismantlability of smartphones. Commonly used joining techniques for the housing are clips that require no tools to reversibly disconnect, snap-fits that do require tools for leverage, screws, adhesives, or a combination of screws and adhesives. Adhesives commonly require the application of thermal energy or chemical solvents to be dissolved.

The prevalence of joining techniques entering the European market among the best-selling smartphones is illustrated in Figure 9. While at the beginning of the decade, reversible joining techniques (clips, screws) were dominant; there was a shifts towards irreversible joining techniques over time. In 2019, close to 80 % of the most popular devices use adhesives to join the housing components. As mentioned previously, this may serve to enable designs that are more reliable in that ingress from water and dust can be prevented. On the other hand, the use of adhesives potentially complicates repairs that may be required to extend the lifetime of devices that have reached a limiting state, such as the failure of a component, a broken display, or a faded battery. The same can be assumed for recycling processes, in which operators need to quickly and safely remove batteries from electronic equipment.

Joining techniques were also analysed for batteries within smartphones, as these may also influence the process of battery replacement or depollution for recycling. While the market share of smartphones in which batteries were not fastened using adhesive was between 62 % and 85 % in the years 2010 to 2012, a trend towards using adhesives to fix the battery can be observed between the years 2013 and 2019 (Figure 10). In the year 2019, all batteries in the best-selling smartphones were fastened using adhesives. Of those, 52 % were fastened using pull tabs. Pull tabs are a specific design of double-sided adhesive tape that loses its adhesive properties when stretched. It has been argued that this design makes repair operations more user-friendly as opposed to adhesives that require thermal energy to be dissolved, however, a further evaluation is not in the scope of this paper.

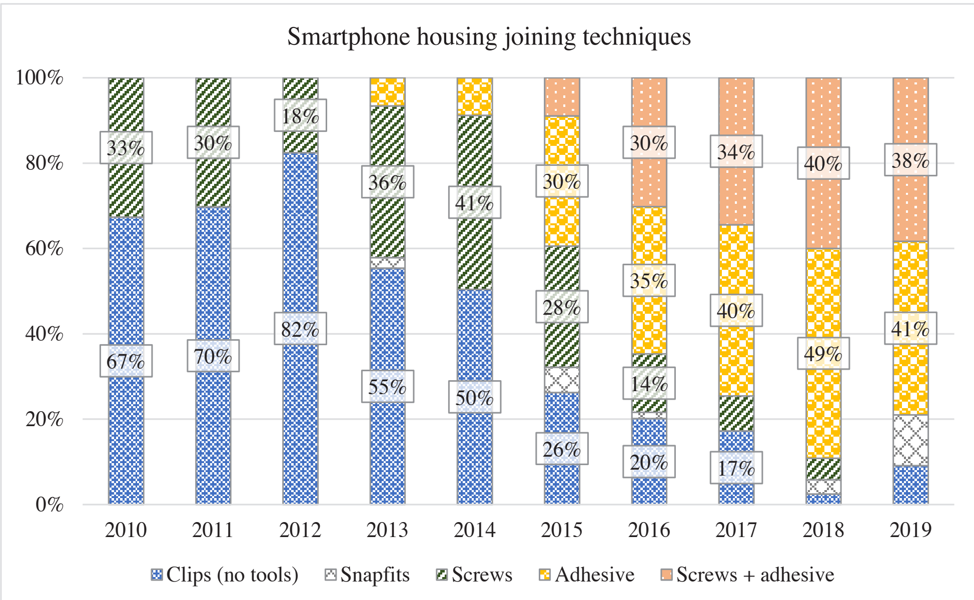

Figure 9: Evolution of smartphone housing techniques weighted by market share among the best-selling smartphones in Europe between 2010 and 2019 (adapted from Berwald et al. 2020)

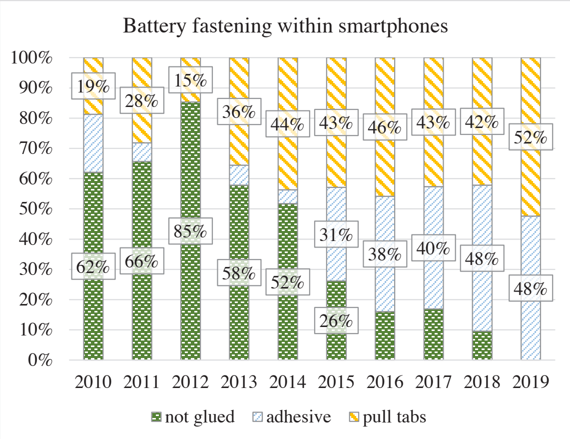

Figure 10: Evolution of joining techniques used to fasten batteries within smartphones (adapted from Berwald et al. 2020)

3.3 Smartphone reliability testing

Results of the tumble test (Figure 11) show that most of the devices had a good or very good test performance (82 %). 21 % of larger phones (> 6.2 in.) performed poorly after 100 drops from a height of 80 cm on a stone floor, as compared to 9 % of smaller phones (< 5.8 in.). “Poor” indicates that the phone is either no longer functioning or that display or housing are significantly damaged. However, these results do not necessarily proof that smaller devices are more likely to survive the tumble test, as other design features may also play a role (e.g. housing material).

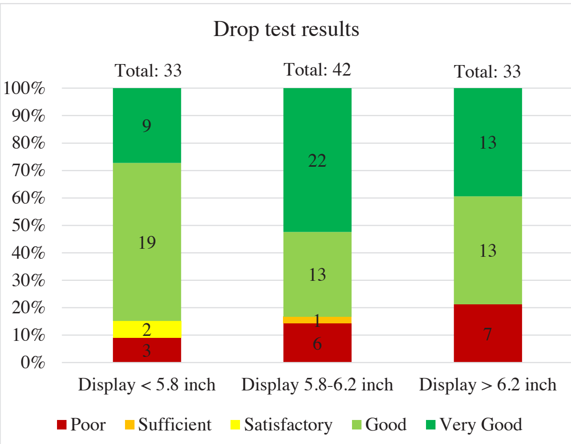

Figure 11: Results of drop tests (100 drops) for 108 phones, by size

When it comes to the cover scratch test (Figure 12), it can be observed that more expensive devices show a significantly better performance. While only 15 % of the devices below 240 EUR had a very good rating, the share was 95 % for the devices above 550 EUR.

The rain test was no problem for any of the devices and all of them performed good or very good, independent of price or battery removability (Figure 13).

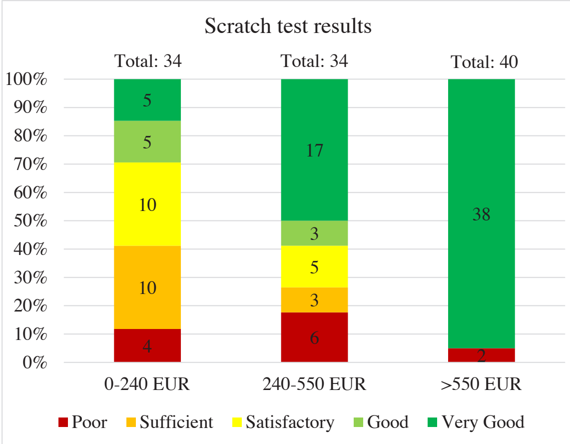

Figure 12: Results of cover scratch tests for 108 phones, by price range

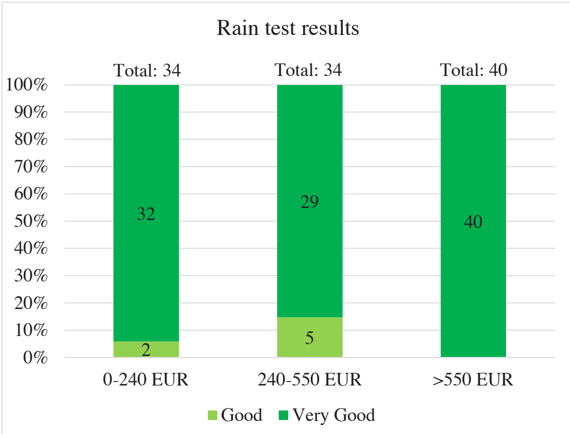

Figure 13: Results of rain tests for 108 phones, by price range

The immersion test was only applied to 32 of the 108 phones, since the others were not certified IPX7 according to EN 60529. All 32 phones featured embedded batteries and the large majority were in the higher price segment above 550 EUR. Only two phones performed poorly during the test, while the others showed either good or very good results (Figure 14).

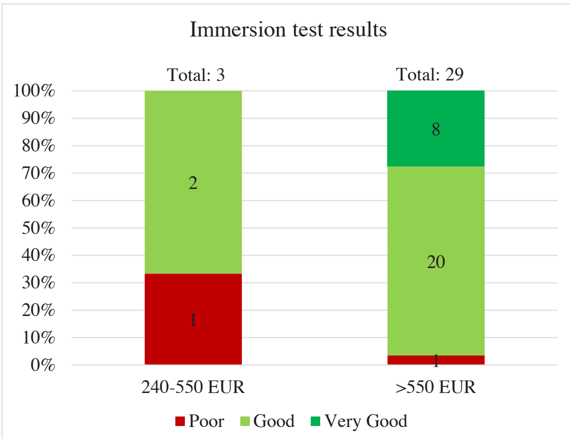

Figure 14: Results of immersion tests for 32 phones, by price range

4 Conclusions

In the first part of this paper, major market trends in technical specifications and material efficiency-related designs were analyzed based on market data covering the best-selling smartphones in Europe. Among technical specifications, the display size, screen-to-body ratio, and battery capacity have steadily increased over the past decade. It remains to be seen whether this increase will continue in the coming years. Assumedly, new designs, such as the emerging foldable phones, may disrupt or accelerate some of these trends. Foldable phones in particular may drastically increase the display size, and therefore also require higher battery capacity, featuring two-cell battery designs. At this point in time it is not yet clear whether foldable phones will remain a niche product or will be able to capture a relevant market share in the future. The amount of available RAM and flash memory appear to have been increasing almost exponentially over the past ten years. Questions remain to which degree Moore's law and advanced heterogenic packaging solutions can continue to support this trend, or whether a slowing down of the increase may be expected in this aspect as well.

For design trends impacting material efficiency, major shifts have taken place over the past decade. In 2019, none of the most popular phones had a user-replaceable battery, and the vast majority was sealed using adhesives. At the same time, the market share of devices with ingress protection rose sharply, to almost 50 % of the market in 2019. Therefore, it may be deducted that the market appears to favor more reliable over more reparable designs. One question in this regard is how well the electronics recycling sector will be able to handle the expected enormous numbers of end-of-life smartphones to be dismantled in the coming years featuring such designs.

Throughout the paper it has been made clear that the data only covers the best-selling devices in Europe, covering a share of the total smartphone market between 41 and 72 %, depending on the year. The "rest of the market" could not be covered due to absence of data, but it is assumed that a major share of devices not covered can be categorized as mid-range and low-end devices, that do not necessarily share all design features assessed in this work. For instance, plastic tends to be a cheaper material compared to metal or glass for the housing parts. Lower amounts of RAM and flash memory, as well as smaller battery capacity, may also be assumed. Similarly, IP-ratings and wireless charging may less frequently be encountered. No information on the accessibility of the battery in this market sector was retrieved for comparison. However, to provide an indication, from the 108 smartphones subjected reliability test by ICRT in their 2018 testing program, featuring devices from all market segments, only 5 featured a user-replaceable battery, while 103 featured embedded batteries.

The test data shows that nowadays most smartphones perform well during rain or scratch tests, irrespective of their price range. While most phones pass tumble drop tests well, larger phones tend to fail this test more frequently. The data further suggests that smartphones with embedded batteries do not perform significantly better than devices with replaceable batteries. The more expensive phones are more likely to pass the immersion test.

Smartphones will likely remain a ubiquitous communication tool for billions of people worldwide. The potential impacts of market trends need to be carefully considered by manufacturers, consumers, and policymakers, in order to steer towards a sustainable development.

5 Acknowledgements

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We want to thank ICRT for kindly providing data from their smartphone testing program, and Counterpoint Research for approval to publish part of their data.

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Customer acceptance of mobile devices with permanently installed batteries and accumulators

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Abstract

The aim of this paper is to critically examine current mobile devices such as toothbrushes with a focus on the consumer behaviour when buying toothbrushes which was examined using an online survey. The survey is particularly concerned with the issue of whether consumers at the point of sale are aware of what kind of toothbrush they are buying and what the impacts, especially the ecological effects, of toothbrushes are. It was therefore analysed whether consumers recognise if an electric toothbrush is a rechargeable or a battery-operated toothbrush, the latter of which has to be disposed of after the energy charge in the battery is empty. In addition, questions were asked on whether consumers are aware of how to recycle electric toothbrushes and which dismantling activities must be carried out before disposal.
The error rate of 18-29% in the recognition of the correct toothbrush model when considering battery-operated products showed the unawareness and incorrect purchase by the customer when buying.

1 Introduction

Products of everyday life are becoming more and more mobile, which usually goes hand in hand with the change from a stationary energy supply, often a cable, to a mobile energy supply. The use of batteries and accumulators gives consumers the mobile freedom they want. However, it leads to the integration of further electronic components into the product, which inevitably causes an increase in the ecological footprint since more material and resources are used. According to the global e-waste monitor an annual per capita average basis of 19.4 kg e-waste was estimated for Germany in 2017, 52% of which was formally collected [1]. The average collection rate of batteries in Germany in 2018 amounted to 47.67%, a number that has changed by only 4.27% since 2011 [2].
Furthermore, the use of batteries and accumulators severely limits the lifespan of the products: In the case of the battery directly as the functionality ends with the exhaustion of the battery; in the case of rechargeable batteries indirectly as the lifespan of the total device also depends on the use of the rechargeable batteries. The rechargeable battery often breaks much faster than the total device, which ultimately causes the in-operability. In addition, in-operability is very often caused because devices are no longer repaired, spare parts are unavailable, consumers are simply overwhelmed or see the defect in the device as a welcome reason to buy a new product [3].

2 Methods and Sample

An online survey was chosen as the method for data collection, which took place within Germany over the course of six weeks between June and July 2020. In the survey, the people interviewed aged 17 to 82 were put in a virtual buying situation in the drug store. A total of 87 people took part in the survey. They first saw a picture of a typical toothbrush sales shelf before being asked about 10 individual toothbrush models, by showing individual pictures of the different toothbrushes, which included three battery operated, two rechargeable and five manual models. The participant could then choose between the answers “manual”, “battery” or “accumulator” toothbrush to determine whether they are able to differentiate between the varying models based on appearance alone.

The special toothbrushes of interest were the battery-operated models from Dr. Best multiexpert Vibration, elmex ProAction Vibration and Oral-B Pro Expert Pulsar. Sold at local drug stores for approx. 4.95 €. With these models it is stated that it takes about three months until the respective battery is exhausted and the toothbrushes have to be disposed of. It then has to be disposed of by removing the battery, which proved to

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be difficult since the bottom did not open easily as tested by one of the research group members, further proving that this toothbrush was not designed to being able to exchange batteries once the original battery is empty. Afterwards the empty toothbrush has to be brought to a recycling centre and the battery to a collecting point available in most drug stores and supermarkets in Germany.

3 Results

3.1 Consumer behaviour

With 48.2%, about half of the respondents indicated that they used an electric toothbrush. Accordingly, minimally more people use conventional toothbrushes for daily tooth cleaning. The recommended use phase for toothbrushes is estimated to be at a maximum of one to three months [4] which almost 52% of the interviewees followed, while around 39% answered that they use their toothbrushes for six months or longer, pictured in figure 1.

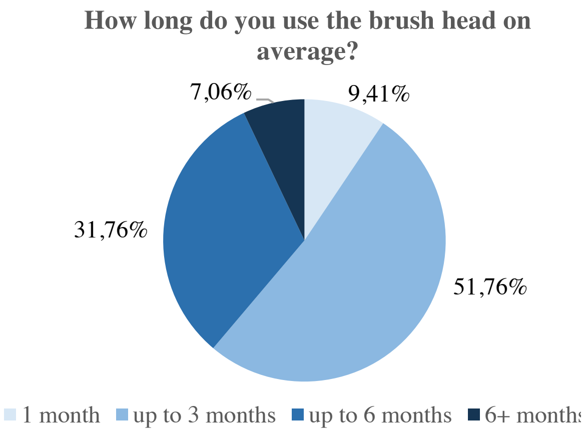

Figure 1: Average time of use for toothbrush

When talking about consumer behaviour and purchase decision one must also consider that past experiences have a big influence [5]. The answers showed that when consumers were satisfied with their toothbrush, they very often resorted to the same toothbrush when buying a new one. Loyalty to a specific toothbrush is therefore high.
Based on the reasons for the purchase decision, the following result is shown. The customers especially look at quality aspects (75%) and price (54%) when purchasing toothbrushes. Followed by sustainability aspects (31%) and the manufacturer's brand (27%).

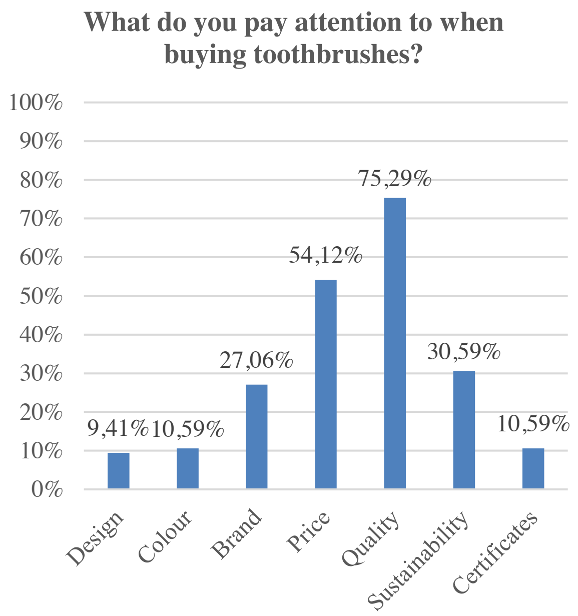

Figure 2: Importance of different criteria during toothbrush purchase

The survey also shows that the number of toothbrushes available in households is larger than the number of people in the household.

Sustainability is becoming increasingly important for people today. This is shown repeatedly by studies such as the “Environmental Awareness in Germany” study prepared by the Federal Environment Agency in Germany. According to the study, 53% saw sustainability, environmental and climate protection as a very important challenge in 2016. In 2018 the percentage increased to 64 and in 2019 to 68% [6]. In our survey, 78% gave sustainability a high priority in their daily lives. With regard to toothbrushes, however, the results of the statements change relevantly. When asked about the importance of sustainability for toothbrushes, only 45.88% mention it (see figure 3). Conversely, this means that the sustainability potential of toothbrushes is not considered so high relevant by consumers. According to the motto, choosing my toothbrush will not save the world.

In the further course of the survey, the respondents were more and more familiar with the properties of the three toothbrush models Dr. Best multiexpert Vibration, elmex ProAction Vibration and Oral-B Pro Expert Pulsar. After dealing with the toothbrushes, they were asked specifically if they could imagine buying the Dr. Best multiexpert vibration. Only 11% answered yes, whereas 89% answered that they would not buy the toothbrush. Throughout the course of the survey, it became obvious that potential customers do not always understand what they are actually buying, but if they understand that it is a complex electronic product that needs to be disposed of after a battery charge, almost 90% do not want to buy it.

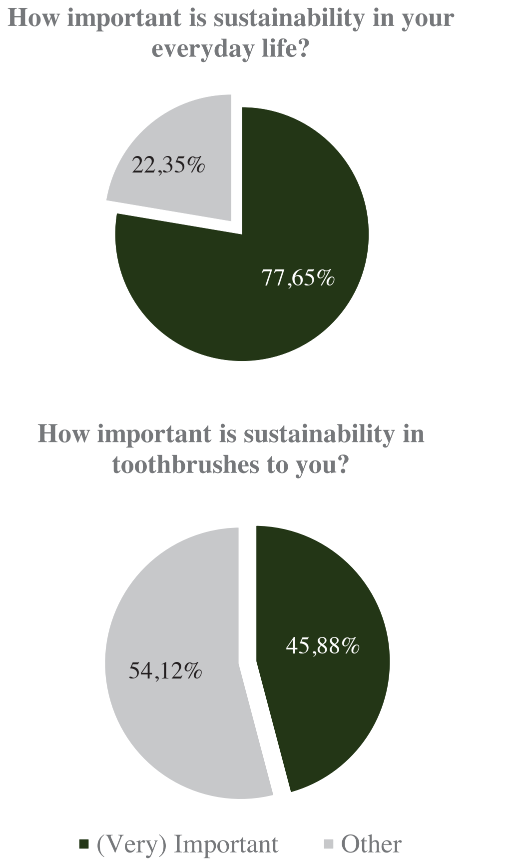

Figure 3: Importance of sustainability in everyday life (left) vs. in toothbrushes (right)

3.1.1 Recognition of correct type of toothbrush

While 40% of the toothbrush models were identified correctly, especially the three battery operated models proved to be difficult for the interviewees to be identified.

Shown in the following diagram are the percentages of the frequently misidentified toothbrush models (figure 4). The error rate of 15-34% clearly demonstrates how easy it is for the manufacturer to visually misguide the customer (If you only look at the three toothbrushes with batteries, the error rate in the detection is 18-29%). Moreover, the indistinct package description and design might lead to purchase mistakes. Oral B Pulsonic Slim is at the forefront when it comes to the toothbrush that has most often been wrongly determined. About a third of those surveyed think that what is operated with a rechargeable battery is a toothbrush that uses a non-rechargeable battery for power supply. Ultimately, for the Oral B Pulsonic Slim it means that with the advent of battery-operated toothbrushes, it is increasingly misperceived. For a long time it was the only toothbrush with a rechargeable battery on the German market, which was still very narrow, all other models with a rechargeable battery built much thicker.

3.2 Recycling process

The recycling process explained on the backside of the *Dr. Best, elmex and Oral-B* toothbrush packaging was described as “For disposal please remove the battery. Afterwards dispose the battery and the empty toothbrush environmentally sensitive and not in normal household waste.” While almost 60% stated the correct recycling process for both battery and empty toothbrush, 35% gave incorrect answers most of which

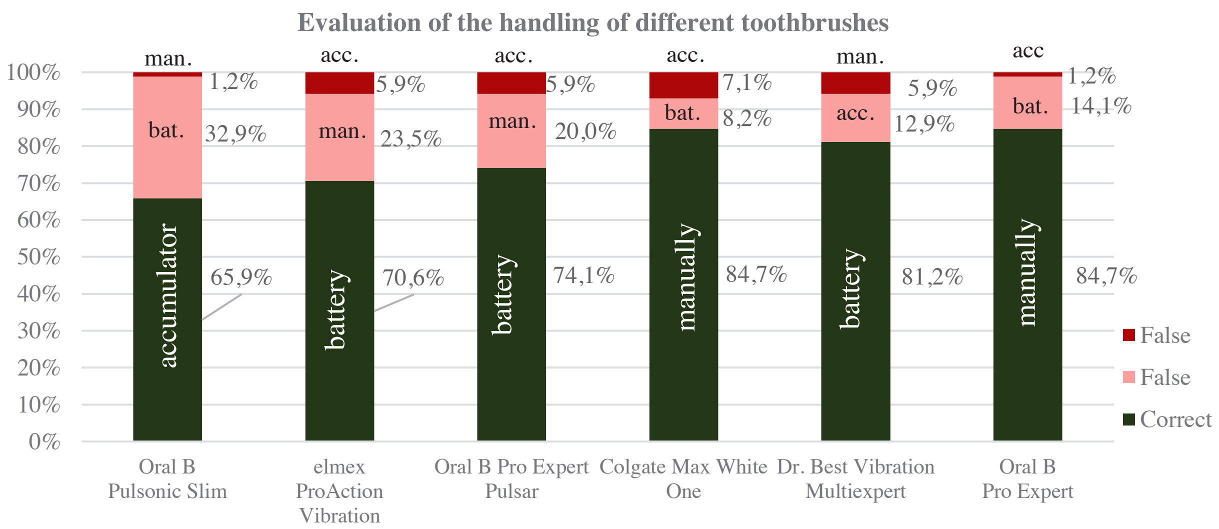

Figure 4: Answers to the question of what type of toothbrush it is

explained that they would throw at least the empty toothbrush or even the whole device in the residual

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waste (see figure 5). On the one hand, the answer shows that a significant proportion of the people interviewed would not carry out the desired process of proper disposal. On the other hand, the products, also because they are certainly protected by the ingress of water, are not built in such a way that the battery removal step in particular is clearly visible and can be carried out easily. Ultimately, there is a great risk that consumers will not remove the battery and the entire toothbrush will be disposed into the household waste.

In addition, and that supports the presumption from before, two respondents gave the correct answer

explaining the recycling process but openly admitted that due to the effort they would still dispose the toothbrush into normal household waste.

Several people explained how they would return the whole toothbrush to the drug store, inspiring the idea that this should be a valid option in the future, so that shops that sell electronic and electric products are also held responsible for the correct recycling of said items. Since drug stores are far more widely spread throughout cities than recycling centres and frequented more often, this would lower the intricateness threshold and the rate of successfully recycled electronic and electric household appliances would most likely rise.

Furthermore, one person expressed their displeasure about the unclear recycling description on the packing, stating that they would have liked more information about the correct recycling process instead of the vague "environmentally sensitive and not in the normal household waste".

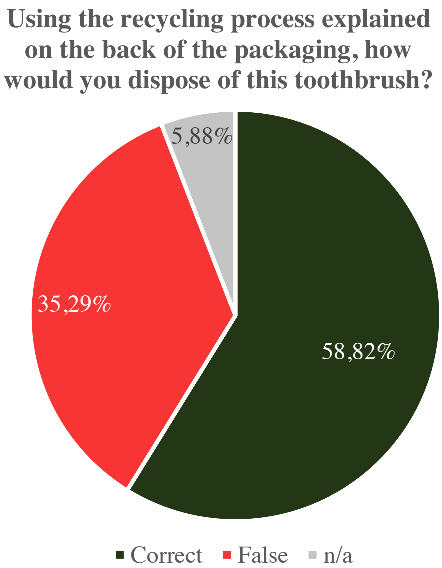

Figure 5: Description of recycling process

4 Discussion

4.1 Veracity and sources of error

While the results of the survey were not surprising, the method used to collect data has to be critically examined. In the online survey, the respondents only saw pictures and should use the pictures to decide what type of toothbrush it is. If the respondents were able to examine each toothbrush pack in a store by himself, the result might have been different. But it must also be said that many buyers will surely only look with their eyes over the shelf, choose a toothbrush, grab it and then buy it. Not everyone picks up all toothbrushes in their selection process, even if they have the opportunity.

Furthermore, the survey group of 87 people is relatively small and does not represent a fitting average of the German population. In addition, many of the interviewees were working in or studying a subject related to sustainability therefore being more inclined to react negatively to a wasteful product. Moreover, some of the age groups were not properly represented; especially the ages of 30 to 44 only had three members whereas young people of 18 to 29 years made up over 70%, most of which were students of an environmentally oriented subject.

Online customers of battery operated toothbrush models praised its small size, well made for travelling, as well as the low price compared to an electric accumulator driven toothbrush, although they do not seem to take into consideration that with an ex-changeability rate of three months the price will soon countervail the initially higher price spent on a rechargeable model. The failure of the device to function after about three months due to a flat battery was even rated as good by some respondents because it reminded them to replace the toothbrush and to buy a new toothbrush.

As the strongest opinion result, we found the almost 90% rejection when asked whether the respondents would buy the Dr. Best multiexpert vibration toothbrush.

As the author of this paper, the question that leads me is whether or not it should still be allowed to manufacture complex electronic products of mass consumption, which are operated with non-rechargeable batteries, although we have so much knowledge about the harmful effects of our economical decisions. Even more, companies, that want to act socially responsible and ustainable, should also ask themselves whether or not electrically owered products with non-rechargeable batteries are a good answer to the challenges of our future.

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A.4

(ECO)PRODUCTS: MOBILITY, WHITE GOODS, AND MORE

Driving Towards Sustainability in the Emerging Information Technology Vehicle

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Abstract

Emerging information technologies such as blockchain, internet of things (IoT), Big Data, and artificial intelligence (AI), have great potential to enhance sustainability outcomes. Through the lens' of Life Cycle Assessment (LCA), circular economy (CE), and relevant case studies, this paper provides a high-level view of these technologies and their potential roles in advancing sustainability agendas. We briefly summarise each key topic and align them with case studies to spur ideas for leveraging the technologies to help achieve sustainability goals.

1. Introduction

Emerging information technologies include a broad range of novel platforms, systems, methods, protocols, and architectures that are still under development and not yet fully mature. Some of these, such as blockchain, IoT, Big Data, and AI are poised to disrupt how we process data and access information—but more important is their possible application towards meeting planetary sustainability goals. There are many ways emerging technologies can advance sustainability goals, including improving data reliability and transparency and the ability to track products and their attributes throughout the value chain to enhance sustainability assessments (See Figure 1). This paper (1) presents the definitions of relevant emerging technologies, namely, IoT, Big Data, AI, blockchain, sustainability assessment methods, namely,. LCA, and CE, (2) discusses how emerging technologies can improve LCA and CE, (3) presents case studies for existing implementations, prototypes, and theoretical frameworks for applying emerging technologies to LCA and CE, and (4) identifies transferable lessons for the electronics sector.

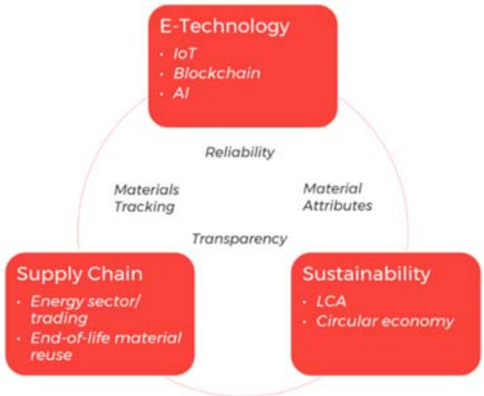

Figure 1: Diagram of overlap and synergies between emerging technologies, supply chain and sustainability

1.1 IoT and Big Data

"IoT" and "Big Data" are often used interchangeably, but they are two distinct concepts with some nuanced overlap. The term IoT was first used in 1999 when Ashton [1] presented to Procter & Gamble (P&G) on the possibility of linking radio-frequency identification (RFID) to the internet in P&G's value chain. The idea anchored on the ability of new RFID, sensor technology, and other embedded smart devices to collect data independently and communicate intelligently through the internet without human-to-human or human-to-computer interaction. IoT typically refers to devices (ranging from sensors and autonomous systems to smart wearables) that can communicate and transfer dynamic data over a network to provide real-time intelligent services. IoT devices generate large sets of unstructured data. Unstructured data, conventionally and semi-structured data, and their analytic systems, are collectively referred to as Big Data—IoT (arguably) comprises most of the multiple streams and rivers that feed into Big Data's ocean. Five fundamental factors (known as the 5Vs) characterise Big Data: volume, variety, velocity, veracity, and value. Recent research has added additional factors: variability, viscosity, virality, visualisation, and validity to the 5Vs [2]. The

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explosion of data and information from IoT and Big Data platforms imposes the need for robust data transparency and reliablity to make informed decisions.

1.2 Blockchain

Bitcoin (the cryptocurrency) is usually the first thing that comes to mind when discussing blockchain. However, blockchain is much more. At its most fundamental level, it is a global, decentralised computational infrastructure with the potential to transform existing business, government, and societal processes [3]. Blockchain, also known as distributed ledger technology, is especially useful for ensuring data transparency between several parties that may distrust each other. The most important blockchain elements are:

1. Distributed ledger: each party on a blockchain can independently access that chain's entire database and history. No single party controls the data or information. Each party can directly verify the records of its transaction partners, without an intermediary.
2. Peer-to-peer transmission: communication occurs between peers instead of through a central node. Each peer node stores and forwards information to all other nodes.
3. Transparency with pseudonymity: every transaction and its associated value is visible to anyone with system access. Each blockchain user (or node) has a unique 30-plus-character alphanumeric identification address. Users can choose to remain anonymous or provide proof of their identity to others (pseudonymity). Transactions occur between blockchain addresses.
4. Immutability and irreversibility of records: users may access, inspect, or add record data, but it is very difficult to change or delete it because the original information leaves a permanent trail (or chain) of transactions. After a database transaction is entered and the accounts are updated, the records are unalterable because they are linked to every prior associated transaction record (hence the term "chain"). A variety of computational algorithms and approaches are deployed to ensure that database records are permanent, chronologically ordered, and available throughout the network.
5. Computational logic: The ledger's digital nature allows blockchain transactions to be tied to computational logic and, therefore, programmed. Users can establish algorithms and rules that automatically trigger nodes transactions [4].

1.3 Artificial Intelligence (AI)

The term AI was first coined in 1956 by John McCarthy and refers to the combination of science and engineering to create intelligent devices for human welfare. In this context, AI can be defined as the ability of machines to learn, acquire, and apply knowledge to perform intelligent tasks for which human intelligence was previously necessary. AI is classified into two broad categories:

1. Weak or Narrow AI: a simulation of human intelligence to optimally perform a single task within a limited context. This type of AI typically operates under constraints and limitations specified in a computer program. An example is AI programmed to play chess.
2. Strong AI or Artificial General Intelligence: This is the type of AI often depicted in Hollywood movies like 2001: A Space Odyssey's Hal—it can mimic or surpass human intelligence for problem-solving. An example is IBM's AI supercomputer WATSON.

AI encompasses a broad set of techniques that can be grouped into six subcategories: machine learning, neural networks, robotics, fuzzy logic, expert systems, and natural language processing.

1.4 Life Cycle Assessment (LCA)

LCA "is the compilation and evaluation of inputs, outputs, and potential environmental impacts of a product system." [5] It is a standardised scientific framework for quantifying environmental impacts across the life cycle (production, transportation, use, and end-of-life) of a product or service. LCA environmental impact assessments typically calculate results such as climate change (greenhouse gas or GHG emissions), water quantity, water quality (e.g., acidification and eutrophication, air quality (e.g., particulate matter), energy consumption and non-renewable material consumption.

1.5 Circular Economy (CE)

CE's goal is to mimic nature. It aims to achieve this by closing resource loops, recovering resources from waste, and eliminating landfill needs uisng the principle that one company's waste might be another's resource. CE principles include designs that follow the regenerative patterns of natural systems to help eliminate systemic waste and pollution and ensure efficient, non-wasteful product and material use. In practice, CE can mean using natural materials that will decompose or leveraging recycling, upcycling, or downcycling processes to ensure the reuse of nondecomposable materials at the end of their first, second, third, or n^{th} life [6].

2 How emerging technologies can be applied to LCA and CE

The proliferation of data from IoT devices such as smart sensors and microcontrollers could revolutionise LCA. Inventory-analysis data collection currently accounts for about 80% of total LCA project time and cost. IoT and Big Data can enable real-time inventory data extraction and environmental impact monitoring at each life cycle stage of products and services. For example, to compute real-time carbon emissions and air quality and traffic data, dynamic inventory data obtained from cars equipped with smart sensors can replace the static data collected from existing inventory databases. IoT and Big Data could enhance the validity and transparency (often points of contention) of temporal and region-specific emissions data. IoT can also actualise the CE concept by improving resource efficiency across the value chain. An IoT-enabled CE will help transform waste streams and by-products into useful inputs elsewhere in that CE. AI can likewise play an essential role in environmental impact prediction, particularly for product use. By analysing historical data, AI techniques can predict future user consumption patterns and their resulting environmental impacts.

Blockchain is a powerful technology that can help achieve sustainability goals, increase value chain transparency, and improve product environmental data acquisition by embedding LCA results into metadata. Products tagged with environmental data can help promote product circularity in line with CE thinking. For example, blockchain can be used to track a product's origins and movement by tracking and preserving its environmental data trail. Tracking Environmental Product Declarations is one way to achieve this. Blockchain could also be used to track conflict minerals, carbon offsets, and details about the renewable energy used in production. Blockchain also has social applications (such as direct giving), which can enhance a product's sustainability by including all three pillars of sustainability (environmental, social, and governance). Blockchain's advantage in tracking this information is that it can help promote product data's authenticity, accuracy, and transparency.

Concerns about using life cycle information for business-related decision-making are usually related to the time required for the data acquisition, and the quality and reliability of that data. However, because IoT and Big Data are digital processes, their data granularity and accuracy are constantly improving through their frequent use and emissions monitoring.

The industrial IoT paradigm involves highly connected systems, products, and processes. A virtual model of this paradigm is known as a digital twin, and it can represent, and therefore track, all of the paradigm's relevant virtual and digital connections. Digital twins integrate AI and Big Data analysis into digital simulation models that update in real-time as their associated physical objects change. A digital twin can be used to determine specific compositions, origins, raw materials, and components in a clearly identifiable way. In this way, a physical object in a highly networked industrial environment can carry information about its proper, safe handling during production, use, and subsequent end-of-life recycling.

Because digital twins of materials and products can already contain information on composition, functionality, origin, and proper handling, adding environmental information is a small step. In some industries, especially electronics, legal requirements for fully declaring all materials used in every component already exist as a prerequisite for sales. Established solutions that leverage data this way can enable the collection and management of relevant information across the entire value chain. They can be repurposed to carry other types of information (such as GHG emissions or water consumption) for other industries in which voluntary value-chain transparency commitments may result in legal and informational needs (e.g., in the automotive or electronics industry).

Digitisation can improve the availability of value-chain sustainability data, and blockchain can ensure its immutable transmission and trustworthiness for manufacturers and consumers. Together, these processes can dramatically streamline LCA processes. Blockchain will also help replace the old model of using sanctions to spur environmental and social improvements with a system based on monetary reward. Verifiably accurate data fosters decision-making confidence, just as using Bloomberg Terminal does for financial analysis. When information is transferred in one direction, money flows in the opposite direction, and the information provider is rewarded. Today, legitimate efforts to protect trade secrets can conflict with information transparency—blockchain can bridge the gap and help guarantee both. While we may never reach full transparency, reliable traceability is achievable.

3 Case studies

While interest in leveraging emerging technologies for LCA has surged over the last decade, their potential is yet to be fully realised. Thus far, research work and industrial implementation have focused on small-scale demonstrations and developing theoretical frameworks [7]. Meanwhile, LCA methodologies are iteratively improving. For example, LCA practitioners and researchers are increasingly expanding the scope of environmental indicators to better include economic and social impact factors [8, 9] and broadening the objects and extent of their analysis from products to sectors, economies, and global concerns [10]. The ongoing evolution of LCA methodologies presents a substantial opportunity to fully utilise the immense potential of emerging technologies to improve and revolutionise LCA.

Davis *et al*. [11] proposed the "Industrial Ecology 2.0" paradigm to replace current industrial ecology practices. The authors argued that the life cycle impact (LCI) background data used for most LCAs is often out-of-date. Likewise, the collection of foreground primary data for LCA studies is time-consuming. The authors reasoned that emerging technologies, such as Big Data, can be used to facilitate the efficient collection, manipulation, and reuse of data. This concept was brought to fruition in a recent Dutch study of the dairy sector, which incorporated Big Data with LCI data using a cloud-based LCA tool. The solution enabled Dutch farmers to receive site-specific GHG emissions footprints from up to 10,000 farms in real-time—a feat that would have taken tremendous time, effort, and resources using standard methods [7].

Another study proposed integrating IoT with a Bill of Materials to create a prototype of a four-layer energy-saving emissions-reduction system. The proposed system will allow the effective integration of new data with existing enterprise information systems (such as enterprise resource planning), as well as product data and customer relationship management systems [12] [7].

These examples demonstrate the immense potential of IoT and Big Data for the electronics sector—in some cases, foreground and background data may be available, but it is not yet in a form useful for generating accurate environmental impact results. For example, when applying Big Data to lithium-ion phone battery use, LCA showed environmental impact estimates that were over 40% higher than traditional data collection methods [13].

Blockchain will play a vital role in the transition to a more sustainable, resilient, and resource-efficient future, and it will likely become integrated into the electronics sector. Blockchain has the potential to revolutionise our global economy by enabling the full traceability of products and services and their corresponding environmental and social impacts throughout their life cycles. This could help alleviate the social issues associated with conflict minerals and critical metals that are used in many electronic devices. The still-nascent social LCA field could benefit from blockchain technology because collecting reliable social data is an onerous task due to multiple, dynamic social issues. Blockchain has the potential to improve the credibility and trustworthiness of environmental data. For example, companies like Everledger are using blockchain, AI, and IoT to provide traceability and origin guarantees throughout the value chain. Counterfeiting is a critical concern for the electronics sector—it could cost the sector billions, impair product reliability, and cause physical injury. Since the material and chemical constituents of counterfeit products are difficult to verify, they can cause end of life issues, such as the release of intractable toxic pollutants into the environment. Blockchain can provide tamper-proof digital fingerprints for electronic products. Such blockchain extensions (called crypto-anchors) can authenticate product origin, trail and destination via blockchain logs. IBM researchers are developing various forms of crypto-anchors, including edible ink on malaria pills, and microcomputers and sensors, smaller than a grain of salt, that can be embedded into products to prevent counterfeiting. Crypto-anchor functionality could even be extended to include IoT and Big Data capabilities and AI-based value-chain optimisation.

AI techniques such as machine learning (ML) algorithms can be harnessed to address LCA's data deficiencies. AI could be applied to LCA’s Life Cycle Impact Assessment (LCIA) step where life cycle emissions are converted to an environmental impact indicator using appropriate characterisation factors (CFs). LCIA is based on fate-factor chemical models [14], such as *USEtox*, which has precalculated CFs for over 3,100 chemicals. As of 2018, the number of chemicals in existence is over 140 million. In the absence of experimental data, fate models use 'proxy' methods, which may introduce uncertainties into LCIA results. ML algorithms can be used as a substitute for these proxy methods—for example, ML algorithms such as Artificial Neural Networks and Random Forest, coupled with Monte Carlo simulation, have been demonstrated to reduce the error range of fate factors [15]. AI techniques can also be applied in the use-phase of product and service life cycles. The pattern recognition and forecasting capabilities of ML methods can be used to monitor real-time emissions and predict future emissions [16] [7].

4 Conclusions

We have illustrated many ways that emerging technologies can enable and improve value chain sustainability. There are also many cross-disciplinary ways in which blockchain, AI, and IoT can support sustainability. For example, using blockchain to avoid double-counting renewable energy would result in the increased accuracy of LCA results for GHG emissions and energy use and spur interest in advancing renewable energy. Integrating blockchain, IoT, and AI will make CE a reality, reform the LCA field, reduce global environmental impacts, and promote a sustainable future. The opportunities to use these technologies to help organisations meet sustainability goals, especially in the electronics sector, are already extensive and will continue to increase over time. Using these technologies in concert to improve sustainability requires coordination—no single market player can do it alone, so the electronics community and other interested sectors must act together to establish methods and standards for life cycle data collection, sharing, and use. The electronics sector has the ability to streamline real-time collection of reliable data and is uniquely poised to benefit from reduced environmental impacts and lead the world in reducing negative social impacts such as forced labour. Even today, technologies like blockchain could be used to meet regulatory requirements, such as (1) the US Dodd-Frank Act for tracking 3TG (tin, tantalum, tungsten, and gold) to help prevent current tracking system problems such as processors producing more certified metals than they take in, and (2) the UK's Modern Slavery Act for eliminating the use of modern slavery.

The electronics industry is uniquely-positioned to lead the way—by implementing the necessary infrastructure and technology, the ability to quantify LCA and CE thinking in real time, as a part of full value chain transparency, will become a reality. Once this technology is fully enabled, the electronics sector will have a responsibility to self-inspect to determine how best to address the significant environmental and social risks (such as the use of rare earth, PFCs, modern slavery, and conflict minerals) that are present in the electronics value chain.

Blockchain, AI, and IoT will enable transparent, immutable, secure, and trustworthy collection and communication of sustainability information to help create a more sustainable world.

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Procedure model for integrating energy efficiency in strategic sourcing of electronic parts and components in the automotive sector – A case study

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Abstract

The paper introduces a procedure model for integrating the aspect of energy efficiency in strategic corporate planning and decision making processes with a focus on the sourcing of electronic parts and components with their related materials in the automotive sector. Based on both a value chain analysis considering global raw material flows, intermediate products as well as suppliers information and a material analysis of electronic components with X-ray fluorescence (XRF) spectroscopy, the model derives energetic indicators, which then could be integrated in further optimisation or simulation tools. The procedure model enables industry to report and adapt the total energy use for manufactured products.

1 Introduction

The sourcing of materials or semi-finished products from all over this world is always related with the 'use' of different types of energy. The energy is required on the one hand for the transformation of the materials and on the other hand for the distribution of the corresponding components through complex global value chains.

Companies define specific production and logistics networks within strategic planning, in the phase of supply chain design (SCD) covering the determination of the production and logistics strategy, the choice of locations, volume allocations as well as the selection of transport modes [1]. While SCD is normally cost-driven, nonetheless the energy consumptions are implicitly determined with the resulting production and logistics network.

Increasing importance of sustainability reporting and in this context the willingness of companies to not just limit the reporting and optimisation actions on their own direct (energy) consumptions but also take up- and downstream processes into consideration, requires adequate data gathering and processing.

The challenge is that in the strategic planning phase the availability of information is limited. Trade-offs between data accuracy and practicability are necessary. Hence, this paper introduces a procedure model for integrating energy efficiency in strategic sourcing decisions of electronic parts and components in the automotive sector considering both, energetic efforts for transformation and transportation.

2 State of the Art

For strategic sourcing decisions material flow analyses (MFA) are powerful tools for getting an overview concerning the global distribution and the flows of materials. There are several material specific analyses and tools to visualise and evaluate material stocks and flows from mining to use and recycling, e. g. for aluminium the global model of the International Aluminium Institute (IAI) [2]. Other works focusing on specific material phenomena like dissipation by providing a valuation method of dissipative losses of special metals [3] or the corporate integration of raw material criticality assessment covering raw material supply risks, environmental impacts and social aspects [4]. Similarly, the ISO standard 20400 guides companies by integrating the aspect of sustainability into corporate procurement processes when dealing with suppliers [5].

Companies are able to quantify the environmental impacts of selective products with Life Cycle Assessment (LCA) [6], [7]. Detailed LCA studies of electronic products are common, but due to its complexity not suitable for SCD. Moreover, the related standards require existing production and logistics structures, which normally do not exist in the phase of SCD.

The result is that especially efforts on the improvement of the energy efficiency are often limited to an operational level. Furthermore, the state of the art shows a separation between company internal and external approaches for the improvement of the energy efficiency. As research on company internal approaches is focusing on renewing production and process technology and the simulation of internal material flows and its impact on the energy efficiency on equipment level [8], [9], [10], research on external approaches analyse the energetic impacts and relationships of transport strategies and technologies [11], [12]. With the “Framework for Logistics Emissions Methodologies“ published by the Global Logistics Emission Council (GLEC) exists a mature framework for calculation and declaration of energy consumption and GHG emissions covering all transport modes [13].

The mentioned research results, standards and methods are often transferred into practical tools or environmental footprint calculators, e. g. for transportation EcoTransIT World [14]. But the linkage of internal and external approaches to an holistic approach for the improvement of the energy efficiency and the handling with the lack of data and complex structures when performing strategic sourcing decisions, need further research.

When looking at the sourcing practice, resp. upstream processes, in the automotive sector one could find the following extremes. On the one hand, there are supplier relationships which are very clear. For the sourced components the material composition and the logistical connections, resp. the origins of the materials used, are known. On the other hand, there are components where the composition and logistical connections are vague and need to be determined for a complete energetic evaluation as input for SCD (cp. figure 1).

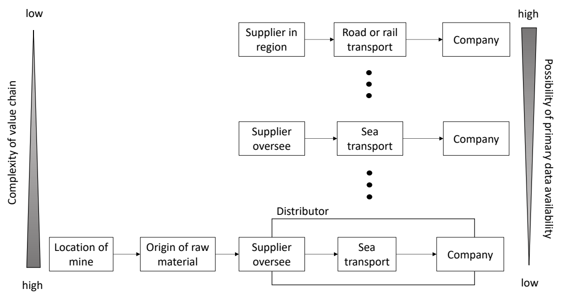

Figure 1: Challenges of data availability in global value chains

For the characterization of components companies have access to reporting structures to avoid the use of conflict materials [15] and to special material databases (e. g. iPoint). Chapter 3.1 explains further challenges and the alignment with parts lists. Company internal material databases in combination with parts lists are a very good starting point to derive energetic key figures for materials or components to be sourced.

Summing up, in the past efforts on the improvement of the energy efficiency were done, but often on a very operational level, e. g. optimising specific equipment in facilities (transformation processes) or renewing technologies in transportation (distribution processes).

Furthermore, sourcing decisions are normally limited to the economic perspective and the reporting of conflict materials (cp. Dodd-Frank Act). For now, a holistic approach on a strategic level considering the energy consumptions of several transforming and distribution processes along value chains is missing.

3 Modelling approach

The procedure model for integrating energy efficiency in strategic sourcing (cp. figure 2) starts with the selection of an electronic part or component, which has to be characterised in a second step using internal and external researches. In general, the procedure model is usable for the planning and set up of a future product portfolio or for the replanning and optimising of existing structures. The six steps of the procedure model will be explained in detail, focusing on the part supplier information and resource model.

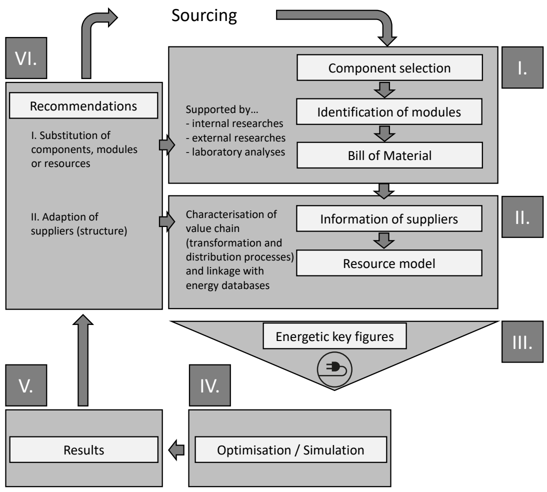

Figure 2: Procedure model for integrating energy efficiency in strategic sourcing

The overall goal is to derive energetic key figures for the parts and components of different suppliers considering region-specific energetic efforts with the linkage between transformation and distribution processes.

3.1 Characterization of Parts and Components

To clarify the scope of the energetic evaluation, in the first step a part or component which is in the design phase or in a replanning phase needs to be selected. Besides electronic components there are also several mechanical or housing components, which could be considered, when looking at components in the automotive sector. For this, it is necessary to characterize the selected part or component by its modules and suppliers, using internal and external researches. As internal data sources special material databases (e. g. iPoint), data sheets or parts lists are valuable. External information could gathered from open access data sheets of comparable parts and components or scientific publications.

Nevertheless, challenges when aligning the information could occur. For example, the sourced parts from different suppliers are processed further but in the end the company internal database only list the material composition of the whole manufactured component. The material information on the level of supplier specific parts, necessary for strategic SCD, is missing. When having access to the selected parts or components laboratory analyses for material characterization, X-ray fluorescence (XRF) spectroscopy for metals, are beneficial to cope with this lack of information.

The result of the first step is a bill of material for the selected component clustered according to the used parts and suppliers.

3.2 Supplier Information

Manufacturing companies and their supplier, especially of electronic components, have normally limited access to information concerning the prehistory of the related parts and components. It is well known from which country specific parts and components were sourced in general, but specific information like used ports or location of production facilities are hardly to achieve. The origin of the materials, which are processed in the parts and components, is also normally unknown. Therefore, upstream processes cannot be mapped. To determine missing information for value chain characterization, the suggestion is to collect information of the distributors and suppliers at first without contact, e. g. public company reports and then via contact persons.

The goal is to go back in the value chain as much as possible and to gather information concerning the origin of materials and subsequent transportation and shipping. In general, companies should prefer and use primary data of their production and logistics network whenever it is available and possible for energy-related strategic sourcing decisions.

3.3 Resource Model

If primary data is not available, the goal of the resource model is to reproduce global supply chains and to derive on that basis energetic relations in the procurement of raw materials, parts and components which then can be used for strategic procurement decisions in corporate context. The outcome is a country specific CED for a material which leaves the country (export) or is further processed in the same country (cp. figure 4).

For that, starting with the extraction of raw materials up to the use of the materials in manufacturing processes, different transformation and distribution processes are considered.

Due to limited information concerning the history and origin of parts and components resulting from supplier information (cp. Chapter 3.2), upstream processes are described insufficiently.

With the information of the supplier the country from which the parts and components are sourced is known, but the origin, resp. the upstream processes, of the raw materials used for parts and components is still unkown.

Against the background of a holistic energetic evaluation of global value chains, these upstream processes need to be integrated. The resource model offers the possibility by considering the geographic differences of the extraction and the processing of raw materials (transformation processes) such as the logistical links (distribution processes) between the transformation processes to calculate the energetic efforts of upstream processes for raw materials.

The material value chain is modelled in the style of the Unified Materials Information System (UMIS) [16] (cp. figure 3), noting that the model, for now, is limited to the stage of raw material production (including secondary production). Relevant material specific transformation processes are identified and structured on that way.

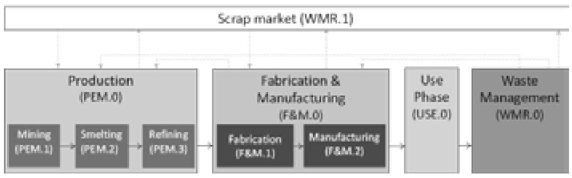

Figure 3: Transformation processes within global value chains [3], [17]

The gained information about the components are combined with material related production and trade information from different databases.

For that purpose databases with international trade statistic, e. g. UN Comtrade Database [18], are evaluated for specific raw materials to answer the following questions:

1. Which portion is domestic production and which is imported?

2. Where are several transformation processes located?

3. What are the transport relations of the material considering the production stages mining, smelting, refining?

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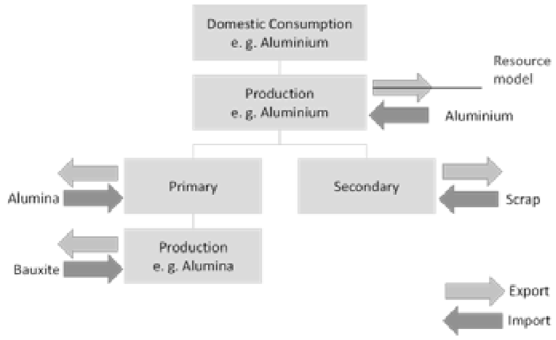

Figure 4: Considered trade flows in the resource model

Then transformation and distribution processes are modelled and linked with life cycle information for different geographical regions. Life Cyce Inventory (LCI) databases are key in this phase. LCI databases provide generic datasets on raw materials. Some LCI databases also provide material datasets for different regions or countries. A common LCI database for example is ecoinvent [19]. From this datasets it is possible to derive the region-specific 'Cumulative Energy Demand' (CED), covering the total of all primary energy inputs [20].

The model evaluates distribution processes according to the used transport modes. Concerning these processes, the model is aligned with the "Framework for Logistics Emissions Methodologies" (GLEC) [13]. This methodical framework covers different methods and standards for calculating the emissions resp. energy consumption for different transportation modes.

With this methodical approach of the resource model it is on the one hand possible to evaluate existing supplier relationships concerning the energetic efforts, on the other hand the resource model offers the potential to plan supplier relationships on a strategic level. Even energy optimized sourcing scenarios are calculable by completing the steps 4-6 of the procedure model.

4 Demonstration

The new procedure model is demonstrated by an automotive industry case study.

A vehicle climate control unit is selected in step 1. Vehicle climate control units are available as classical mechanical solutions with keys, buttons and rotating actuators. A newer development are multi-touch displays. During this research a mechanical solution with more than 400 components, containing mechanical as well as electrical parts and components, is selected.

Then different modules like the printed circuit board (PCB) are identified using internal information, e. g. parts lists and a material data base. For mechanical components the composition is normally known as well as the logistical connections.

Concerning the electronic components the composition and the related logistical connections need to be determined with additional supplier information or material characterization methods. Although an estimated overall composition for the PCB is available, a material characterization on parts level, necessary for energy-related strategic decisions for this parts, is missing.

Therefore, XRF spectroscopy is applied to finalize the bill of material on parts level. A first indication for the material composition of an aluminium capacitor is shown in table 1.

Material	Capacitor
Aluminium	52%
Carbon	25%
Polymers and others	23%

Table 1: Component characterisation

In step 2 the relevant logistical and geographical information of the suppliers are structured and linked with the resource model.

In an anonymous market where in most cases only the distributors are known, it is challenging to gather information concerning further upstream details. Although it was still possible to get information about the composition out of datasheets and databases, information concerning production locations are hardly to achieve. Distributors, and if known manufacturers, were asked via contact persons in these companies for the required information. The most common challenges were obsolete contact persons, low willingness to provide additional data and no knowledge of production location by the distributor on its own. Nearly 80% of electronic parts were analysed to determine the logistic structure. At this point distributors and manufacturers could not provide further information about the origin of raw materials in electronic production.

To bridge this gap the resource model can be used, which is now described exemplarily in the context of the material aluminium. The model is parameterized with region specific material input values for the considered transformation processes. For aluminium the processes mining of bauxite (PEM.01), the refining of bauxite to aluminium oxide (PEM.03), the smelting aluminium oxide to aluminium (PEM.02) and secondary production are considered. For clarification, it is mentioned that for aluminium in contrast to figure 3 the refining process is before the smelting process. In addition, these material input values are important to derive the quantities, which are transported between transformation processes.

Moreover, the different CED values for the described transformation processes are derived from ecoinvent and are integrated in the model. Table 2 shows exem-

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plarily the smelting (PEM.02) for the primary production of aluminium with the region specific values available.

Region	CED (MJ / kg)
Africa	198
Asia	330
Australia	216
China	222
Europe	158
Gulf States	243
North America	162
Russia	156
South America	167

Table 2: Region specific CED of the smelting for primary production of aluminium

The model calculates the average CED values for aluminium (1 kg) leaving the USA and China, with the described parameters and the trade statistics in the background.

The average CED for the USA counts for 149 MJ. This value considers the corresponding upstream processes of aluminium and the imports mostly from Canada. Aluminium oxide and bauxite for the domestic production is imported predominantly from South America and Australia (cp. figure 5). The average CED for China counts for 270 MJ. Bauxit for the domestic production is imported mostly from Guinea and Australia.

The calculated average CED for the USA is lower than the CED of the smelting for primary production of aluminium in North America because of the dominating secondary production in the USA. For China the calculated average CED is higher, due to the consideration of upstream processes.

Combining the average CED with the quantities resulting from the material characterization of the capacitor, step 3 of the procedure model derives a region specific energetic CED for this part. Having the situation that this part A can be sourced identically from two different suppliers X in the USA and Y in China, with the presented model it is possible to uncover energetic differences when sourcing parts globally. If available values for manufacturing could also be added up.

The last relation between supplier and company is not integrated in the region specific CED to allow the simulation or optimisation of different transport scenarios, which is directly in the scope of the company when performing SCD from a perspective considering energy efficiency.

5 Conclusion

The procedure model guides manufactures of electronic parts, especially in the automotive sector, by implementing the aspect of energy efficiency in strategic planning processes when sourcing specific materials or semi-finished products from all over this world.

The benefit if this approach in comparison to more established environmental footprint calculators is, that besides the sole calculation of (energy) consumptions, also simulation and optimisation for energy-related strategic sourcing is possible.

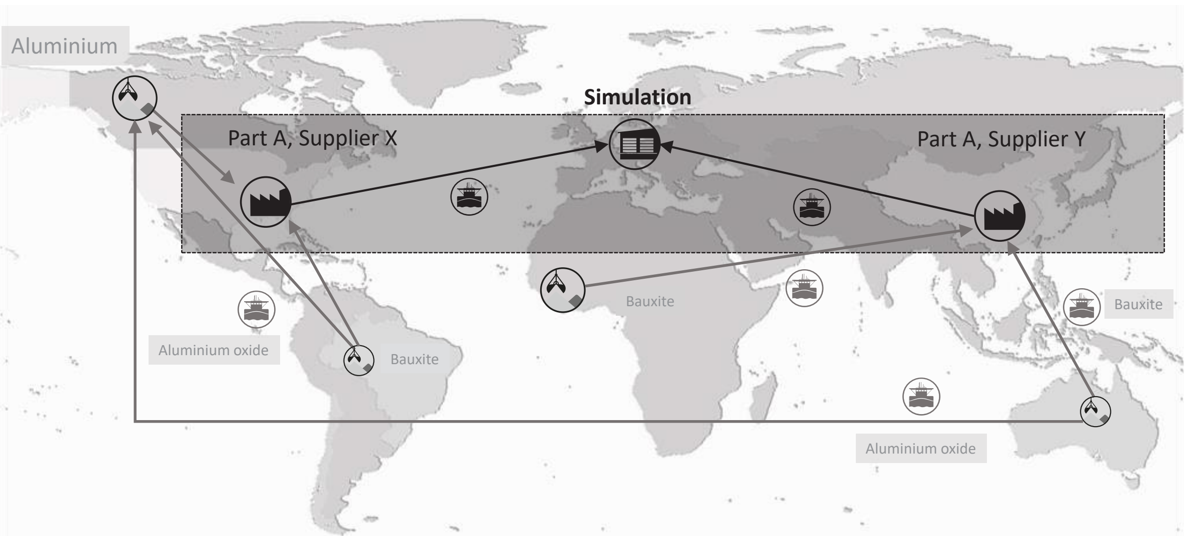

Figure 5: Visualization of aluminium value chains

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The presented model links logistics and transformation processes and enables energetic SCD in the sourcing phase. It provides default values for selected materials and requires only the information of origin (manufacturing country or country of final assembly) from a part or a component. The default values are on a high abstraction level thus enabling companies to launch into energy efficient SCD. However, for more precise calculations primary data can always be added.

The idea of integrating the aspect of energy efficiency in the SCD routine of the company is relatively new. Therefore, there are no established procedures for data gathering and evaluation. This essential limitation leads for now to a lot of manual work when aligning data.

The mentioned method XRF spectroscopy for material characterisation, for example, is not considered as a regular process. Its idea is to fill the lack of information selectively. Nevertheless, there are still data lacks and uncertainties when looking at secondary production activities.

Further research will focus on adequate data gathering in different value chains and developing a software based toolbox to ensure usability as well as scalability and to verify the practicability of the model for energy efficient material sourcing.

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A life cycle simulation method focusing on vehicle electrification and sharing

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Abstract

Car- and ride-sharing services are being increasingly utilized around the world have the potential to promote the diffusion of electric vehicles. Therefore, it is important to simultaneously-estimate environmental load changes resulting from adoption of sharing services and electric vehicles over time and throughout vehicle life cycles. In this study, we propose a life cycle simulation method that simultaneously focuses on diffusion of both sharing services and electrification. The diffusion of sharing services changes the number of required vehicles of each use type in each simulation time. To match the number of required vehicles, the method includes the process which allocates the production volume for ownership and sharing services, and then for gasoline and electric vehicles. The results of a case study show that sharing services will mitigate increases in resources consumption due to electrification.

1 Introduction

The automotive industry is currently undergoing a period of great change, one factor in which is car- and ride-sharing services. Diffusion of these services are expected to decrease production volumes and to reduce carbon emissions and other environmental loads due to manufacturing (CO_2) [1], [2], [3]. On the other hand, ride-sharing services can incur detour routes for picking up passengers, thereby increasing operational environmental loads [4], [5]. Sharing services influence the environmental loads of multiple processes in the vehicle life cycle, making it important to evaluate the environmental loads of sharing services throughout the vehicle life cycle.

Sharing services are one driving force for the diffusion of electric vehicles (EVs) [6], [7]. EVs generally have lower CO_2 emissions than do conventional gasoline vehicles (GVs) [8], but EVs consume more resources than do GVs [9]. It is important to simultaneously estimate changes in environmental load due to both over time, but few previous studies have done so.

In this study, we propose a life cycle simulation (LCS) method that simultaneously considers sharing services and electrification to calculate changes in dynamic environmental load due to their diffusion. LCS is a methodology for dynamic evaluation associated with production plans and collection projects [10], [11].

2 Related work

Car-sharing services involve vehicle sharing by multiple groups, while ride-sharing services share user movements [12]. Diffusion of car-sharing services decreases the number of privately owned vehicles, in turn decreasing the number of manufactured vehicles [1], [2], [3]. Car-sharing services can also decrease travel distances when combined with public transportation [13].

Like car-sharing services, ride-sharing services are expected to reduce the number of privately owned vehicles [14]. However, ride-sharing services can also increase total travel distances of vehicles [3], [4], [14], increasing environmental loads due to increased usage over the vehicle life cycle. Changes in the number of vehicles and the occurrence of detour routes are results from user behaviour, so studies of sharing services generally focus on user behavior in sharing services.

Many studies conducted environmental evaluations of EVs throughout their life cycle [8], [15], [16]. Conducting life cycle assessments of both GVs and EVs, Hawkins et.al. showed that EVs decrease environmental load by about 20% compared with GVs [8]. Environmental loads of EVs are highly dependent on the power supply mix in the target area [15], [16], and diffusion of EVs is predicted to increase material resource consumption [9]. These studies set scenarios related to EVs diffusion and scenarios depending on national policies in target countries.

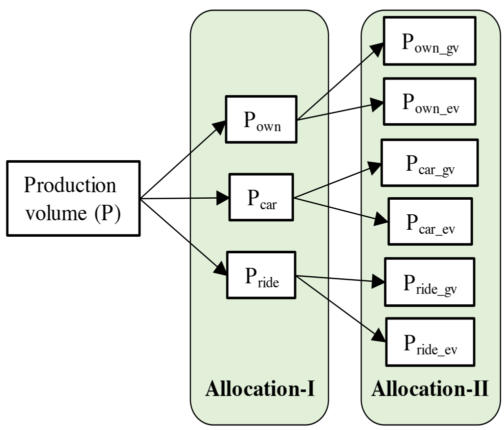
The authors have used the LCS to evaluate environmental loads resulting from diffusion of sharing services [17]. That study considered user behavior scenarios in sharing services, but, did not consider predictions of EVs diffusion.

3 Simulation method

We propose a simulation method that simultaneously considering models for diffusion of both electrification and diffusion of sharing services in LCS. These models are of different types. Namely, the electrification model depends on national policies and vehicle market trends. Therefore, the ratio of EVs in the vehicles sale is determined in advance. On the other hand, sharing services diffusion model depends on user behavior. Therefore, the number of required vehicles for each user type changes with each simulation time. For these reasons, it is neccesary a process to allocate the production volume to ensure the number of vehicles needed for each use type in each simulation time, and to allocate the production volume among GVs and EVs.

This method includes an allocation process to reflect the impact of diffusions of sharing services and electrification. The allocation process includes two allocation steps (Allocation- Ⅰ and Allocation- Ⅱ), which reflect the effects of diffusion of sharing services and electrification in parameters for the developed LCS models sequentially. The proposed LCS method comprises the following steps; 1) select target products, 2) develop LCS models, 3) model an allocation process, 4) model product life cycle systems, and 5) calculate.

In this study, we set two scenarios of the diffusion of sharing services and electrification in the allocation process instead of in the models. The scenarios influence the production volume of vehicles. As Figure 1 shows, the production volume is first allocated based on target uses (Allocation- Ⅰ), then based on target products (Allocation- Ⅱ). Allocation- Ⅰ reflects the effects of sharing services diffusion, such as decreases in total production volume. In Allocation- Ⅱ, the breakdown of production volumes is changed.



own: Privately owned, car: Car-sharing, ride: Ride-sharing, gv: Gasoline vehicle, ev: Electric vehicle

Figure 1: Behavior of allocation process

4 Case study

4.1 Target product

The target products were GVs and EVs. Table 1 shows specifications for each product. A GV consists of a body and an engine, while an EV consists of a body, a motor, and a lithium-ion battery (LIB). Demand for public transportation is not considered. The average lifetime of GVs and EVs is set to 130,000 km, a value calculated from average vehicle durability and average annual travel miles in Japan [19]. We also assume that LIBs are replaced when their remaining capacity is less than 80%. The average LIB lifetime is set to 100,000 km [20].

Product	Specification	Reference
Gasoline vehicles (GV)	1300-cc internal combustion engine equivalent (Compact car)	[18]
Electric vehicles (EV)	Corresponsive as above. Energy density of battery: 24kWh.	[18]

Table 1: Specification of target products

4.2 LCS model of user behavior

We set travel demand to develop an LCS model representing user behavior. Travel demand represents the scale of each user type. An increase in travel demand for sharing services indicates further diffusion of those services. The unit for travel demand is person-kilometers. The number of vehicles used depends on the travel demand by user type. The vehicles used in car- and ride-sharing have higher utilization rates and travel longer distances compared with privately owned vehicles. In this study, we set maximum utilization rates for car- and ride-sharing, and calculated the number of vehicles in each usage type as

$$N_{own} = D_{own} / (P_{own} \cdot M_{ave}), \quad (1)$$

$$N_{car} = D_{car} / (P_{car} \cdot M_{ave} \cdot U_{car}) \quad (2)$$

$$N_{ride} = D_{ride} / (P_{ride} \cdot M_{ave} \cdot U_{ride}) \quad (3)$$

where D is the travel demand, P is the average number of people per vehicle, U is the maximum utilization rate, and M_{ave} is the average monthly mileage of privately owned vehicles.

The travel mileage by user type depends on the average number of passengers and the travel demand. For ride-sharing, the effective distance ratio assumes extra travel mileage for pick-up distances. The effective distance percentage refers to the percentage of ride-sharing mileage with passengers. Each mileage was calculated as

$$M_{own} = D_{own} / P_{own} \quad (4)$$

$$M_{car} = D_{car} / P_{car} \quad (5)$$

$$M_{ride} = D_{ride} / (P_{ride} \cdot E_{ride}) \quad (6)$$

where E_{ride} is the effective mileage ratio during ride-sharing services.

4.3 Life cycle process model

We developed an allocation process and a model that includes life cycle process models for GVs and EVs. Figure 4 shows the life cycle process models including the allocation process. The repair process involves replacing the body in the GV model, and the LIB and the Body in the EV model. The allocation process is populated with information regarding production volumes resulting from usage processes, in which information is first allocated considering diffusion of sharing services (Allocation- I). The diffusion of sharing services decrease the production volume for privately owned vehicles. This production volume information is then allocated to GVs and EVs (Allocation- II). Finally, the allocation process outputs an information flow of production volumes to the manufacturing stage of each lifecycle model.

4.4 Evaluation scenario

In this study, CO_2 emissions and total material requirement (TMR) were used as environmental impact indicators. TMR comprehensively evaluates direct and indirect resource flows [21]. Table 4 shows parameter values used in this simulation. Average numbers of people per privately owned vehicle include both passengers and drivers. The simulation area assumes a city in Japan with population 400,000 where vehicle-sharing services are not provided. The initial number of privately owned GVs is set to 200,000. The total travel demand is a constant value. The simulation period is 20 years, from 2015 to 2035.

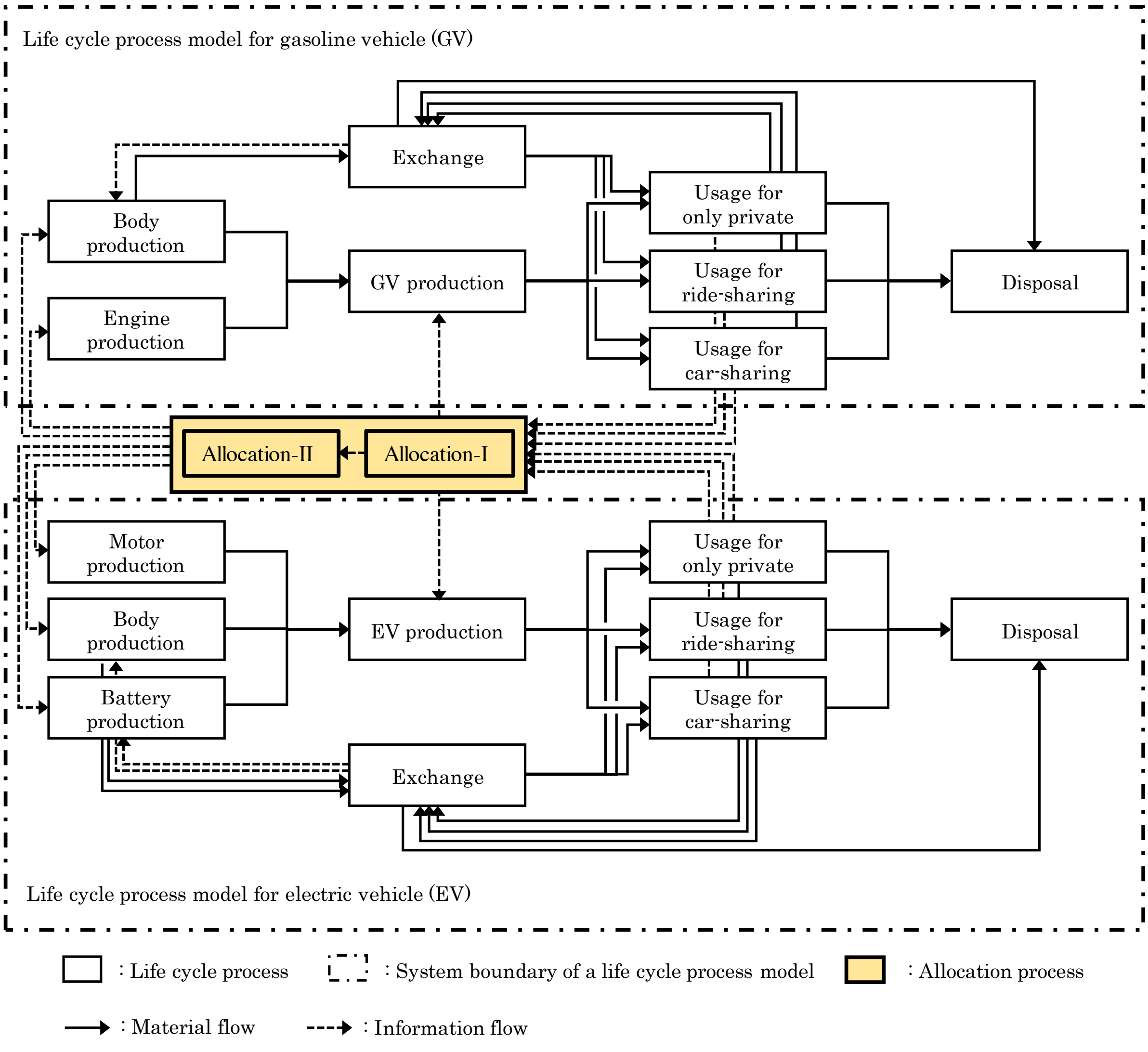


Figure 2: Developed life cycle process models

Symbol	Parameter	Value	Reference
P_{own}	Average number of people per privately owned vehicle	1.3	[22]
M_{ave}	Average monthly mileage per privately owned vehicle	833 (km)	[23]
P_{car}	Average number of people per car-sharing vehicle	1.3	
U_{car}	Maximum utilization rate of car-sharing vehicles	5	
P_{ride}	Average number of people per ride-sharing vehicle	2	
U_{ride}	Maximum utilization rate of ride-sharing vehicles	4	
E_{ride}	Rate of effective mileage during ride-sharing	0.5	

Table 2: Parameter values

Carbon intensity of GV in the usage phase is set to 0.22 kg-CO_2/km [24], and that of EV in the usage phase is set to linearly change from 0.073 kg-CO_2/km in 2015 to 0.045 kg-CO_2/km in 2035 [25]. TMR intensity of GV in the usage phase is set to 0.13 kg-TMR/km, a value based on the TMR intensity of oil [21]. TMR intensity for EVs in the usage phase is set to linearly change from 0.26 kg-TMR/km in 2015 to 0.20 kg-TMR/km in 2035 [21].

We set four scenarios: private GV only, EV diffusion, sharing diffusion, and EV & sharing diffusion. In the private GV only scenario, EVs and sharing services are not diffused. We assume that car- and ride-sharing will each account for 25% of total travel demand in 2035. Regarding the EV diffusion rate, we assumed that 30% of sales volume in 2030 will be EVs, a value based on the target set by the Japanese Ministry of Economy, Trade and Industry [26]. We assume that all vehicles sold in 2050 will be EVs.

5 Simulation result

Figures 3-5 show the simulation results. Fluctuations in these results are due to the probability distribution for discard rates. Figure 3 shows the accumulated CO_2 emissions, with the results of the GV-only scenario assumed to be 100% and the other scenarios converted to percentages based on these values. No significant change in cumulative CO_2 emissions can be observed.

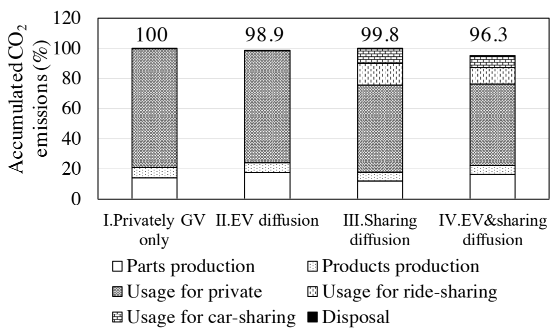


Figure 3: Accumulated CO_2 emissions

Confirmation of increases or decreases in CO_2 emissions for each life cycle process shows that when EVs are widely used, CO_2 emissions from usage decrease, but CO_2 emissions from production increase. This is related to the high CO_2 emissions per unit of EV production. This case study also considered LIBs replacement, which causes further CO_2 emissions. Car- and ride-sharing diffusion decrease CO_2 emissions from production, but increase CO_2 emissions from driving, due to increases in total travel mileage through detour routes as by ride-sharing services diffuse. Further, since shearing services increase per vehicle utilization, shared vehicles are disposed of sooner than privately owned vehicles.

Figure 4 shows the monthly TMR in each scenario. The scenarios in which EVs are not diffused does not confirmed significant changes. In the scenarios including EV diffusion, however, TMR increases over time. This is reasonable, since the TMR for EVs during manufacture and use is higher than for GVs. Figure 5 shows the accumulated TMR for each scenario. TMR in scenarios including EVs is much larger than in GV-only scenarios. Moreover, TMR for LIB production accounts for 19% and 18% of total TMR under the EV diffusion scenario and EV & sharing diffusion scenario, respectively. These results indicate the important of extending LIBs lifetimes and reuse. Figure 5 also shows that shar-

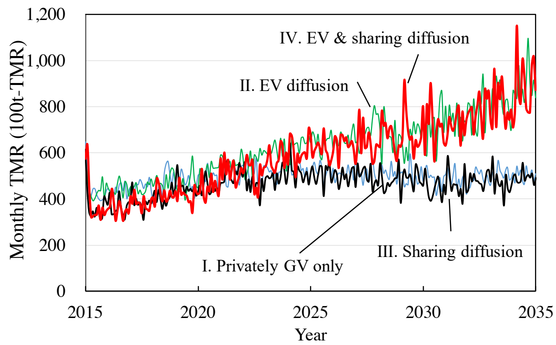


Figure 4: Time evaluation of monthly TMR

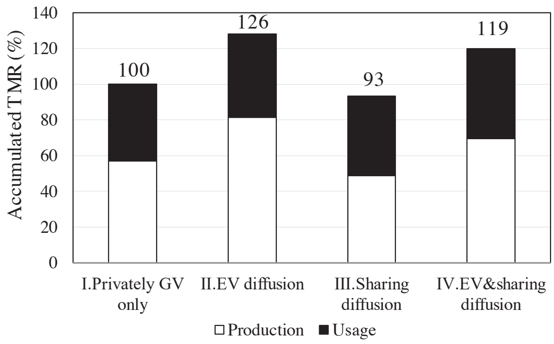


Figure 5: Accumulated TMR

ing services diffusion decreases vehicle TMR emissions. From these results, sharing services are useful in mitigating the increases of resources consumption due to the electrification.

6 Discussion

We verified behavior of the allocation process. The allocation process first reflects changes in usage intensity between user types on production volume. In the car- and ride-sharing diffusion scenarios, the overall production volume is expected to decrease. After accounting for changes in usage intensity, the demand substitution from GVs to EVs is reflected in the breakdown of production volume. Figure 6 shows the breakdown of the production volume before and after the treatment of the allocation process at a particulat simulation time. In the EV diffusion scenario, there is no change in the overall product volume because car- and ride-sharing services are not diffused. However, the breakdown of the product volume changes with an increased production volume for EVs. The sharing diffusion scenario confirms the overall production volume decreased. In the EV & sharing diffusion scenario, the production volume of EVs increased while the total production volume decreased. These results indicate that the allocation process represents changes in usage intensity and demand substitution. Therefore, the behavior of the allocation process is reasonable. On the other hand, in this study, we replaced the models for sharing services diffusion and electrification with scenairos, so each model should be developed and linked to the LCS.

We conducted a sensitivity analysis to confirm the robustness of the life cycle model. Figure 7 shows the results of sensitivity analysis based on the EV & sharing diffusion scenario, in which each parameter value is changed from -50% to 50%. Sensitivity of the average number of passengers during ride-sharing was greatest, followed by sensitivity of the rate of effective mileage during ride-sharing. Both parameters are related to ride-sharing, and CO_2 emissions are likely to increase as a result of decreased transport capacity per ride-sharing vehicle due to the decrease in average number of passengers during ride-sharing, along with the increase in extra miles due to the decreased effective distance ratio. It is necessary that these sensitive parameters are further detailed. In addition, this study considered only automobiles as means of transportation. However, collaboration between sharing services and public transportation would likely improve transportation convenience. Moreover, such collaboration has the potential to decrease vehicle travel distances [13]. Therefore, it is necessary to develop a multi-modal model that includes other means of transportation such as buses and trains.

As future studies, it is important to develop the models of sharing services diffusion and electrification, and link them to LCS models. In addition, it is necessary to develop more detailed models to consider the sensitivity parameters. However, these models are difficult to develop in LCS because of time scale differences between models. In response to this challenge, a hybrid simulation architecture consisting of a socio-technical system, a lifecycle system, and specific process models would be useful [27]. In that simulation architecture, socio-technical and specific process outputs would be used as boundary conditions, allowing the simulation

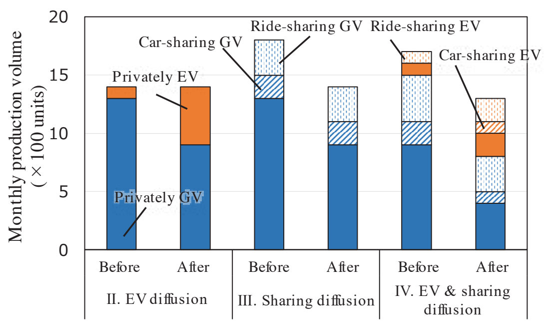


Figure 6: Breakdown of production volume before and after the allocation process

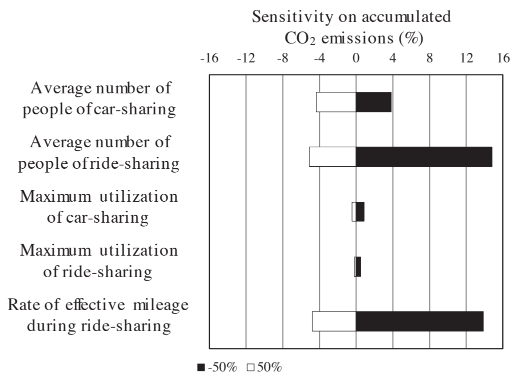


Figure 7: Results of sensitivity analysis on CO_2 emissions

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architecture to accommodate models with different timescales.

7 Conclusion

We proposed a life cycle simulation method focusing on diffusion of sharing services and electrification. The point of the proposed method is including an allocation process for reflecting the effect of the diffusion of sharing services and electrification in the LCS model. We conducted a case study and demonstrated the validity of the proposed method.

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Sustainability Criteria for White Goods

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Abstract

This paper develops a catalogue of criteria for the sustainability assessment of household dishwashers as an example for white goods. Drivers for this are the implementation of the Ecodesign Directive and sustainability strategies that companies define. While the focus of the Ecodesign Directive was previously on energy efficiency, now resource and material efficiency is in the focus.

A multi-stage literature research had been carried out on existing catalogues of criteria for assessing the ecological dimension of sustainability aspects in the different product categories of electrical appliances.

The research results were summarized and introduced into an evaluation system, which served as a basis for the development of the catalogue of significant criteria. Applicable criteria were identified, the criteria were adopted to the product category of household dishwashers in accordance with the method for multi-criteria decision support.

The summary of the results shows a catalogue with 66 individual criteria in nine different categories. Although the responsibility of sustainable product design is primarily with the manufacturer, the system boundaries were chosen to include criteria from the design phase to disposal of the product.

For example, resource productivity and replacement of non-renewable materials with renewable ones contributes largely to sustainable development. The limitations of the catalogue presented are to a large extent in the use phase and in user behaviour because it influences the total energy and water consumption.

The application and suitability of the catalogue of criteria, as well as the contribution to sustainable development and for society were evaluated. A recommendation for further action was concluded. Finally, possible uses and further developments of the catalogue of criteria are described.

1 Introduction

The aim of the present work was the identification of requirements for the sustainable design of white goods with the example of household dishwashers in the context of the expansion of the Ecodesign directive [2] towards material efficiency and sustainability of products in general.

Companies thrive for strategies to make themselves sustainable. One major part besides the operation of the company's facilities and the supply chain is the manufactured product itself with the influence of the product design.

A catalogue of criteria was developed for the assessment of the sustainability of white goods. Motivation for this activity was based on the additional measures on material efficiency that the ecodesign directive requires as a second policy focus in addition to the energy efficiency requirements that are already widely implemented. As a result, 66 criteria in nine categories were identified.

Literature research was done to identify criteria existing for electronic products in general. An evaluation system was defined and applied based on multi criteria decision support to develop a catalogue specific for white goods.

To look at the influences of Regional specifics and in order to be able to address unique specific resource and consumable requirements dishwashers were selected as an example.

During the development of the criteria it was important to include all phases of the life cycle with focus on the design and manufacturing phase.

2 Baseline of the Criteria Development

Principles of sustainable development were used as a baseline such as Efficiency, Consistency and Sufficiency addressing the increase of productivity, renewability of the resources and the limitation of use.

Also it was important to focus on the applicability of the criteria and the benefits for the single actors.

3 Principles of Sustainability Criteria

Sustainability of electronic products uses certain principles such as expansion of the lifetime, reparability, modularity, expandability, design for End of Life and Information, for example on material types or environmentally preferred use.

According to UBA [1] (German EPA) environmentally preferred product design involves reduced energy and raw material use, the increased use of renewable materials, increased longevity including endurance, reparability, adjustability and functional extension. Additionally, reusability and recyclability are important.

Also emissions shall be reduced, for example Volatile Organic Compounds, noise or radiation.

4 Existing Systems

A number of systems and labels already address the sustainability of electronic products, such as PROSA, EPEAT, Blue Angel, EU Ecolabel, Energy Star, N Cert, or Eco Top Ten amongst others. They all have different areas of application, focus of evaluation and

importance. None of them comprehensively approaches the sustainability of white goods.

Figure 1: Examples for Existing Sustainability Eco-labels

5 Multi Criteria Decision Analysis

A hierarchy of goals was created. As main goal the sustainability of Dishwashers was defined. Level 1 Criteria were assigned, selected from the Eco Design Directive, the Concept of environmentally preferred product design and existing systems.

Single Level 2 criteria were assigned that had to be measurable (with a unit), had to have an optimization goal (direction) and were finally also assigned a priority.

An comprehensive rating system the attribute of required and optional was found to be useful.

The develop Criteria had to have the following criteria: A good description to be able to identify what needs to be addressed. Verification requirements had to be added to proof validity. Quantitative thresholds or quotes had to be defined and a motivation and benefits assessment had to be done for each criterion.

6 Criteria Groups

In the end the criteria were grouped to reflect the following topics:

- Reduction of Materials of Concern
- Design for End of Life
- Product Lifetime
- Energy use / Emissions
- Recyclability of Product and Packaging
- Company Environmental Performance and Sustainability
- Supply Chain

Additional new fields identified and found to be important with white goods

- Consumables
- Renewable and Biobased Materials
- Innovation
- Indoor Air Quality

7 Reduction of Materials of Concern

Similar to existing sustainability catalogues focus should be in the existing regulations with extend of thresholds or slight extend of some substance ranges.

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Regarding RoHS for example the acceptable level of CrVI could be further reduced below the regulatory threshold. Regarding Phthalates the longer chain Phthalates could be included that are banned in toys for example.

8 Recyclability and Reparability of Product and Packaging

Regarding Recycling Recycled and Biobased plastic content shall be declared.

To simplify disassembly the variety of connection technologies shall be reduced. Irreversible connections shall be avoided down to the level of functional units.

Moreover, recycling and recoverability quotes shall be published yearly for the products.

Regarding packaging the packaging materials shall not contain halogens, be easily or manually separable as well as compostable or recyclable at a high rate. The number of different packaging materials shall be reduced. Avoiding plastic packaging or bleaching agents could be considered in the rating as well. Recycled content of the packaging shall be declared. The packaging ratio shall be reduced by a minimum amount.

Accessories shall not be packed separately. A transport packaging takeback system shall be provided also for B2C packaging.

9 Efficiency

Specific to white goods consumables are important. The availability of consumables may also vary.

Intelligent dosing recommendations based on load sensing, temperature actual water hardness or other shall be given to the user. Also the environmentally preferred use / programs in certain applications shall be recommended.

In addition power use in operation as well as water consumption are important

10 Ecodesign Requirements for Dishwashers 2019/2022/EU

The EU has in the meantime released the regulation 2019/2022/EU. This regulation defines the requirements as follows:

- Programme requirements
- Energy efficiency requirements
- Functional requirements
- Low power modes
- Ressource efficiency requirements
- Information requirements

Also Measurement Methods and Calculations were defined.

- Energy Efficiency Index
- Cleaning Performance Index
- Drying Performance Index
- Low Power Modes

In detail with the following parameters to be monitored

- „Eco“ programme energy consumption
- „Eco“ programme water consumption
- Cleaning performance index
- Drying performance index
- Programme duration
- Power consumption in off mode
- Power consumption in standby mode
- Power consumption in delay start

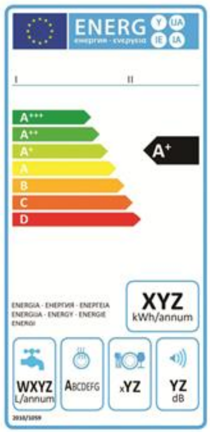

Figure 2: EU Energy Label

11 Summary and Outlook

Potential sustainability criteria for dishwashers have been evaluated. Some criteria are quite similar to existing rating standards for other electronic devices other are new and specific for white goods and dishwashers. The criteria could be used as a starting point for standardization

12 Literature

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Adopting Circular Economy in the Household Appliance industry: an overview of cases

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Abstract

Circular Economy emerged as a tool to achieve sustainable development. The household appliance industry is a promising arena for studying the adoption of Circular Economy. However, literature lacks a thorough systematization of current Circular Economy practices in this industry. Therefore, this study aims to explore how Circular Economy is adopted by the household appliance industry through multiple case studies. Fourteen primary and secondary cases are analyzed, mapping: the 4R strategies of reduce, reuse, remanufacture and recycle; the levers adopted; the role of digital 4.0 technologies as enablers. The analysis confirmed the 4R hierarchy, even though cascading is still not widespread. Servitised business models turn out to be the most used lever. IoT, Big Data & Analytics emerged as enablers especially in the service field. Although preliminary, this exploratory research lays the foundation for a stronger and more systemic understanding of the adoption of Circular Economy in the household appliance industry.

1 Introduction

Circular Economy (CE) recently emerged as a new sustainable paradigm to address resource scarcity and climate change [1]. By decoupling economic growth from resource extraction, CE has been conceptualized as an alternative to the current linear economy, which is based on a 'take-make-dispose' scheme [2]. CE strategies include the implementation of closed-loop systems based on activities like reuse, remanufacture and recycling, the sale of the function rather than the product in itself and business approaches characterized by collaboration and sharing [3], [4]. In a CE, the value is not related to increasing sales and flows of materials, but to the ability to use resources in multiple cycles and reducing waste and consumption [5].

The household appliance industry is a promising arena for studying the adoption of CE, given its environmental pressure. In fact, households appliances stress the environment throughout their whole lifecycle: to produce them, the European industry uses every year about 500kt of steel, 200kt of plastics, 60kt of copper and 40kt of aluminum; during usage, the total energy and water EU consumption sums up to 25 TWh and almost 2 km^3 of water per year; at the end of life, only 35% of appliances are collected and recycled in the EU each year [6]. This paper focuses on household appliances since these goods have a high potential for reuse, recycling and product-life-extension [7]. Moreover, household appliances do not rely on fashion, an issue that could be an obstacle to restorative practices [8]. However, literature still lacks a thorough analysis and systematization of current CE practices in the household appliance industry. Consequently, this study aims to systematize how CE is adopted by the household appliance industry by the means of multiple case studies. The remainder of the paper is organized as follows. Section 2 presents the methodology adopted for the research and the original Research Framework developed to guide the case studies. In Section 3, each case is briefly described. Section 4 discusses the findings. Lastly, conclusions, managerial implications and limitations are drafted in Section 5.

2 Methodology

2.1 Case study

To systematize how CE is adopted by the household appliance industry, a multiple case study methodology was adopted [9]. To enhance the validity and the reliability of the research, an original Research Framework has been developed (see Section 2.2). Both primary and secondary cases are carried out, involving start-ups and global players. Cases were selected according to a judgmental sampling technique. Each case: (i.) focuses on household appliances such as washing machines, fridges, dishwashers, and so forth; (ii.) concerns companies having undertaken projects to achieve CE by narrowing, slowing or closing the loop [10]. Geographical areas covered included the EU and USA due to linguistic reason. In total, 14 cases are analyzed (See Appendix). For *primary cases*, semi-structured interviews were carried out. For each interview, specific guidelines were drafted to outline the topics investigated and the questions asked (see Section 2.2). Each interview lasted 2 hours, and different company roles were consulted. Interview scripts were transcribed, coded, and validated with respondents. To enhance validity, triangulation with secondary sources has been carried out. *Secondary cases* were selected from technical reports from public and private organizations focused on CE. When it has not been possible to obtain information directly from the company website, technical reports and newspaper articles have been used to learn more about the cases and their application. The findings have been used to fill the original research framework presented in Section 2.2., which outlines how CE is adopted by the household appliance industry.

2.2 Research Framework

This paper develops an original research framework (Figure 1) to analyze the case studies. The framework is built upon previous research on CE, and brings together the strategies, the levers, and the enablers of CE in the household appliance industry. The different case studies were analyzed to map: (i.) the CE 4R scheme pursued, i.e. whether Reduce, Reuse, Remanufacture or Recycle strategies are applied; (ii.) the CE levers adopted, i.e. whether Circular product design practices, Servitized business models options or Supply Chain management actions are undertaken; and (iii.) the role of digital 4.0 technologies as enablers. In the following, the criteria for classification of each option have been defined.

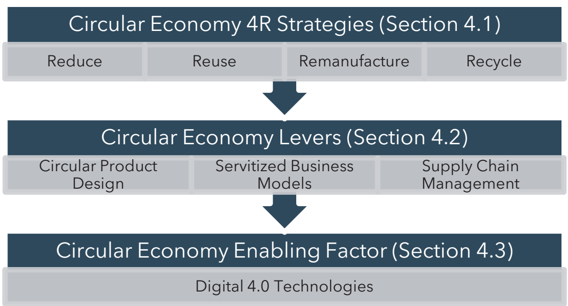

Figure 1: The Research Framework

The CE '4R' scheme of reduce, reuse, remanufacture and recycle has been adopted to discern among recovery strategies [7]. An organization follows the *reduce* strategy when it improves resource efficiency. In this way, the organization causes a reduction in the flow of goods produced or a reduction in waste and energy consumption. The *reuse* and *remanufacture* strategies imply a second-hand market and the recovery of the product at its end-of-use stage, i.e. when customers decide to discard them. While reuse involves repair activities to recirculate products, remanufacture requires more processes and often disassembling activities to recirculate parts and components [11]. Lastly, *recycle* focuses on recirculate materials by processing waste and discarded products to obtain secondary raw materials. The product must be demolished and loses the added value achieved in the manufacturing phases.

Companies and organizations may act on three levers to implement CE and pursue the 4R strategies. These levers are circular product design, servitized business models and supply chain management. *Circular product design* maintains the value of products for as long as possible by narrowing, slowing or closing the resource loops [10]. These practices allow the use of fewer or recycled materials, the extension of the product lifecycle and the enhancement of multiple lifecycles. Examples of circular design practices are material selection, design for sustainable behavior, design for attachment and trust, durability, standardization and modularity, design for disassembly or reassembly. *Servitized business models* change the relationship between companies and customers, facilitating contracts that sell the functional access rather than the product. Servitized business models can be e.g. after-sales services like maintenance and repair, leasing and pay-per-use contracts and sharing activities. Lastly, *supply chain management* aims to integrate the actors along the entire supply chain and induces cooperation to facilitate the transition to CE. Stronger collaboration simplifies recovery activities. Moreover, a close relationship between companies and customers is needed for introducing a servitized business model. Supply chain management for CE includes cooperation activities and the implementation of a reverse logistic. The latter refers to a closed-loop system that takes place when a company manages to recover its waste.

The implementation of the three levers can be supported by enabling factors like digital 4.0 technologies [4]. *Internet of Things* (IoT) technology refers to sensors applied to mechanical appliances or electronic equipment and gives information on conditions and functioning of the products. *Big Data and Analytics* allow revising data collected by IoT to improve decision-making processes and prevention systems. *Cloud platforms* are software that allows sharing data or multimedia materials. The sharing of information can enhance the offer of services rather than products and the connection between supply and demand. *3D printing* allows realizing three-dimensional objects starting from a computer model through additive manufacturing.

3 Case Studies

3.1 Primary case studies

3.1.1 Astelav (Ri-Generation)

Astelav is an Italian company, founded in 1963 and located in Turin, which manages the supply of spare parts for household appliances. The group employs 60 people and in 2018 recorded sales of 13 million euros. In 2017 Astelav, together with SERMIG (SERvizio

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MIssionario Giovani, a charity association) started the Ri-Generation project, aiming at recovering and sell back household appliances like washing machines, dishwashers, and tumble dryers that have reached the end of life. These products, which would otherwise be disposed of, are collected by the company directly from costumers or through logistic centers, to be sold back in one of Astelav distribution centers or through the online website. Moreover, the company does not just sell recovered products but supports costumers during all the usage phase, offering assistance at a discounted price. The Ri-Generation project can lead several benefits, both for the customer side and the supply chain. Customers can save money buying recovered appliances whose price is lower than that of new ones. On the supply chain side, this initiative allows to decrease costs of disposal and the need for new materials. The Ri-Generation initiative generates also social benefits since refurbishment is more labor intensive than direct manufacturing. On the environment side, Ri-Generation reduces waste production avoiding appliances from being landfilled or exported.

3.1.2 Bundles

Bundles is a Dutch start-up born in 2014 that commercializes household appliances using servitized business models. The team employs 10 people and in 2016 reached 100 subscriptions. Bundles does not manage the production or transportation but attends to the selling phase offering pay-per-month and pay-per-use contracts. Customers do not pay the product but the laundry service it offers, transferring a fixed tranche or a quote based on water and energy consumption. The household appliances are Bundles propriety. Thus, at the end of the contract, Bundles recovers them, repairs parts (if necessary) and sells them back to another customer. In case the product cannot be repaired Bundles send it to the first supplier that reuses the spare parts. Bundles collaborates with Miele, a household appliances OEM, that guarantees the quality of products and helps create a circular supply chain. Moreover, Bundles supports the customers during the entire usage phase, offering maintenance services and personalized advice on how to use the device more efficiently. These services are possible thanks to digital technologies as IoT and Big Data. The devices are equipped with sensors that register information on the machine condition and on energy and water consumption. Data are sent to the Bundles online platform and delivered to customers. Bundles contracts can be economically advantageous for clients since the latter use a high-quality device without the need to buy it. Bundles activity leads also to environmental benefits, since the devices sold by Bundles are all A+++ ranked (lower energy, water, and detergent consumption during usage) and pay-per-X contracts facilitate reuse and recovering practices.

3.1.3 Bloomest

Bloomest is one of the most important brands in Italy designing and selling self-service laundries. In collaboration with Miele, the household appliances OEM, Bloomest designs and built laundries. Since 2005, it helped more than 650 people to build their own self-service laundry, mostly on Italian territory. Bloomest activity simplifies the opening of new laundries, offering the possibility to share washing machines, so reducing the need for washing machines and tumble dryers to satisfy customers' request. The company also offers training courses and the chance to choose between different facilities from low budget ones to the most expensive but fully automated and built to reduce energy and water consumption. Moreover, Bloomest recently started a program to completely digitalized the facilities. Digitalization allows connecting all the devices to a central system to monitor consumption and revenues. The Bloomest initiative has a positive impact on the environment, since sharing models reduce the number of devices placed on the market.

3.2 Secondary case studies

3.2.1 Whirlpool (PolyCE)

Whirlpool is a household appliances producer, founded in 1911, that acts on a global level. Over 90,000 employs work for Whirlpool in about 70 production centers, for a total sale of about 21,000 million dollars. In 2017, Whirlpool joined the PolyCE initiative, a project financed by the UE Horizon 2020 program. About 20 companies and organizations are joining the PolyCE (Post-Consumer High-tech Recycled Polymers for a Circular Economy) initiative, committing themselves to develop correct practices in the production, use and disposal of plastic materials. Recycling plastics is still complex and many security requirements, like the conformity for alimentary contact or the durability of materials, are still uncertain even for the more common materials like PPS or PP. To be effective from the production to the recycling phase, PolyCE brings together companies and organizations that act along the entire supply chain. Whirlpool, by joining this project, intervenes in the production phase choosing recycled materials instead of virgin ones. Whirlpool manages to use up to 32% of recycled materials in the design of new appliances.

3.2.2 SOS Accessoire

SOS Accessoire operates is a French company founded in 2008 by Olivier de Montivault to help customers to repair their household appliances autonomously. The headquarter of the company is in La Verrière. The company employs around 25 people. SOS Accessoire offers a platform where customers can look for spare parts for their household appliances and order them online. SOS Accessoire sells the spare parts also on platforms like e-bay or amazon. The company offers more than 25,000 spare parts that can be assembled using tutorial videos and instructions available through the online platform. The online platform contains 400 tutorial videos on how to replace parts and fix appliances. The use of the online platform is possible through a customer account. The platform helps customers to identify the problem, how to solve it and which is the replacement part to order. The order is usually processed in 3-4 days. SOS Accessoire collaborates with the main household appliances brands to guarantee the same characteristics and performances of the original products. Using SOS Accessoire platform can be economically advantageous for customers that can save 4-5 times the requested price for repairs activity.

3.2.3 PocketWatt

PocketWatt has been a three-year project from April 2016 until March 2019, co-financed by the UE Horizon 2020 program. The objective of the project is to simplify the reading and comprehension of energy labels for European household appliances (washing machines, tumble dryers, dishwashers). Pocketwatt is also the name of the mobile App created to accomplish this purpose. The PocketWatt application is available on smartphones and laptops. It provides information on the environmental impact of household appliances, thus helping customers to compare products based on their energy efficiency. Customers can find information scanning the QR code of products sold by those companies that participate in the project. This initiative helps to reduce energy consumption because customers are led to choose energy efficient products. The pilot project has been first developed in Spain and the UK, for then been extended in the Czech Republic, Germany, and Italy. The head team is independent and not related to any kind of company. To run in the proper way the project needs a strong collaboration between Original Equipment Manufacturers (OEM) and retailers. In fact, OEM must give to retailers the necessary details about the products, so that customers can consult them at the store. Using PocketWatt lead to save energy in the usage phase for customers and to reduce the environmental impact. OEM and retailers participating in this project improve their green brand image as companies that take into consideration the environmental aspect.

3.2.4 Rowenta

Rowenta is an historic German brand (founded in 1909), which produces household appliances and small electronic devices. Recently, the company decides to guarantee a service life of at least 10 years for the new range of products. To attain this goal, Rowenta intervenes on the design side and offers maintenance and repair services. The new products are designed to be easily repaired, in a way to also simplify disassembly and re-assembly steps. Moreover, the repairability of the products is tested to consider potential improvements. To encourage customers in repairing their household appliances instead of replacing them, Rowenta provides an efficient technical assistance service. The repairing service is made by Rowenta professional technicians, while the nearest repairing center can be localized by web or by telephone support. To ensure the immediate availability of replacements, the company stocks the spare parts and guarantees the delivery at the reparation center in 48 hours. Besides this traditional technical assistance service, Rowenta is testing 3D printing to produce spare parts in a way to reduce storage costs. 3D Printing spare parts allows reducing the need for moving them. Instead, only the digital file can be electronically sent directly to the technical assistance centers, in a way to manufacture directly on-site and on-demand only the parts needed for repair. Repairing products instead of replacing them reduces the environmental impact and can be economically profitable for customers.

3.2.5 Relight

Relight is a company founded in Milan in 1999 that manages waste collected in Italian territory. The company focuses on WEEE and more specifically on fluorescent lamps and cathode-ray-tube devices. Relight owns a specific disposal center and has the Italian authorization to process and recover waste. Relight has an internal vehicle fleet and directly control waste transport. Moreover, the company is also part of the Italian ‘Albo Gestori Rifiuti’, so it can transport hazardous waste. Relight treats waste whenever possible or connects its clients with external disposal companies. Relight treats glass, metal, and rare earth elements. From its birth, Relight recovered 2.500 tons of glass from old TVs, reusing it to produce ceramic tiles. Relight put waste back into the production chain, thus helping to reduce the resource consumption and the related environmental impact.

3.2.6 AquaFresco

AquaFresco is a mechanism designed by three MIT graduate students to reuse washing machines' wastewater. The AquaFresco project won the third prize of the ‘Water Innovation Prize Competition’ in 2014. The AquaFresco system enables the reduction of water consumption cleaning up the water after its first use and reusing it more and more time. The mechanism uses a polymeric filter that clean up the water, recovering 95% of the washing cycle's water. According to the three MIT designers, thanks to the implementation of this mechanism, users could reuse the same water. The device consists of a stand-alone unit that can be paired with different kinds of washing machines. The idea of the designers is to create a device that can be paired with 3 or 5 washing machines at the same time. Up to now there are 3 hotels and 3 laundry-services that are testing the system in the US. Moreover, the system can be ameliorated using IoT to control water quality. This system allows to obtain environmental and economic benefits. The AquaFresco system, indeed, reduces the overuse of water and water pollution. The large-scale use of this technology can be also economically advantageous. According to some estimates made during the project, a big Hotel that spends about 10,000 dollars per week in water and detergents could save 500,000 dollars per year using the AquaFresco system.

3.2.7 Gorenje

Gorenje is a household appliances OEM, founded more than 60 years ago. The headquarter is in Velnje (Slovenia) but Gorenje works in 90 countries. The company employs about 11,000 people and has a turnover of 1,3 billion euros. Gorenje products can be bought on the company online platform but are generally sold by retailers. In 2014 Gorenje joined the ResCoM (Resource Conservative Manufacturing) project, a project co-financed by the UE under the Horizon program, that saw the participation of twelve organizations. The project ended in 2017 and aimed to promote CE initiatives helping companies in the transition from linear to circular practices. Gorenje, thanks to ResCoM, developed a new business model for washing machines based on leasing contracts. In this new approach, washing machines are firstly sold to premium clients, which use them for a pre-defined period, then the devices are recovered and re-sold to customers with a lower budget. Gorenje simplifies remanufacturing activities directly in the design phase by conceiving washing machines with a modular structure and standard components. Gorenje is also considering adding sensors to the washing machines to obtain information on the devices conditions as well as energy and water consumption. The project has been followed by ReCiPSS (Resource-Efficient Circular Product-Service-Systems), again co-financed by the EU. Gorenje, thanks to the new investments provided by ReCiPSS, will test and implement the new business model on a large-scale. Gorenje estimated that this new approach could lead savings for each washing machine of about 146 kg of virgin materials, 21 kWh of energy during the production phase and 18 kWh of energy during the usage phase.

3.2.8 Homie

Homie is an initiative developed in Delft university (Delft university of technology, Netherlands) to test new business models in the white goods market. Homie focused on the move from classic buying and selling contracts to pay-per-month and pay-per-use contracts. Homie provides services in the cities of Rotterdam, Delft and Hague. Homie intervenes in the selling and usage phase, managing the contracts and supporting customers who wish to access washing machines and other household appliances instead of buying them. Homie offers washing machines produced by Zanussi-Electrolux to guarantee high quality and A+++ ranked devices. During the usage phase, Homie provides repair services and advice on how to use the device more efficiently. At the end of the contract, Homie sells the washing machines to other customers, repairing them if necessary. Customers pay monthly and the rate differs based on the number and type of washing. Sensors placed in the washing machines allow Homie to track how customers use the devices. Homie uses data and information collected by sensors not just to calculate the monthly rate but also to implement a personalized customer experienced, advising on how to use the device in the best way possible. The initiative found his primary source of enhancement in the Technology Foundation branch of the NWO (Netherlands organization for scientific research), an organization under the control of the Ministry of Instruction. Then, in 2018, Homie received funds by the UE program ReCiPSS. Homie activity is beneficial for customers and the environment. Customers can use high-quality washing machine paying less, thanks to pay-per-month contracts. Then Pay-per-month contracts make it easier to close the loop and reuse products. Together with the more efficient use of washing machines, Homie reduces waste and bring benefit for the environment.

3.2.9 The Machine du Voisin

The Machine du Voisin is a French initiative developed by four students of the Skema Business School. The objective of the project is to connect washing machines owners, which want to share their device, with people lacking the possibility of owning one. The students created a platform where washing machine owners can register their device, specify place and time available and so arrange with the other members of the platform that need to use the washing machine. This initiative focuses on sharing, changing the classic business model, and so reducing the total number of washing machines on the market. Customers to access the service need only to register on the platform. Moreover, on the platform, they can leave comments and read other customers' experiences. This initiative can be economically beneficial for clients since machine owners can ask for a modest remuneration. Moreover, people with low budget or space problems do not need to own a washing machine.

3.2.10 The Increvable

The Increvable is the name of Julien Phedyeff's project regarding a washing machine built to last 40 years.

Julien Phedyeff is a designer graduated at the École Nationale Supérieure de Création Industrielle of Paris. He presented the project in 2015 at the Observeur du design, a contest organized by the APCI (Agence pour la Promotion de la Création Industrielle) recognized by the French Economy ministry, Finance ministry and Culture ministry. The Increvable is a washing machine designed to extend its life cycle and thus opposing to planned obsolescence. To achieve this goal, Phedyeff designed a washing machine extremely easy to assemble and disassemble, to simplify repairing and substitution practices. Thanks to this design the washing machine would not be easily discarded. The customer can repair the device on his own, saving on repairing and maintenance costs. To help customers in the repair activities, Phedyeff created an app that provides tutorials on how to assemble and repair the washing machine. Moreover, the washing machine is designed also to change aesthetically, modifying the color and so considering the possibility of emotional obsolescence. To offer a high-quality product at an affordable price the washing machine is created to be assembled by customers, to remove assembly costs to the final price. The Phedyeff's washing machine being projected to last is a possible solution to reduce resources exploitation and excessive waste production.

3.2.11 WeWash

WeWash is a spin-off project born in the context of the multinational company Bosch. Bosch is a historic German brand founded in 1886 that produces spare parts for the automotive and household appliances. WeWash is the initiative of three Bosch members that created an app to simplify the sharing of washing machines. In 2014 they proposed the idea to Bosch and a year later they set up their own company. They collaborated with the Bosch Thermotechnology team and Bosch supported the initiative presenting it at organized events. The objective of WeWash is to promote sharing to reduce the number of washing machines on the market. Customers who want using the app should register on a dedicated platform. The platform allows verifying if somebody is using the shared washing machine, to reserve it and to know when the wash cycle is finished. This initiative modifies the usage phase thanks to digital technologies. To use We wash, an IoT kit is sufficient and adaptable to every kind of washing machines. The IoT kit is placed between the device and the power plug. Moreover, WeWash accepts credit card simplifying payments. The 'Citadines Arnulfpark' Hotel and 'The Reserl' student residence, both in Monaco, are testing the WeWash service.

4 Analysis and discussion

The application of the framework to the 14 cases and the comparison of the results provides an overview of the implementation of CE in the household appliances industry.

4.1 Circular Economy '4R' Strategies

Literature proposes an ideal hierarchy to follow among the 4R strategies to obtain increased benefits [7]. This hierarchy considers *reduce* practices as the most valuable, followed by *reuse*, *remanufacture*, and *recycle*. In the beginning, organizations should implement resource efficiency and waste prevention. Then, they should try to reuse products as much as possible. When reusing is not feasible, they should try to remanufacture them. At last, they should recycle waste to recover raw materials. The initiatives in the paper respect this hierarchy, since 11 cases on 14 follow the reduce strategy, while three exploit reuse practices and just two of the initiatives concern remanufacture and recycle (Figure 2).

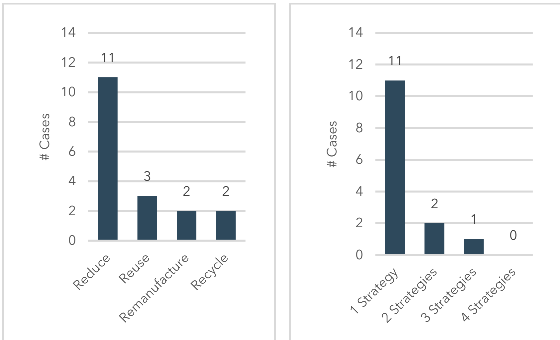

Figure 2: Frequency and diffusion of 4R strategies

Even though sometimes literature recognizes that reduce strategies do not deal with waste [10], anyway this issue do not make it less worthwhile for a CE. Reduce is a prevention approach, and it is the first step to reach a CE because it deals with the potential abolition of the concept of *waste*. On the contrary, strategies like reuse, remanufacture and recycle deal with the reprocessing of products which are already or nearly *waste*. Anyway, establishing a hierarchy does not mean that organizations should abandon recycling. Initiatives should apply the 4R in a cascading process [12]. However, Figure 2 shows that only one initiative pursues all the 4R concurrently, while most of them employ only one single strategy.

4.2 Levers and enabling factors

The lever mostly employed is the shift from linear business models to servitized business models (Figure 3). Ten cases out of 14, indeed, apply servitized business models to facilitate the transition to CE. These could be easier to implement than circular design strategies since changes in the business model do not require to modify facilities or production techniques. Also, servitized business models are based on the relationship between customers and organizations, so that the development in this sector could rely on a change in

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customer-mentality towards sustainable issues. The circular design is still a practice rarely used, since just five projects out of 14 introduced circular design practices on their production processes. Approaches to easier disassemble or improve material selection are still in a prototypical phase and are far from been implemented in industrial practice. There are, indeed, many circular design ideas and proposals, but they need a radical change as well as extensive funding. Supply chain management has been adopted through collaboration and reverse logistics. The high number of initiatives that applied this lever confirms the necessity of a more holistic and shared approach for the transition to CE. Few companies, alone, will not be enough for a real enhancement.

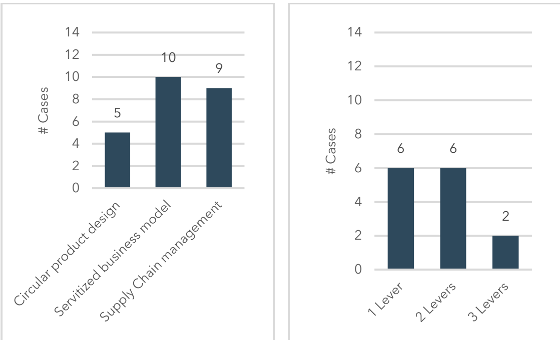

Figure 3: Frequency and diffusion of Levers

The number of initiatives that use at least two levers is relatively high, even if just three out of 14 projects employ all of them (Figure 3). A possible explanation can be related to the importance of collaboration between organizations when the project deals with circular design strategies and between organizations and customers when the project concerns servitized business modelling.

4.3 Digital Technologies as enabler

The IoT is a technology used by many initiatives that made possible changes otherwise unattainable, for example, the data collection indispensable to offer pay-per-use contracts (Figure 4). Big Data and Analytics generally employs data collected by IoT but implies a more accurate analysis and has been exploited by fewer initiatives. Cloud platforms are significant most of all for sharing projects. Platforms, indeed, revolutionized the organization of sharing, allowing to extend it to the entire digital community. These first three technologies relate to the services sector, while 3D printing is potentially relevant for design and fabrication processes, even though still underdeveloped. The number of initiatives that employ digital technologies is remarkable, but an increase in this number could lead to a CE more rapidly. The exploitation of digital technologies can be extremely advantageous, but many organizations may consider too risky moving away from traditional production strategies.

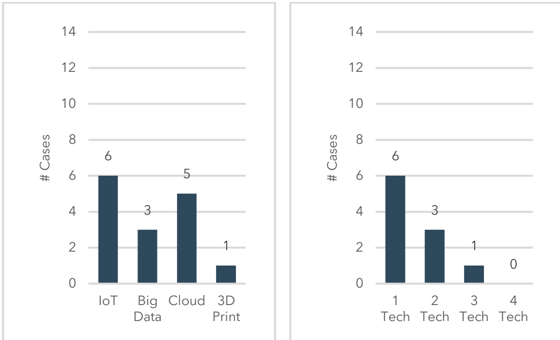

Figure 4: Frequency and diffusion of enablers

There are no projects that employ more than two technologies (Figure 4). The initiatives that apply 3D printing are part of a different context, so that is not unexpected if 3D printing appears alone, not combining with the other technologies. However, it would be desirable a simultaneous use of the first three technologies, since they deal with the same data and computing them with different tools, at the same time, could increase the benefits obtainable.

5 Conclusion

Although preliminary, this exploratory research lays the foundation for a stronger and more systemic understanding of the adoption of CE in the household appliance industry. In a nutshell, the analysis contributes to research by the means of the four following findings: (i.) the *4R hierarchy is confirmed in practice*, since 11 out of 14 cases dealt with reduce, while less than 4 cases dealt with reuse, remanufacture and recycle; however, *cascading is still not applied* in the household appliance industry; (ii.) *servitised business models (such as leasing or pay-per-use) turn out to be the most used lever*, followed by circular product design and supply chain management; (iii.) lastly, *IoT, Big Data & Analytics emerged as enablers especially in the service field*.

This study has managerial implications too. It proposes an improved managerial understanding of the adoption of CE in the household appliance industry. Lastly, this study presents various limitations. The analysis is still at a high-level and descriptive, mainly due to the limited number of primary cases, the difficulty of verifying secondary cases results, and the limited amount of initiatives examined. An extension of the database, with more primary cases in it, could lead to an increase in results robustness. Also, this study considers only the household appliances industry. Given the high generalization potential of the framework, an application to other industries (as the electronics, ITC or automotive) is suggested.

6 Appendix: the fourteen case studies

Case	Reduce	Reuse	Remanufacture	Recycle	Circular Product Design	Servitized Business Model	Supply Chain management	Internet of Things	Big Data & Analytics	Cloud Platform	3D Printing
Astelav (Ri-Generation)			X			X	X				
Bundles	X	X				X	X	X	X	X	
Bloomest	X					X	X	X			
Whirlpool (PolyCE)				X	X		X				
SOS Accessoire	X					X				X	
PocketWatt	X						X			X	
Rowenta	X				X	X	X				X
Relight				X			X				
AquaFresco	X				X			X			
Gorenje	X	X	X		X	X	X	X	X		
Homie	X	X				X	X	X	X		
The Machine du Voisin	X					X				X	
The Increvable	X				X	X					
WeWash	X					X		X		X	

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Towards new ways of organizing ecodesign, the case of EEEs

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Abstract

Ecodesign consists in integrating the environment from the design stage of products and services, and during all stages of their life cycle, to reduce their total environmental impact. If ecodesign has long remained a technical subject, lacking openness to other parts of the organization and to stakeholders at large, ecodesign practices have evolved in recent years, considering new societal expectations. This communication seeks to better characterize the new ways of organizing ecodesign in the case of the EEE sector, historically ahead of its time. 23 semi-structured interviews and two workshops were realized with members of pioneering companies in ecodesign in the EEE sector, and members of support organizations. We highlight the coexistence of two regimes - a techno-centric regime, and a still emerging responsible eco-innovation regime – of which we discuss the characteristics, promises and limits.

1 Introduction

Ecodesign consists in a purposeful strategy to integrate environmental criteria in the design of a product or service, considering all the stages of its life cycle: extraction of resources and materials, energy used during the manufacturing process, logistics, use phase, recycling or disposal. The aim of this proactive approach is to develop eco- innovations, i.e. products that not only have a reduced environmental impact compared to conventional products, but which are also commercially successful, thus contributing to an ecological transition [1]. Ecodesign is often designated as a crucial lever to tackle environmental Grand Challenges such as global warming, resource depletion or waste accumulation. Ecodesign has emerged as a new corporate practice in the 90's, supported by the development of a new expert community around Life Cycle Assessment (LCA) and by public authorities by means of different incentives (ecolabelling schemes, public green procurement policies, regulations including ecodesign requirements, etc.).

However, more than twenty years later, the results are quite disappointing [2,3]. The diffusion of these practices is still limited and its recognition by customers and the public remains modest. This apparent lack of effectiveness is quite paradoxical as ecodesign is a major lever of sustainability public policies and as many companies pretend to conduct such strategies.

If the drivers and best practices for ecodesign implementation have been investigated, few analyses have tried to understand the obstacles encountered by companies having deployed ecodesign [4]. However, several studies have highlighted the fact that, historically, emphasis was placed on the development of technical tools to the detriment of its integration into the organization and strategic decision-making process [5;6]. What is more, for a long time, ecodesign has been approached from the strict company scope, and not from a broader value chain or ecosystem perspective. These elements reflect the fact that ecodesign has long remained a technical subject, lacking openness to other parts of the organization and to stakeholders at large, suggesting legitimacy and efficiency issues.

2 Theoretical background and research questions

Responsible innovation (RI) for companies has been recently introduced in the management science literature as a normative concept that can be defined on the basis of three norms [7] :

- Avoid harming people and the planet (avoiding harm)
- Improve conditions for people and the planet (do good)
- Coordinate with others for the sake of protecting the people and the planet

Tackling Grand Challenges, i.e. massive social and environmental challenges that have important negative effects on people and the planet [8], is often presented as being the purpose of RI.

Definitions of RI emphasize the importance of governance structures and processes opened up to stakeholder involvement as in the seminal definition proposed by Von Schomberg [9] : RI is « a transparent, interactive process by which societal actors and innovators become mutually responsive to each other with a view to the (ethical) acceptability, sustainability and societal desirability of the innovation process and its marketable products ». In line with this definition, Stilgoe et al. [10] have proposed four dimensions of responsible innovation processes: anticipation, reflexivity, inclusion and responsiveness. Similarly, but at the corporate level, Scherer and Voegtlin [11] argue that « corporate governance should influence the corporate innovation process so that the outcomes are socially acceptable (legitimacy), meet sustainable development goals (effectiveness) and use appropriate means (efficiency) so that the resulting innovations avoid harm and do good to society and the planet ».

With this framework in mind, we propose to study the practices of ecodesign and eco-innovation, and their evolution. Indeed, ecodesign practices in the field of electrical and electronic equipments have evolved in recent years and now present characteristics close to those of responsible innovation, namely avoiding harm, doing good, and setting up new governance mechanisms.

Then, our research questions are the following : How to explain the difficulties related to the dissemination and the success of ecodesign practices? How have these practices evolved over time and how could the problems encountered be related to the historical framing of the issue? To what extent can recent ecodesign practices be said to be more responsible?

3 Methodology

To grasp how organizations have taken up and framed the issue of ecodesign from an historical perspective, and to account for the evolution of organizations' ways of thinking and acting, we took a genealogical approach [12, 13]: in order to understand the different problematizations of ecodesign that have successively emerged over time, their influence on organizations' pratices and conversely, a systematic analysis of academic articles and grey literature on ecodesign was conducted.

To analyze the obstacles that organizations have had to overcome over time, the past and current methods, and the governance mechanisms experimented by companies with regard to ecodesign, a series of 23 semi-structured interviews and two workshops were conducted. Initially, these interviews were carried out with the French Environment and Energy Management Agency (ADEME) and eco-organizations. Then, pioneering companies in the field of electrical and electronic equipments, i.e. companies giving strategic priority to ecodesign and recognized for their actions in this area for several years by these agencies were surveyed, as well as organizations supporting the development of the approach such as private consulting firms.

By interviewing pioneering companies and experts of the field, and conducting a content analysis, we have seeked to identify changes in the way ecodesign was apprehended and implemented, and the future agenda to make these practices more legitimate, effective and efficient. To complete the interviews, secondary data such as environmental activity reports or ecodesign best practice guides drafted by these companies were also used.

Concerning the intents of ecodesign and eco-innovation, we relied on Voegtlin and Scherer's responsible framework [7] to identify how eco-innovations are intended to avoid harm or do good. Concerning the governance of innovation, we have seeked to identify how actors were supposed and did actually coordinate with each other responsibly. In order to do so, we drew upon the framework proposed by Scherer and Voegtlin [11] to characterize the legitimacy, the effectiveness and the efficiency of the ecodesign practices.

4 Findings

Based on our genealogical analysis of ecodesign and empirical investigation, we distinguish between two historical regimes. The first, that we propose to call a rational-legal regime, has been dominant in the last twenty years. While this regime is still of considerable importance, its inherent limitations have led to the development of a more responsible regime, seeking to meet legitimacy, effectiveness and efficiency.

4.1 The rational-legal ecodesign regime

4.1.1 The characteristics of a regime based on instrumental rationality

Ecodesign is a term that has been coined and promoted by environmental experts who wanted to enhance a prevention environmental strategy as a key lever to meet ambitious environmental political targets. Its initial promoters were experts of a new epistemic community organized around Life Cycle Assessment (LCA), a quantitative method of environmental impact assessment standardized in 1997 (ISO 14040 standard). In this initial framing, ecodesign was seen as prospective and rigorous approach aiming at assessing all the environmental impacts of a product during its life cycle, and helping decision makers to make the right design choices (selection of technologies, materials, energy, product architecture, etc.). The figure of the environmental expert whose legitimacy relied on his scientific, technical and regulatory knowledge predominated [14], and the stakes of the approach rested on the adoption and the development of advanced environmental assessment tools such as LCA and their integration into traditional product development processes [15]. In the 1990s and at the beginning of the 2000's, efforts were mainly made in three directions :

- *Towards regulators and policy makers* to make ecodesign a privileged method. After having favored curative approaches for many years, ecodesign was promoted as an efficient prevention strategy aimed at reducing pollutions at the source. Considerable legislative progress was made at European level in the 1990s and early 2000s. Early on, in several European Union regulations and directives, emphasis is placed on the need to produce products and services with a lower environmental impact throughout their life cycle. A few years later, more explicitly, a general framework for ecodesign, but also specific requirements for electrical and electronic equipments have been defined [16].

- *Towards decision-makers and designers* by means of mediating instruments such as decision- aid LCA tools. To this end, they were encouraged to participate to training programs organized with the support of public environmental agencies, and to surround themselves with specialists, whether they hire them or call upon them in the context of consulting missions.
- *Towards customers* through environmental labelling as an instrument to make the environmental performance of products visible and credible. The environment being considered as an expert asset [17], an asymmetry of information between companies and customers was assumed. Environmental labelling (ex : ecolabels) appeared to be the solution to inform consumers about the environmental quality of products and restore the terms of exchange.

Finally, this regime rested on (1*) a firm-centric approach*, ecodesign being the result of individual company products initatives to comply with the law, and anticipate future legislative developments; (2) *an instrumental approach*, ecodesign requiring rigourous assessment methods such as LCA to make the right decisions; (3) *an asymmetry of information hypothesis* between businesses and consumers explaining the use of environmental signalling. Since ecodesign was supposed to spread on the basis of instrumental rationality, i.e the use of scientifically based techniques and legal mechanisms -ex : ecolabels-, we propose to call this regime a “rational-legal ecodesign regime”.

4.1.2 The characteristics of a regime based on instrumental rationality

The rational-legal ecodesign regime dominated from the mid-90s onwards but soon came up against several limitations.

First, the *internal legitimacy* of the approach was undermined by the use of complex environmental assessment tools. Many companies had entrusted the ecodesign process to one or a few environmental experts that found themselves isolated, the other business units considering ecodesign as an additional constraint rather than an opportunity. This has led to only marginal improvements in products whereas a more global involvement of the whole company could have led to a more in-deph reflexion on the products, their functions, and their identities.

As a direct consequence, another limitation of the regime lied in its difficulty to *promote ecodesigned products to customers*, i.e. in its ability to transform the ecodesign approach into eco-innovations characterized by a limited environmental impact and a commercial success through a discourse that made sense to the consumer, especially in the B2C sector. The failure to include certain departments such as marketing explains the lack of attention paid to the customer: customer creation value has been largely neglected in this approach. What is more, environmental signalling that had emerged as the optimal valuation method for the client was found inefficient by many companies. The message delivered was considered overly complex and insufficiently visible on the packaging that already contained a lot of information. These elements explain the difficulty for customers to distinguish ecodesigned products from so-called conventional products.

More importantly, ecodesign strategies have *mainly focused on avoiding harm objectives*, i.e. mainly on the environmental impacts avoided with reference to a business-as-usual scenario. Put differently, the rational-legal regime made it possible to consider the reduction of certain environmental impacts in a preventive logic, but did not capture the other positive dimensions and consequences of the approach, while they could be valued by society and thus by consumers -for instance, the improvement of living conditions in developing countries backed by a reduction in the extraction of certain materials.

➔ Relying on highly technical and confined approaches does not appear to constitute an efficient means to make ecodesign and eco-innovations environmentally and commercially successful. The development and commercialization of “incremental” eco-innovations and the difficulty of promoting them to consumers question the efficiency and effectiveness of the approach. With regards to governance, the process was neither interactive nor reflexive, conducted by environmental experts whose internal and external legitimacy was contested. The rational-legal ecodesign regime quickly reached its limits and lower-than-expected diffusion of practices became apparent.

The obstacles encountered by companies implementing this type of approach has led the actors to find solutions, which eventually led to the development of new methods, organizations and governance mechanisms, toward more responsibility.

4.2 Towards a responsible eco-innovation regime

4.2.1 An open approach to consumers and society

In the last few years, companies that had implemented a techno-centric ecodesign approach have progressively realized the discrepancy between the growing sustainablility expectations of customers and society, and the shortcomings of their product portfolio offers. In certain sectors, such as food, cosmetics but also electronics, pressures from consumer associations, NGO's and the media on environmental and social impacts have become significant. Every sector is now exposed to scandals and controversies. Some of them like food and most recently cosmetics and clothing sectors are already suffering from it. The electrical and electronic equipment sector which makes important use of scarce resources and controversial materials, consuming a lot of energy, and producing across the world, sometimes under questionable social conditions is not spared. The health aspects related to the use of certain substances or the emission of waves are other examples of issues that are increasingly being raised. These new expectations and pressures have played a key role in the change of practices and hence, in the regime evolution. If the rational-legal ecodesign regime has not disappeared, it now coexists side by side with a regime characterized by more responsibility.

As the perceived legitimacy of products and brands is traditionally based on a positive image of quality, healthiness and transparency, the controversies are potentially devastating for companies. Consequently, the agenda of responsible innovation and eco-innovation has come to the front of their strategy these last years. More and more top managers have become aware of the need to go further in terms of environmental and social commitments but also to integrate, more concretely, these commitments in the product and service portfolio, consistently, to guard against greenwashing charges. To align corporate commitments with product portfolio, top managers have encouraged the initiatives of other actors, including designers, marketers, stylists, production staff or CSR managers, who questioned an overly technical and rational approach that missed its target.

Several producers and retailers started to frame the issue differently, integrating various internal and external stakeholders into the process, paying particular attention to customers and society as a whole, favoring interactivity, reflexivity and transparency. Meanwhile, public agencies and other support organizations -trading associations, producer responsibility organizations, consulting firms- also concluded that the instrumental and firm-centric approach was not enough. A need to develop an entire ecodesign ecosystem to create the conditions according to which ecodesign and eco-innovation might become effective was felt, and has materialized in several collective action mechanisms such as exchanges through networks and clubs, development of platforms gathering case studies and best practices.

More specifically, in this new approach, three critical issues have become salient:

-First, based on our interviews, we have observed that more and more companies are using ecodesign approaches to meet commitments that go beyond a simple target to reduce the environmental footprint of their products. They realize they have a responsibility towards the planet and towards people, who now expect strong commitments, that need to be reflected in product and service offers. As a result, companies move beyond legislative requirements, committing to voluntary labels and norms to "do not harm", and, above all, demonstrate a growing willingness to "do good" by participating in the achievement of several sustainable development goals, directly - climate, protection of aquatic life, biodiversity conservation- or indirectly linked to the environment -reducing poverty through local production, fair trade and healthy living conditions. Eco-innovation is now seen as the approach linking major commitments made at the strategic level, and products placed on the market. If environmental assessment tools are still used, they are now put at the service of a more open approach to internal -production, quality, marketing, communication…- and external -consumer organizations, consulting firms specialized in eco-innovations or eco-responsibility- stakeholders. These stakeholders, previously overlooked, are now integrated into participative ecodesign projects, and participate by using other kinds of methods -ex: creative methods such as design thinking- to account for societal expectations.

-Therefore, the scope of the issues dealt with within the framework of ecodesign has considerably broadened. In the previous regime, the criteria that were supposed to matter for customers were solely those included in LCA or related tools. In this approach, looking at what consumers and society at large value most, companies and stakeholders have found out that these criteria were not the only ones that mattered. More than that, it turned out that the criteria were not fixed but evolved over time and had to be identified pragmatically in the course of interaction between companies, customers, and other stakeholders. In this stakeholder-centric approach, other environmental issues, like microplastics that end up in oceans, protecting biodiversity, reparability and durability -key elements in the electric sector-, and other social issues like healthiness or local origin have been identified as highly valued criteria. It has become salient that the vast majority of consumers were not buying ecodesigned products solely for their environmental characteristics, but were increasingly looking for “co-benefits”, beyond environmental aspects such as price, status, health, security, emotions etc. [18]. In this perspective, the issue for companies is to identify, for each product, the relevant “green bundle” [18], i.e. the association of co-benefits that best satisfy the customer, society at large, and which reflect the major commitments made by the company. Indeed, consumers are not buying products or a brand, but the social reputation attached to the brand. Companies are looking for greater social legitimacy, and then give much importance to stakeholders’ legitimacy judgments.

-Finally, a major issue of this new regime is to manage to simplify the message to customers without compromising transparency of information. Finding a catchy product communication, that consistently highlights the various co-benefits associated with the product is still a challenge today, particularly for the B2C sector. First opportunities are emerging around the development of product ranges identifiable by a simple logo and motto but also around playful and gaming logics featuring characters that tell the story of the product. Developing a coherent and comprehensive storytelling through appropriable mediating instruments has been put forward in the interviews.

Because of the openness, interactivity and reflexivity that characterize this emergent regime, we propose to call it the responsible eco-innovation regime: it establishes a participative process for building ecodesign with a multiplicity of internal and external stakeholders, with the aim of producing effective and impactful eco-innovations. It results in a new value proposition based on “bundles” that fit the consumers’ needs and expectations.

4.2.2 The challenges associated with this emergent regime

If it is still too early to assess the real impacts and effects of this emergent regime on sustainability transitions, it looks a priori more in line with societal evolutions. However, unexpected problems, obstacles or limits could hinder its development. In particular, even if the approach seems more relevant vis-à-vis customers and society, the rigor of the method to evaluate the benefits of eco-innovation is questionable. The strength of the rational-legal regime lied in the robustness of the environmental performance measure through the use of standardized science-based methods. In the new pragmatic approach, sustainability issues are broader, sometimes blurry, their scope varying across time and space. Beyond environmental aspects considered in LCA, other environmental issues have emerged and are taken into accounts by companies that now develop “responsible”, “eco-responsible” product lines, or “positive impact” products. The vagueness of these statements, and the variable scope of the criteria taken into consideration, that are sometimes difficult to measure, may undermine the legitimacy of this approach, and complicate the choice of the message to be sent to the consumer.

Thus, above all, the main challenge faced by the responsible eco-innovation regime is to find a balance between its rigor and its relevance, to develop and legitimate certifiable and auditable methods for social and environmental performance measurements without limiting to pre-existing tools -ex : social LCA.

5 Conclusion

The aim of this communication was to better understand the obstacles to the dissemination and success of ecodesign practices. For that purpose, an attempt was made to analyze the initial framing of ecodesign, its limitations, and the practices and solutions implemented by pioneering companies in the field of electrical and electronic equipments to overcome these limits, through the framework of responsible innovation.

Based on a genealogical approach, and an empirical exploration, we have identified two regimes that we propose to call the “rational-legal ecodesign regime”, and the “responsible eco-innovation regime”. The rational-legal ecodesign regime, based on technique and expertise, focusing on avoiding harm, dominated between 1995 and 2015. If this first regime still exists, the responsible eco-innovation regime has emerged in response to new societal expectations in recent years, advocating openness to stakeholders, and an interactive and reflexive governance with these actors, for the purpose of achieving “do good” objectives, beyond avoiding harm. Using the reading grids of Scherer and Voegtlin [7, 11] we analyze these two regimes through the characteristics of responsible innovation (summary in appendix A.)

Through this study, we contribute to understand how ecodesign approaches are organized, instrumented, governed and how they evolve over time. We provide a better understanding of the challenges faced by emergent eco-innovation practices. In particular, we stress the importance of building co- benefits beyond standard environmental performance per se and the need to adopt techniques to produce legitimacy around eco-innovations.

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Appendix A. Ecodesign regimes through the prism of responsible innovation

Rational-legal regime		Responsible eco-innovation regime	
Do not Harm		**Do not Harm**	
Goal	Compliance to legal rules and legislation anticipation	Goal	Compliance to legal rules and legislation anticipation Commitment through voluntary labels, norms
Practices	Classical environmental assessment (LCA and related tools)	Practices	Extended environmental assessment (LCA + others)
Actors	Environmental internal and external experts	Actors	Environmental internal and external experts
Do Good		**Do Good**	
Goal	No direct "Do Good" will	Goal	Contribute to the achievement of SDGs, be part of the solution to Grand Challenges
Practices		Practices	Definition of corporate vision Co-benefice offers
Actors		Actors	Organization members from design to marketing Various stakeholders acting as consumer and society intermediaries
Governance		**Governance**	
Legitimacy	Rational and pragmatic	Legitimacy	Social
Effectiveness	Limited impact on a unique goal (responsible production)	Effectiveness	Stronger impacts on several SDGs (No poverty, good health and well-being, responsible production and consumption)
Efficiency	Lack of interactivity, reflexivity	Efficiency	Interactive and reflexive forms Participatory processes

Decomposing software obsolescence cases – a cause and effect analysis framework for software induced product replacement

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Abstract

Harmonising the lifetime of the hard- and software symbiosis of electronic products is critical to extend the overall useable lifetime. Premature obsolescence triggered by software is characterised by complex software-hardware systems, involved actors and various cause-effect dependency paths, making a quantitative analysis of software obsolescence driving factors from a socio-ecological perspective a difficult task. This ongoing study collects and analysis systematically prominent software related obsolescence cases as the “Apple iPhone slowdown” and “Sonos Speaker Trade Up”, by combining few existing theoretical approaches to a novel analysis framework. Methodologically, each obsolescence case has been first decomposed into its hardware-software and manufacturer-supplier system. In a second step, information have been gathered including brand, model, release price and date, discontinuation notification date and event as well as software support history. Root causes have been identified and successive individual actions and justifications by the product manufacturer recorded. Effects of those actions have been clustered into four categories that are critical for usage and indicate severity of the actions. First results show that extensive worries about product quality (performance, system speed, functionality) as well as resources (financial) are used to justify obsolescence driving decisions. Further reasons include safety and security to protect the user. First conclusions and alternative actions have been proposed for software obsolescence-critical steps, waiting for the argumentative counteroffensive from the manufacturers.

1 Introduction

Technological advances in terms of mass availability of storage and computational speed enabled new functionalities and short innovation cycles. Like a tree growing technological layers can be seen in households from mp3 players, mobile phones, digital cameras over first smart speaker, AI supported video streaming to a cloud based society with steady connectivity of people and things. The product lifetimes of each generation is not only determined by the weakest physical link that will fail first but cases increase where software induces the hardware to become obsolete concerning compatibility, security or functionality. In the field of socio-ecological research, the phenomenon of software obsolescence has so far been little researched and understood. However, the growing understanding of problems by other social actors and interest groups shows the growing need to conduct more research here. Initial consumer surveys show that 30% of consumers have already replaced an electronic device due to software problems [1].

Literature tangles or discusses causes and effects for software related obsolescence cases directly by providing root cause categorisation or indirectly by characterising the software state in terms of software quality measures (ISO25010) and labelling (blue angel): Several references analyse software obsolescence in particular commercial of the shelf software (COTS) used in industrial environments with reliability and safety-critical focus (avionic, military systems). A current meta analysis provides a comprehensive overview on COTS categories, metrics for COTS obsolescence cost, OM strategies, processes, tools and methods [2]. Authors conclude on a lack of literature on models and frameworks analysing hardware-software system (CPS) interdependencies and related obsolescence. End-user devices and customer perspective is less researched and requires the consideration of new obsolescence dimensions. A study on green software indicated the software-related obsolescence of hardware, but could not conclude on causes and effects [3] [4].

Some studies use three categories to cluster obsolescence root causes: technological, functional, logistical [5] [6]. On the other hand, effects on software are characterized by software quality measures. The recently developed German label “Ressourcen- und energieeffiziente Softwareprodukte” [7] provides criteria to evaluate software towards its information transparency, resource and energy efficiency. Complexity and process standardisation allowed to consider only desktop applications in this first label version. Three main categories are resource and energy-efficiency, downwards-compatibility and the autonomy of use. Latter is characterised by data formats, transparency (source code, end-of-support, license), continuity (min. 5 years of support), de-installability, offline functionality, modularity and no-advertisement.

The goal of this study is to combine above existing approaches to identify software inducing causes as well as effects. A comprehensive framework for case study characterisation is proposed that enables to estimate the probability of replacement by including and understanding the complexity arising from:

- Software – hardware systems
- User – Manufacturer relation
- Evolution of causes, actions and effects

Important finding from previous literature on system modelling and cause and effect analysis are taken up and extended towards this scope. This study defines software obsolescence (SO) or software-related obsolescence as the process of decreasing software quality properties and the associated product systems as a result, triggered by the software itself or changing requirements for the functional or non-functional properties of the software.

2 Method

A two tier approach was developed as it was found practicable to understand obsolescence dimensions. First, a system diagram initially helps decomposing underlying cases towards important actors and interconnections. Second, the core method structures steps by the temporal occurrence (evolution) of causes, actions and effects. Furthermore the final impacts on customer dissatisfaction and probability of replacement are indicated qualitatively.

2.1 Milieu-Material system diagram

First, for the systemic decomposition of obsolescence cases a generic system diagram is derived using two main dimensions of the “7Ms” for cause-effect analysis [8]. Figure 1 shows the matrix of these two dimensions: material (vertical) and milieu (horizontal). The “material” dimension is inspired by the OSI-model [9], condensed to three main layers hardware, embedded software and application or service (layers are not necessarily technically connected). The dimension “milieu” consists of part or service supplier (3rd party), manufacturer and user. Interactions and dependencies between layers and dimension are multi-directional. Elements within the matrix are derived categories by underlying obsolescence cases.

2.2 Temporal Cause-Effect analysis

The bow-tie scheme in Figure 2 shows the second tier

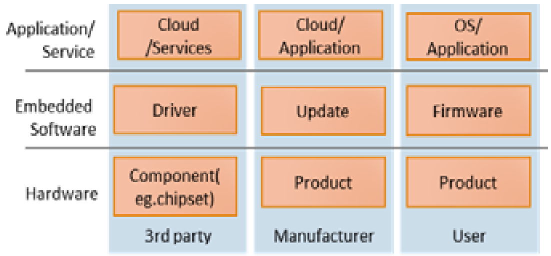

Figure 1: Generic system diagram decomposing obsolescence cases into milieu and material

of the analysis, including three consecutive steps from (1) initial root causes that mostly lead to (2) one specific actions by manufacturers that has (3) several effects software quality. Furthermore case study specifications (0) are recorded.

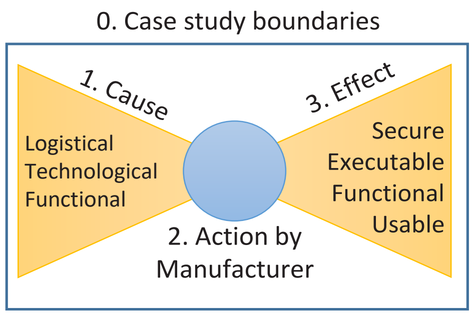

Figure 2: Analysis steps of obsolescence cases with underlying boundaries and embedded methods

(0) Case study boundaries: Each obsolescence case is characterised by affected model, release price (list price) and continuity in terms of age of the device till event of software obsolescence, calculated from the release date. For transparency, software-product change notification (SPCN) is recorded, describing the warning or transition time from announcement of software-product change (e.g. discontinuation of cloud services) to the actual event.

(1) Cause: Shown in Table 1, the root cause dependency tree from [6] is extended towards cloud services, allocated into category “logistical”.

(2) Action: Root causes lead to obsolescence inducing actions by manufacturer, including built-in device chips, over the air (OTA) updates, cloud and support discontinuation. Furthermore official manufacturer statements to justify the actions are categorised by safety, security, quality, performance (system speed, functionality) and resources (financial).

Table 1: Root causes dependency tree, adapted from [6]

Technological	Legal	License
		Copyright
	Support	Technical
		Updates
		Expansion
Functional	Compatibility	System
		Peripherals
Logistical	Infrastructure	Build
		Test
		Integrate
	Distribution	Network
		Portable
		Cloud

(3) To cluster effects from the actions on software quality, characteristics from ISO 25010 (functionality, performance, security, maintainability, reliability, portability, compatibility, usability) are narrowed down to four characteristics that are critical for usage.

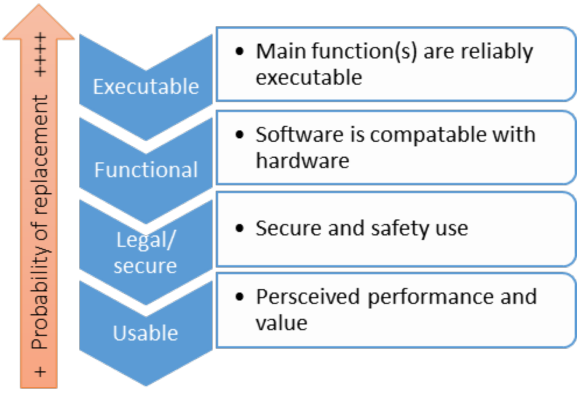

Figure 3: Critical software quality characteristics, ranked by probability of device replacement if effected

Figure 3 ranks the characteristics by criticality or severity from top to bottom, indicating the probability of replacement. For example if an SO event results in low performance (usability), probability of replacement is lower compared to a state of non-executable main function.

Finally the impact on user dissatisfaction is indicated by deriving a “frustration index” that is based on warning time (SPCN), costs per device age and severity of effects. Furthermore a qualitative analysis of customer sentiment in reviews on amazon.de has been included. The amount of SO related reviews are divided by all reviews to make the index comparable.

3 Results and discussion

Table 2 shows an overview of selected cases and categories recorded for product group mobile device, smart home and home entertainment. Results show some minor overlaps in causes, actions and effects, as well as price relation. Mostly 3 device models are affected within one SO event. Mobile devices show highest costs per year, followed distantly by home entertainment and smart home devices. At the same time, effects of rather expensive devices are less severe – main functions are not affected, though usability and functionality are restricted, while cheaper (smart home) devices are limited on important functions. Software-product change notifications are assumed to correlate with dissatisfaction and media attention (not visualised).

From a root cause perspective, functional updates either by 3rd parties or the manufacturer itself commonly rises hardware requirements and therefore lead to compatibility problems of old devices by a slowed down system. Manufacturers took actions from an OTA update to cloud or update discontinuation, always argued with decreased quality (performance). Further software inducing characteristics can be found case specific:

3.1 Case: Apple iPhone slow down

Apples functional update enabled the system or apps to use higher peak voltages that were possible for new batteries but caused unexpected system shutdowns by low battery state of charge, higher chemical age or colder temperatures [10]. It is assumed, this effect came unforeseen and was patched by the performance slowdown of affected devices [11]. Apple argued that lifespan of devices can be extended by increasing system stability while decreasing performance. Despite less severe effects (usability/performance) and battery management as a commonly applied method for performance reduction [12], apples short notice communication lead to legal obsolescence case in France [13].

3.2 Case: Belkin NetCam shutdown

The Belkin case was caused by the shutdown of a security video service platform (iSecurity cloud), were

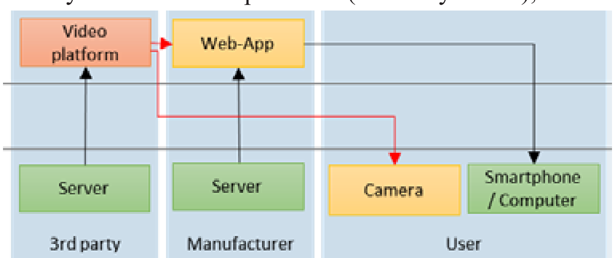

Figure 4: Belkin case system diagram indicating obsolescence inducing action and medium (red) and effected elements (yellow).

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end-consumer hardware (Wemo Netcam security cameras) rely on. It is assumed that this platform was run by a 3rd party, as the manufacturer statements are passively formulating ("the platform we use is shutting down") [14] and action (cloud shutdown) has taken place on short notice with 1 month warning time. Additional argumentation for this assumption is the necessity for user to have a paid-subscription for the service platform. A reason for the unclear statement could be that the outsourcing of security relevant software services to a 3rd party should not be promoted. Finally, the cameras are not executable and therefore obsolete as usage of third party software is not possible, leading to high probability for replacement. Customer are offered a refund under special conditions, assumingly to reduce dissatisfaction.

3.3 Case: Sonos smart speaker support end and Osram lightify

Sonos provided up to 16 years of functional update support (security updates are still provided) considering the date of first products releases. Though it was found that products are still sold until today by distributors without information on software update discontinuation at the point of sale (POS), leading to dissatisfaction of customers and users (expressed on amazon.de and Sonos community forum). As manufacturer options to communicate discontinuation product information are limited, it is assumed that Sonos tried to prevent the (re-)selling of affected devices by promoting a "trade up programme". This led to several effects: on the one hand attention was drawn to the discontinuation of updates to inform users, proper recycling options and a voucher for compensation were offered. Latter was offered if affected products were set to a software induced recycling mode by users, preventing any further use (not executable) and therefore reselling. On the other hand, users felt deceived as Sonos promoted "regular updates with new functions and services will keep your speakers up to date" and the programme is seen to stimulate product exchange [15]. Though discontinued products are still usable within a mixed use mode, left behind devices are not compatible with up to date ones. This contradicts another advertisement by Sonos "All Sonos speaker and components are connected with each other by WLAN" [16]. As all devices are connected by one system (one fits all), the high software integration comes with operating comfort but creates a system lock-in effect. Finally, some users demanded that Sonos communicates the expected software support at the POS.

Similar case study characteristics can be found in the-Osram lightify case [17]. While causes and actions overlap, major difference are the price and warning time, leading to overall less controversies and dissatisfaction. It has to mentioned, that the event of software obsolescence not yet occurred.

4 Conclusion and outlook

Thie established mixed-method analysis framework on causes, actions, effects and further measures allowed to structure factors that determine software obsolescence. The system diagram support the understanding of actor dependencies. Based on this, assumptions were made for the indication of socio-ecologic impacts and further influencing factors have been found:

- The probability of product replacement is indicated by costs per device age and the severity of effects on software quality, in particular main functions, using four parameter executable, functional, legal and usable that are ranked by criticality.
- User dissatisfaction is linked to warning time (SPCN), costs per device age and severity of effects. To reduce user dissatisfaction, advertised or main functions should be retained at a usable level. Warning time is critical to user dissatisfaction und used as a bases for legal actions.
- 3rd party dependencies trigger update and service discontinuation as well as short warning times.
- Severe dissatisfaction arises from user attached or bound to one system eg. by having several devices of one brand or are used to one system, of which only single devices become obsolete and a change of the entire system will be expensive (lock-in effect).
- Brand-specific vouchers offered as compensation could indicate manufacturers interest to make products obsolete and stimulate sells of own new products while refund compensations rather try to reduce customer dissatisfaction that might be triggered by 3rd party SO events.

The use of release date and list price are don't reflect the actual device age when the SO event occurs. Product are sold even beyond the SO event, on which customer complained about their recently bought device not knowing about the update stop. Conclusively products have to be taken out of the market or discontinuation warnings should be provided prior buying.

Balancing these factors can reduce probability of replacement and user dissatisfaction. Further factors to consider and analyse in ongoing research are options for open-source or third party product continuity and supply chain control. When obsolescence cases become prominent or with noticeable effects the media uptake and customer backlash can lead manufacturer to rethink and redirect strategies. Besides 3rd party dependencies, (obsolescence management) costs are important obsolescence drivers. Conclusively complex case structures need further validation and inclusion of missing factors.

Table 2: Overview on case study boundaries, causes, actions and effect. Severity and Frustration are derived estimations.

Case study boundaries							Cause			Action (manufacturer)			Effect (Software)		Second effects	
Product group	**Brand / Case name**	**Model**	**Release price**	**Age (y) at SO event**	**Costs/ year**	**SPCN (month)**	**0. Cause (root)**	**1. Cause**	**2. Cause**	**0. Argument**	**1. Action**	**2. Action (medium)**	**0. Effect (function)**	**1. Effect**	**Severity (Probability of replacement)**	**Frustration**
Mobile device	Apple iPhone slowdown	6	699	3	**233,0**	**none**	OS update (functional)	Compatibility	System (spontaneous shutdown)	Quality	Update (OTA)	Firmware (user)	Performance	**Usability restricted**	+	XXX
		6S	739	2	**369,5**											
		SE	489	2	**244,5**											
		7	759	1	**759,0**											
Smart Home	Osram Lightify shutdown	Home Gateway	30	7	**4,3**	**18**	Functional update	Compatibility	System (performance slow)	Quality; Functionality; Resources	Cloud stop	Cloud (manufacturer)	Compatibility; Home Automation connectivity	**Functionality restricted; Usability restricted (system lock-in)**	++	X
		LED Flex	65	7	**9,3**											
		LED Lamp	30	7	**4,3**											
Smart Home	Belkin NetCam shutdown	F7D7601	119	7	**17,0**	**2**	Logistical	Dependency	Supply chain	Cloud-Service shutdown	-	Cloud (3rd party)	Video	**Not executable**	++++	XX
		F7D7602	149	7	**21,3**											
		F7D7606	?	7	**?**											
Home entertainment	Sonos smart speaker support end	Play 5	579	16	**36,2**	**12**	Functional update	Compatibility	System (performance slow)	Quality Functionality	Support stop	Firmware (user)	Security; Compatibility; New functions	**Functionality restricted; Usability restricted (system lock-in)**	++	XX
		Connect	399	13	**30,7**											
		Connect:amp	579	13	**44,5**											

5 Acknowledgements

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Ecodesign of sustainable primary batteries for single use devices in a circular economy

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Abstract

Today, conventional primary batteries are manufactured at distant places with raw materials exhaustion and transported along thousands of kilometers to the point-of-use. After usage, only a small percentage of them are recycled, with high-energy consuming procedures, whereas the rest end up incinerated in landfills, generating toxic greenhouse gas emissions and leaving behind a significant carbon footprint. The upcoming wave of power hungry Internet-of-Things (IoT) sensing nodes will increase exponentially the primary battery demand in the near future thus aggravating the environmental impact associated to its production and the generation of waste electrical and electronic equipment (WEEE) after its operation lifetime. Here, the way primary batteries are designed and developed is re-shaped by implementing a circular economy strategy, i.e. raw material selection, manufacturing process, energy capacity, operational time and disposal are assessed to built-up batteries that minimize the environmental impact along their entire life cycle.

1 Introduction

Since the invention of batteries in the mid XIX century, this technology has evolved into tiny packages able to deliver high energy densities. Due to their suitability in many areas, batteries have become today ubiquitous power sources that feed portable devices as diverse as laptops, smartphones, medical devices, data loggers or toys. Further, their use is expected to increase due to the rise of the Internet-of-Things (IoT) scenario, which is enabled by multiple energy autonomous systems that are comprehensively capable of sensing, diagnosing, deciding and actuating in a communicative and collaborative way, leading to a digitalized new era.[1] Although IoT is still in the early stages of growth, current estimations point to more than 9 billion connected devices around the world. This number is expected to increase exponentially, with estimates ranging from 25 billion to 50 billion devices in 2025.[2] Energy autonomy of sensing nodes was identified as a key enabling feature that will have to be implemented in a sustainable manner. A significant financial and technological effort to obtain power sources able to harvest energy from the environment (light, heat and movement) that could provide IoT nodes with the sought-after autonomy has been invested during the last decade. Yet, state-of-the-art sensing devices make use of batteries, as they are the sole candidates to provide sufficient power output in a reliable manner. Although rechargeable - thus reusable - batteries seem to be the more sustainable solution, many applications rely on primary alternatives, e.g. where hygiene considerations prohibit a reuse (medical devices), where logistics requirements make a return of batteries very unlikely (RF temperature trackers), or where sensors are supposed to monitor environmental conditions at remote locations and systems will have to remain in these natural environments (environmental sensors in agriculture). Moreover, new applications in sectors like wearables and medical devices require batteries to be adapted to product sizes and form factors that make recycling even more challenging, since it is much harder to separate the battery from the device, thus aggravating the environmental impact associated to the generation of waste electrical and electronic equipment (WEEE). With an annual generation of 45 million metric tons,[3] WEEE is rapidly becoming the largest waste stream worldwide (Figure 1).[4], [5] According to a report from the World Economic Forum, the material value of our spent electronic devices globally amounts to $62.5 billion, three times more than the annual output of the world's silver mines.[6] Indeed, WEEE can be a source of highly valuable materials but still it will require energy and resources to manage, collect, process, re-purpose. WEEE should be properly managed but nowadays is sent away to places in the world where it can cause environmental and health problems.[7] The problem is even more critical when this waste is not even collected properly and ends up in landfills where in many cases is incinerated. One of the most hazardous components in e-waste are batteries, as they need special and dedicated recycling processes due their content of heavy metals and hazardous materials.[8]

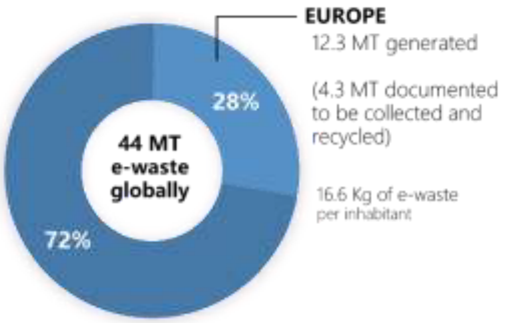

Figure 1: E-waste generation in Europe only in 2016, adapted from [3]**.**

Primary batteries have shown to be unsustainable and generate a significant environmental impact, especially during manufacturing and end of life (EoL) - if not treated correctly. In addition, ongoing strategies related to ecodesign, collection, repurposing and recycling of batteries for large-scale application cannot be directly applied to small-size battery formats – due to the diverse variety of uses, their ubiquity and that the success of the strategy depends primarily on the end-user responsibility/consciousness, availability of dedicated collection routes and governmental involvement. This is reflected in the percentage of primary batteries that are collected for recycling in Europe: in 2017, approximately 226,000 tons of portable batteries and accumulators were sold in the EU-28, while only about 100,000 tons of waste portable batteries and accumulators were collected for recycling, representing ca. 46%.[9] It is clear that although significant efforts are being undertaken at EU level to create a sustainable framework for secondary batteries that mostly focuses on the recovery of valuable elements but also includes the incorporation of sustainability into battery design[10], [11], the value chain and environmental impact of primary batteries within the burst of new IoT autonomous devices is being disregarded.[12] The European Commission (EC) has identified batteries as a strategic value chain where the EU must strengthen investment and innovation through an industrial policy strategy that builds an integrated, sustainable and competitive industrial base.[13][14] For primary batteries to become a key driver of the EU's industrial competitiveness and an example for sustainable development, it is crucial to not only increase investments in this area, but to also change the way the batteries value chain is approached, as well as the associated products in which primary batteries are the most convenient (sometimes unique) energy solution.

2 Improving primary battery life cycle

Our aim is to change the current paradigm of primary batteries from 'one-size-fits-all' to a new 'tailor-made' model where batteries are ecodesigned to follow the life cycle of the device to be powered in order to minimize their environmental impact along their value chain, particularly addressing key stages of the value chain such as raw materials selection, manufacturing, operation and end-of-life. In this way, for the first time sustainability is taken as main priority in primary battery development, above currently simplistic criteria based on performance and production costs.

A close look to their life cycle reveals that primary batteries follow an obsolete linear economy model; they are manufactured from scarce and non-renewable raw materials extracted from mines at locations that are very distant from the point of use. Then, they are transported thousands of kilometres and distributed worldwide creating large carbon footprints and (if properly collected) they are recycled with high-energy consuming processes. In contrast, we propose to develop batteries with different formats that cover a wide range of existing and future electronic devices, customized to provide the required autonomy for a specific application, and thus minimizing the amount of electroactive material compelled to squander by the use of standard-size batteries for a single use. All materials used as electrodes, electrolytes or structural components will be non-toxic and selected to meet specific end-of-life requirements and a safe and scalable manufacturability. This set of prerequisites will lead to choose materials without supply chain risk and move towards materials obtained from a sustainable bioeconomy[15] via biorefinery processes or recovered from recycling processes. Furthermore, energy and cost efficient manufacturing methods from Industry 4.0 will allow a decentralized local production and consumption model, in which batteries will not have to travel long distances to reach their destination but rather be constructed, distributed, consumed and repurposed locally, fostering local industrial growth and competitiveness.[16] Finally, to completely round up the innovative approach, batteries will be made in compliance with end-of-life scenarios up to now unconceivable, e.g. following the waste valorization route of the product they have powered, being capable to be composted/biodegraded or recycled with paper/cardboard without compromising the established recycling methods. This holistic battery development approach provides a systemic and sustainable pathway to redefine portable electrochemical energy power sources to meet technological needs of current society without compromising future generations.

3 Successful use cases

Some pioneering sustainable battery approaches have already found good fit at several application sectors.

3.1 Medical diagnostics

In the point-of-care diagnostics sector, portable electronic readers/instrumentation require a source of electrical power to perform advanced functions. This need has been fulfilled with either primary or secondary batteries. Regardless of their autonomy, batteries must be replaced or recharged periodically to maintain the device operation. This may seem a simple task in developed regions with reliable electric power grids and ubiquitous battery supplies. However, it can be quite challenging in low-resource settings, which is precisely where this kind of portable diagnostic devices are needed the most. Additionally, uncontrolled disposal of used batteries is becoming a severe problem in such regions of the world, as there is not only a lack of environmental regulations but also proper recycling facilities. Furthermore, today we find commercial products in the market based on single-use battery-powered electronic devices. For example, the Clearblue Digital pregnancy test providing unambiguous results and accuracy to the user or Abbott's Freestyle Libre glucose monitoring patch that provides continuous information to detect low/hi glucose peaks and reduce pain and nuisance of finger pricking. These applications demonstrate the indisputable need for digitalization but leave too much responsibility to the user for the correct disposal of the device and its parts, which in the majority of the cases are disposed of at general waste containers.

The startup company Fuelium presents a novel technological solution to the power requirements in portable diagnostics, following the specific life cycle of the devices in this field.[17] Fuelium paper-based batteries are eco-friendly and have a non-toxic electrode composition that avoids any specific recycling needs. These paper-based batteries are activated upon the addition of a liquid sample. In the case of analytical diagnostic devices this liquid can be the same sample to be analysed (e.g., urine, blood, saliva). The sample flows by capillarity action through the core paper membrane of the battery and activates the electrical power generation as it reaches the electrodes. For this reason, Fuelium batteries do not suffer from self-discharge because they do not contain any electrolyte until the liquid sample is added. Therefore, shelf-life is not affected by self-discharge as it happens with commercial batteries. Fuelium battery materials and fabrication processes are compatible with the standard lateral flow mass production manufacturing (*e.g.*, sheet-to-sheet and roll-to-roll) which not only reduces manufacturing and integration costs but also allows test and battery straightforward integration (Figure 2). Compared with standard primary batteries (*e.g.*, coin cell, AA and AAA batteries), Fuelium batteries can be customized to only generate the indispensable amount of energy (in terms of power and duration) required by the application.[18], [19] Standard basic units have a 1.5 V nominal voltage, and they can be stacked to provide multiples of that voltage. The battery size and design can be customized to provide different power and autonomies in the ranges of 10's to 100 mW from hours to weeks. In this way, batteries can follow the main value chain stages of lateral flow devices, from the materials used, fabrication methods, storage conditions, short-term operation until the disposal considerations. With their particular features, Fuelium batteries constitute a new paradigm in the energy supply for single use diagnostic devices.

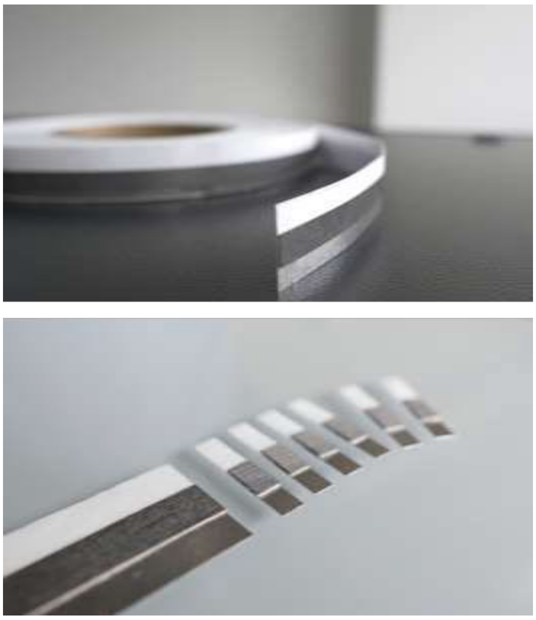

Figure 2: Fuelium paper-based batteries in roll and backing card formats.

3.2 Environmental monitoring

In recent years, some academic approaches have started to propose degradable and dissolvable batteries that could potentially ease the environmental impact after disposal.[20]–[33] The self-appointed 'biodegradability' of these approaches relies of their capability to be disintegrated in tiny parts or even dissolved in molecules. However, they all fail to prove biodegradation processes according to regulated standards (OECD Test 311,[34] ISO,[35] ASTM,[36] US EPA[37]), which entails conversion of organic matter into methane and carbon dioxide as a result of the biotic degradative processes of microorganisms present in natural environments. The PowerPAD, a metal-free organic redox chemistry-based device that we reported a few years ago, showed truly biotic degradation after standardized tests, cell stacking capability and competitive performance.[38], [39] The first published prototypes showed that batteries can be produced with all-organic materials, deliver enough power to substitute a Li-ion coin cell battery in a water monitoring device and then undergo a biotic degradation (based on standardized tests) at the end of their operational lifetime. More recently, architecture design improvements have led to extended operation time and optimal faradaic efficiency.[40] This battery biodegradability feature can be an optimal end-of-life for applications beyond environmental monitoring, such as precision agriculture,[41] or as a standalone electric power source at low resource settings lacking recycling infrastructure. This technology changes the unsustainable portable battery paradigm, from considering it a harmful waste to a source of materials that can improve the environment, enrich soil or remove toxins from water beyond the ordinary life cycle of a battery.

Figure 3: PowerPAD battery and its biodegradation in soil.

4 Conclusions

Here we anticipate solutions to address the upcoming problem of uncontrollable WEEE generation with a disruptive approach that radically changes the current primary battery paradigm, from a toxic waste to a reusable source of raw material that can even nurture soil or restore natural systems. In the proposed approach, all materials used as electrodes, electrolytes or structural components are non-toxic and selected to meet specific end-of-life requirements and a safe and scalable manufacturability. This criteria compel the selection of materials without supply chain risk, leaning towards materials obtained from a sustainable bioeconomy or recovered from recycling processes. Energy and cost efficient manufacturing methods from Industry 4.0 would allow a decentralized local production and consumption model, in which batteries would not have to travel long distances to reach their destination but rather be constructed, distributed, consumed and repurposed locally, fostering local industrial growth and competitiveness. Batteries can be customized to provide the required autonomy for a specific application, and thus minimizing the amount of electroactive material compelled to squander by the use of standard-size batteries for a single use. Finally, to completely round up the innovative approach, batteries will be made in compliance with end-of-life scenarios up to now unconceivable, e.g. following the waste valorization route of the product they have powered or being capable to be composted/biodegraded. This holistic battery development approach provides a systemic and sustainable pathway to redefine portable electrochemical energy power sources to meet technological needs of current society without compromising future generations.

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Potential life cycle energy, emissions, and material savings by lean packaging concepts

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Abstract

A wide variety of products - which need packaging - exist in large ICT companies. The large amount of packaging waste - such as carton, wood, plywood, plastics, and paper - is notorious. Therefore, packaging is an important part of an ICT company's cost & emission reduction strategy. At present, traditional packaging (TP) technologies consume considerable resources, and generate unnecessarily high amounts of pollution and waste. So called lean/smart packaging (LSP) concepts could help reduce such emission, resource and waste footprints. To promote the cost-effective LSP further in an ICT company, simplified life cycle assessment (LCA) is applied to four case studies comparing concepts for TP with LSP. The aim is to further explore the presumed environmental advantages of the LSP approaches. The volume and weight of LSP concepts are on average more than 75% lower than the TP concepts. According to the LCA, these mass reductions mostly result in significantly reduced energy use and eco-costs.

1 Introduction

Sales revenue growth has benefited from the fact that the logistics system has undergone rapid development. A wide variety of products - which need packaging - exist in large ICT companies. One of the main contributors to air pollution globally may be the packaging industry [1]. Hence, the interest in packaging sustainability is increasing [2],[3]. Paradoxically, per functional unit in ICT goods life cycle assessments (LCAs) the production of packaging materials themselves usually contribute insignificantly to the life cycle impact [4]. However, especially air transports distribution impacts may be impacted significantly by packaging design. Also the large amount of packaging waste - such as carton, wood, plywood, plastics, and paper - is notorious. Therefore, packaging is as an important part of an ICT company's energy-saving emission reduction strategy. At present, traditional packaging (TP) technologies consume pointlessly high amounts of resources, generate excessive pollution and waste. So called lean/smart packaging (LSP) concepts could help reduce such emission, resource and waste footprints. The LSP is based on six design principles: reduce, return, reuse, material recycle, recover (energy) and degrade. This is coherent with packaging eco-metric improvement within eco-design processes [5]. Packaging is also addressed by ICT good circularity scoring methods [6].

To promote the cost-effective LSP further in an ICT company for ICT network infrastructure goods, parametrized life cycle assessment (LCA) in SimaPro version 9.0.0.31 is applied to four case studies comparing concepts for TP with matching LSP concepts. The aim is to further validate the presumed environmental advantages of the LSP solutions. The intention is to improve the understanding the impact of packaging materials in ICT LCAs and in the ICT sector and inform policy for green development in industry. Ship transportation is default in the present analysis. End-of-life treatment is outside the studied product system merely consisting of material production and ship transport. Regarding assessment of total environmental burden, the recent trend is to use numerous weighting indicators instead of one or two mid-point indicators (e.g. acidification [7]). Hence, one primary energy indicator Cumulative Energy Demand (CED) and three "eco-cost" weighting methods - Environmental Priority Strategies (EPS), Life Cycle Impact Assessment Method based on Endpoint modelling (LIME) and International Life Cycle Data network (ILCD) - are included.

2 Packaging concepts

The driving forces for LSP are mainly to reduce TPs

- Excessive packaging
- Material costs
- Fuel cost in logistics
- Mass
- Volume
- Packaging waste in landfills
- Non-recyclable packaging materials
- Non-reusable packaging materials

Here follows four distinct use cases for TP and corresponding LSP: pallets, cover boards, gap fillers and complete packages. Each is evaluated with four indicators. The overall hypothesis is that LSP impacts are more than 50% lower than TP for all 16 comparable pairs.

2.1 Pallets

The development and application of plastic-steel pallets, instead of plywood pallets, is done to reduce weight and wood consumption. Plastic pallets [8] are known replacements to wood ones but the present plastic-steel pallets have not yet been evaluated. The functional unit (f.u.) is "one pallet transported 10000 km by ship."

2.1.1 Wood – TP

The wood in the TP case weighs around *A* kg. It is expected that around 40 MJ/kg is used to produce this kind of pallet [8].

2.1.2 Plastic/steel - LSP

The plastic-steel pallet weighs around 0.36×*A* kg with steel slightly dominating the total mass.

Results are shown in Section 3.1.

2.2 Cover boards

The development and application of cover boards is also done to reduce weight and wood consumption. Thinner paper boards can here replace wood ones. The f.u. is "one cover board transported 10000 km by ship."

2.2.1 Wood - TP

The wood in the TP case weighs around *B* kg per f.u. It is expected that around 40 MJ/kg of energy [9] is used to produce this kind of cover board.

2.2.2 Paper - LSP

The weight is reduced by 68% compared to the wood board, e.g. 0.32×*B* kg. Paper has a production energy intensity of ≈11 MJ/kg [10]. It is anyway assumed that that around 21 MJ/kg is used to produce this kind of cover board.

Thanks to the mass reduction, the logistics impact is hypothetically also reduced.

Results are shown in Section 3.2.

2.3 Gap filling protection

A package often have gaps between the product and the outer package material. The development of new gap filling methods is done to reduce the packaging volume and reduce waste. The f.u. is "packaging material for one EEE module transported 10000 km by ship." EEE module production - and EEE mass effect on ship transport - are excluded.

2.3.1 Foam – TP

The expanded foam in the TP use around *C* kg per f.u. It is expected that around 30 MJ/kg is used to produce this kind of foam.

2.3.2 Film - LSP

The mass of the plastic film in the LSP is 0.17×*C* kg per f.u. It is expected that around 20 MJ/kg is used to produce this kind of film. Comparing TP with LSP, the packing materials volume is reduced by 99% and the mass by 83%, respectively.

Results are shown in Section 3.3.

2.4 Complete packaging

The development of complete packaging is done to reduce weight and volume. Predominantly, more EEE goods can be stacked per pallet. However, this packing rate effect is not included. The f.u. is "one complete package for one EEE good transported 10000 km by ship."

2.4.1 Separate parts – TP

The TP solution consists of three different pieces and three different materials having a total mass of *D* kg.

2.4.2 All-in-one – LSP

The LSP solution consists of two different pieces and two different materials having a total mass of 0.19×*D* kg.

Results are shown in Section 3.4.

3 LCA results

As a reminder, the studied product system consists of raw material aquisition, packaging production and a standard transport to the use stage of the packaged ICT good. As such the LCA is limited and does not have a life cycle perspective.

3.1 Pallets

CED, EPS, LIME and ILCD results are shown in

Figure 1.

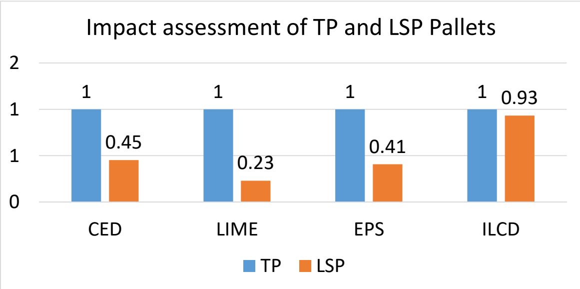

Figure 1: Pallet results – TP vs. LSP

Despite smaller mass used, CED results suggest that the plastic-steel solution is not equally less energy intensive as wood. No replanting or photosynthesis effects are included. Wood has under certain circumstances a high renewable biomass related primary energy.

LIME2 eco-cost results in Figure 2 reflect that wood resource extraction (cutting down the trees) affects land use negatively which in turn is a concern for primary productivity.

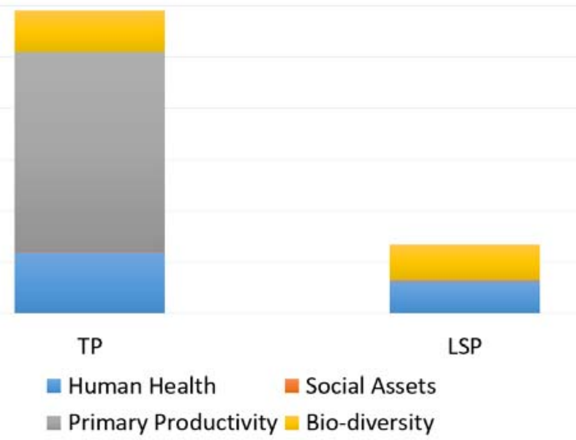

Figure 2: Pallet results – TP vs. LSP for LIME

For EPS2015, Figures 3a and 3b show that TP have issues with land occupation related to wood. This is less of a problem for LSP.

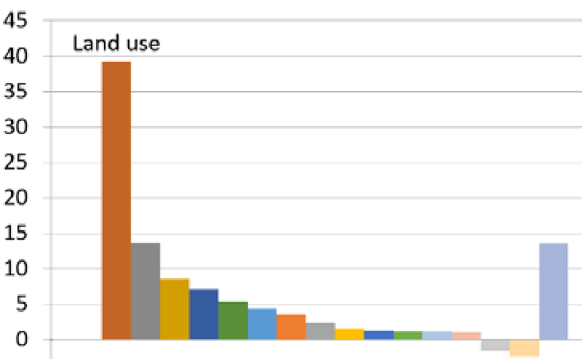

Figure 3a: Pallet results – TP contributors to EPS

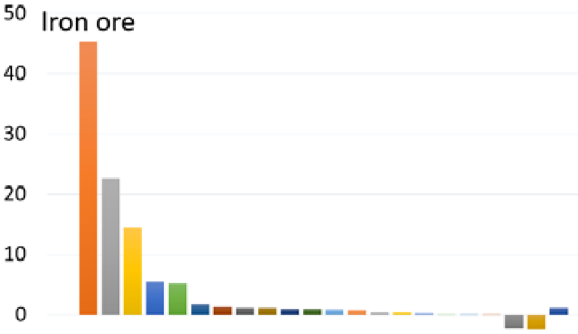

Figure 3b: Pallet results – LSP contributors to EPS

On the other hand, as shown in Figure 4, ILCD rewards wood used in TP via the photosynthesis and for its renewability. Still, it does not make TP better than LSP.

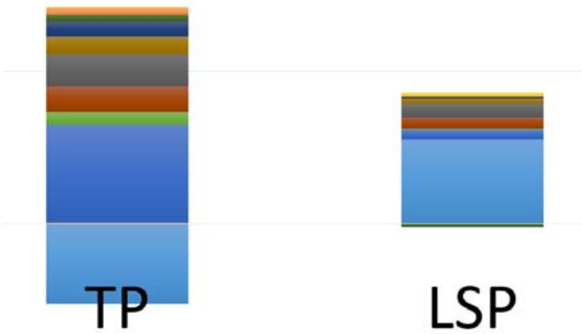

Figure 4: Pallet results – TP vs. LSP for ILCD

Anyway, LSP is less than one order of magnitude better than the TP for all four indicators. A larger difference is usually required between weighted scores in order to be more certain of the conclusions. A t-test [11] - LOG(1/0.93)/SQRT((0.044^2+0.037^2)) ≈ TINV(0.61,150) – on the values in Figure 1 shows that there is a ≈61% probability that the ILCD scores for TP and LSP could be the same. Corresponding values for LIME, CED and EPS are 0%, 3% and 0%, respectively. Superficially, the differences seem enough.

Transport savings contribute to 1-4% of the total savings (Table 1).

Table 1. Origin of total savings for pallets

	Material savings	Transport saving
CED	99%	1%
EPS	97%	3%
LIME	96%	4%
ILCD	Not reasonable	Not reasonable

For ILCD the results are more difficult to interpret as the method include photosynthesis. Wood evaluations are more complex than first assumed.

3.2 Cover boards

CED, EPS2015, LIME2 and ILCD results are shown in Figure 5.

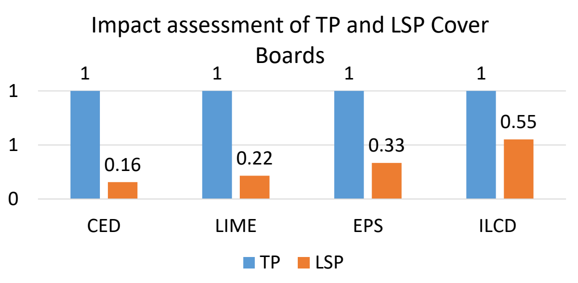

Figure 5: Cover boards – TP vs. LSP

For CED and LIME the environmental impacts are reduced more than the relative mass.

As shown in Table 2, transport savings contribute to 1-43% of the total savings%.

Table 2. Origin of total savings for cover boards

	Material savings	Transport saving
CED	99%	1%
EPS	98%	2%
LIME	96%	4%
ILCD	57%	43%

The explanation for ILCD transport savings being higher for ILCD is to be found in the photosynthesis effect for wood. For CED, EPS and LIME the relative material savings are 66-84% but for ILCD only 36%. Simply put, the relative transport savings going from TP to LSP are equal to the mass reduction, 68%.

3.3 Gap filling protection

CED, EPS, LIME and ILCD results are shown in Figure 6.

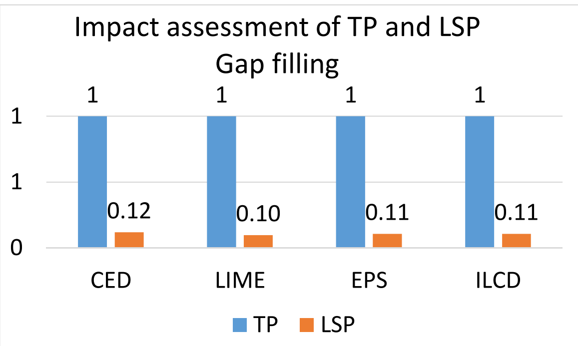

Figure 6: Gap filling protection results – TP vs. LSP

All environmental indicators show considerable saving potentials. This is not surprising as the mass is reduced by 83%.

As shown in Table 3, transport savings contribute to 1-6% of the total savings.

Table 3. Origin of total savings for gap filling

	Material savings	Transport saving
CED	99%	1%
EPS	99%	1%
LIME	94%	6%
ILCD	95%	5%

3.4 Complete packaging

CED, EPS, LIME and ILCD results are shown in Figure 7.

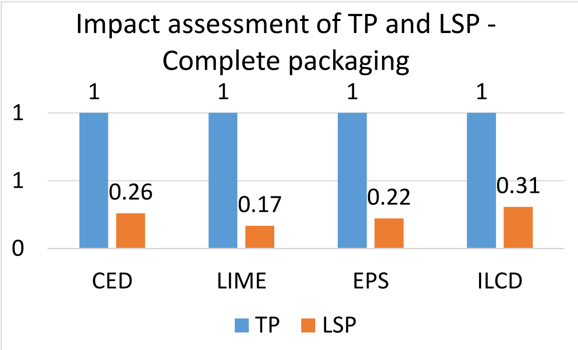

Figure 7: Complete packaging results – TP vs. LSP

All environmental indicators show considerable saving potentials. This is not surprising as the mass – and thereby transport impacts - is reduced by 81%. However, only the relative LIME score is reduced more than the relative mass.

As shown in Table 4, transport savings contribute to 2-11% of the total savings.

Table 4. Origin of total savings for gap filling

	Material savings	Transport saving
CED	99%	1%
EPS	98%	2%
LIME	94%	6%
ILCD	89%	11%

4 Discussion

Environmental and technical performance decision-making is not always one and the same. Especially if the analysis is not done holistically. As suggested by Figure 1, the hypothesis that heavier wood pallets are worse than lighter plastic-steel pallets (TP>LSP) is not clearly falsified on the basis of the ILCD results. Most other comparable pairs show TP>LSP.

Wood is sustainable as long as there are no large removals of wood during forest harvesting [9].
The LCI data used in the Pallet and Cover board cases include photosynthesis – for which a straight-forward and simplified mathematical model from [12] and [13] is shown in Equation (1) - and the LSP is still better.

$$F_c = f(LAI) \times f(PAR) \times Min\{f(VPD), f(REW)\} \times f(T) \times f(T_{min}) \times f(S) \times f(CO_2) \quad (1)$$

Where
F_c=carbon (in glucose) flux created by photosynthesis (mol $m^{-2}s^{-1}$)
LAI=Leaf Area Index, amount of leaves in the crown of the tree (leaf m^2/ground m^2)
PAR=Photosynthetically Active Radiation, light intensity of carbon fixing (mol $m^{-2}s^{-1}$)
VPD=Vapour Pressure Deficit (number)
REW=Relative Extractable Water (0 to 1)
T=Air temperature
T_{min}= Minimum air temperature
S=Stage of acclimation, seasonality of the photosynthesis activity (0 to 1)
CO_2=carbon dioxide available to the plant (e.g. tree) (share)

Is wood good or bad as packaging material ingredient? If the tree is cut down - to make e.g. plywood - that tree cannot really be part of the photosynthesis unless corresponding more trees have been grown to compensate. The overall environmental effects of trees are multifaceted involving e.g. biodiversity and land use issues.
Claims about wood and paper, which focus on one emission, should not be accepted lightly.

In environmental system analysis it is recommended to check carefully the harmonization of all models used [14]. In this limited LCA, the amount of materials used and the modelling of forestry, wood and related products bring more uncertainty than standard LCI databases. Literature checks confirm that standard LCI databases/literature are valid enough to draw conclusions. When analysing the potential environmental impact of wood related packaging materials, it is important to be aware of which eco-cost methods – and LCI data - include photosynthesis and biodiversity degradation, and which do not.

Transport savings are often presumed as a big advantage for LSP. Actually, as shown in Tables 1-4, the present study did not confirm this suspicion as only ship transport is included. Air transportation - having 1-2 orders of magnitude higher environmental footprint than ship transport per ton×km – would probably highlight transport savings more for the distribution stage.

5 Conclusions

Lean smart packaging (LSP) has significant eco-cost saving potentials for ICT network infrastructure goods and beyond. LSP is >50% lower than TP for 14 of 16 comparable pairs.

6 Next steps

The effect on the eco-cost of using waste paper and biodegradable materials may be included. Other important parameters - for further variability assessment to be incorporated in a complete packaging LCA – are:

- several modes of transport
- quantity of specific wood type saved and relation to photosynthesis
- recycling efficiency including collection rate
- reuse rate and lifetime where applicable
- marginal effects of packing rate in distribution
- waste handling option

If operational, a total integration and optimization [15] should be attempted, setting the packaging solution into the grand scheme of things.

7 Acknowledgements

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8 Literature

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B

CIRCULAR MATERIALS AND RECYCLING SYSTEMS

B.1
MATERIAL RECYCLING, SORTING AND SEPARATION

Liquids in capacitors from WEEE

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Abstract

PCB-containing capacitors are becoming a smaller and smaller proportion of the collected capacitors from waste electrical and electronic equipment. The focus of our study was to determine what liquids may be found in PCB-free capacitors and if these substances are of environmental concern. In a large sampling campaign, over 5000 capacitors were collected from Swiss recycling facilities. We determined the share of PCB-containing capacitors. In large household appliances, 0.5 per cent of the capacitors contained PCBs and 1.7 per cent of the capacitors were suspected of containing PCBs. A majority of capacitors from fluorescent luminaires still contains PCBs.
For PCB-free capacitors in waste electrical and electronic equipment, no systematic work existed to determine which liquid substances they contain. According to the specifications of the relevant standards and regulations, PCB-free capacitors must also be removed from electrical appliances if they contain “substances of concern”. We have developed a definition for the term “substances of concern” in our study. From the collected capacitors, thirteen mixed samples of liquids from PCB-free capacitors were prepared for chemical analysis.
To classify the substances as concerning or non-hazardous, we developed an evaluation scheme based on the H-statements of the GHS. Nine substances of concern were found in non-polarised cylindrical capacitors, six in electrolytic capacitors and four in microwave capacitors. All substances of concern have been assessed regarding their thermal stability and also to some extent regarding their ecotoxicity.
A revision of the WEEE directive’s removal requirement for capacitors is recommended. Best practices are proposed on how to treat both PCB-free and PCB-containing capacitors in waste electrical and electronic equipment (WEEE) today.

1 Classification of capacitors

Numerous different types of capacitors are possible in technical applications. They are divided into several different classes in the specialist literature on electronic components. The recycling industry parlance uses a much simpler classification model for capacitor types which we also use in this paper:

- Non-polarised cylindrical capacitors refer to all capacitors which have a more or less cylindrical shape and are not electrically polarised.
- Electrolytic capacitors are polarized and refer here to aluminium electrolytic capacitors. These are cylindrical and have a marked negative pole.
- Microwave capacitors refer to the non-polarised capacitors with aluminium housing used in microwaves. These microwave capacitors are systematically a subset of the non-polarised cylindrical capacitors.
- Small dry capacitors refer to polymer or metal film capacitor on non-cylindrical shape. They are typically found on printed circuit boards, most of the time of cuboid shape.

Figure 1: Non-polarised cylindrical capacitor from a collected large household appliance

Figure 2: Electrolytic capacitors collected from WEEE

Figure 3: Microwave with typical capacitor

2 Sampling and analysis campaign

Over 5 000 capacitors larger than 2.5 cm in at least one dimension were collected during an extensive collection campaign. For each appliance category they were classified according to their manufacturer, model number, production year, type of construction and PCB content according to the chemsuisse capacitor list [1]. For 21 capacitor models which could not be classified the PCB levels were determined by chemical analysis.

From the collected samples, eight mixed samples of PCB-free capacitors were prepared for laboratory analysis of the liquid substances. Capacitors from several appliance categories were combined for a mixed sample. For example, the capacitors from laptop power supply units and desktop computers were combined into one mixed sample.

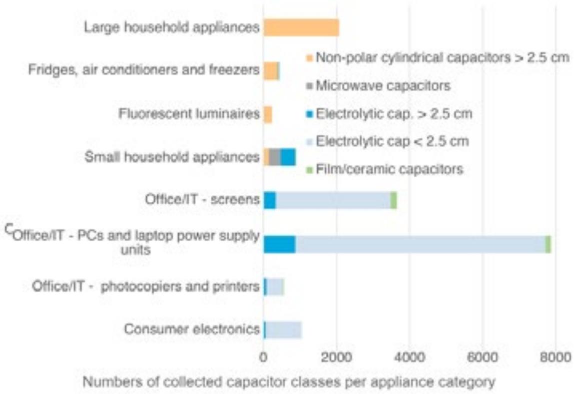

Figure 4: Numbers of collected capacitors per category of collected WEEE

The liquids from non-polarised cylindrical capacitors were removed and mixed together to form mixed laboratory samples. The same method was applied to microwave capacitors. Although electrolytic capacitors contain liquids, these are absorbed in the blotting paper of the capacitor and thus do not leak. The coils were therefore removed from the housings and used to form mixed samples. The contents of the mixed samples were chemically analysed in a laboratory via gas chromatography–mass spectrometry (GCMS), and in the case of electrolytic capacitors, via liquid chromatography–mass spectrometry (LCMS).

In addition to the aforementioned mixed samples, 5 samples of oil from single models of non-polarised cylindrical capacitors have been analysed with the same approach in the same laboratory. The goal of this exercise was to gain a better insight into the variety of liquid mixtures used in capacitors.

The 20 largest peaks from the chromatograms of the GCMS analyses were evaluated.

3 Definition of substances of concern

Electronic components consistently contain toxic substances, such as copper in cables, lead in solder joints or flame retardants in plastics. Since the definition of substances of concern is used in connection with the advance removal of capacitors, care should be taken to ensure that the definition of substances of concern in capacitors covers only those substances which require separate treatment during processing.

According to Annex VII of the WEEE Directive [2] and also the CENELEC standard EN 50625-1, “electrolytic capacitors containing *substances of concern* (height > 25 mm; diameter > 25 mm or proportionately similar volume)” must be removed from waste electrical and electronic equipment. A full-text search in European legislation on substances of concern results in hits within two regulations and four directives [3]. None of the mentioned regulations or directives define the term substance of concern. For use in practice, it is essential to define the term “substances of concern” for the recycling of WEEE. Such a definition is suggested here as follows.

All substances classified by the REACH Regulation [4] as substances of high concern and thus listed in Annex XIV are considered substances of concern in recycling. All substances listed in Annex III of the Rotterdam Convention [5] are considered substances of concern in recycling.

Substances that are banned or subject to severe restriction according to national laws are considered as substances of concern.

We determined the H-statements for all liquid substances in capacitors found during the literature research and laboratory analyses. The following criteria were used to classify the substances as substances of concern or not of concern using the H-statements:

- Substances with chronic effects on organisms even in small concentrations are classified as substances of concern. These include classifications as carcinogenic, mutagenic, fertility-impairing and with unspecific chronic effects.
- All substances that are toxic or very toxic to aquatic life are considered substances of concern.
- Substances with fatal effects are regarded as substances of concern. Substances which are classified as toxic or harmful to health according to the GHS are not regarded as substances of concern in recycling. Substances with the classification H304 are an exception. This is because these substances can reach the lungs when swallowed due

to their low viscosity and can thus cause pneumonia. This hazard is not relevant if the substances are highly diluted in mixtures. In addition, the oral route of exposure is not relevant in recycling.

- Substances which are potential allergens are not classified as substances of concern. These hazards are not uncommon for substances in WEEE and must be considered in the recycler's workplace health and safety practices.
- Physical hazards do not qualify a substance as a substance of concern.

If a substance is classified as concerning according to its H-statements, we must also check whether the substance is sufficiently stable in the environment to have a harmful effect. Rapidly biodegradable substances are eliminated in the environment so rapidly that the hazard they present to ecosystems is locally limited. This restriction does not apply to CMR substances which are carcinogenic, mutagenic or teratogenic. These substances can have a direct impact on humans via recycled material without first ending up in open systems.

H-statement	Hazard
H300	Fatal if swallowed
H310	Fatal in contact with skin
H330	Fatal if inhaled
H340	May cause genetic defects
H341	Suspected of causing genetic defects
H350	May cause cancer
H351	Suspected of causing cancer
H360D	May damage the unborn child
H360FD	May damage fertility May damage the unborn child
H360Df	May damage the unborn child Suspected of damaging fertility
H361	Suspected of damaging fertility or the unborn child
H361d	Suspected of damaging the unborn child
H370	Causes damage to organs
H372	Causes damage to organs through prolonged or repeated exposure
H400	Very toxic to aquatic life
H410	Very toxic to aquatic life with long-lasting effects
H411	Toxic to aquatic life with long-lasting effects

Table 1: List of H-statements which qualify a substance as a substance of concern

4 Share of capacitors containing PCB

Some WEEE categories may be equipped with capacitors that contain PCB, others do not. Categories that only contain electrolytic capacitors and small dry capacitors can be considered free from PCB. These are notably IT equipment and consumer electronics – as always, when dealing with waste, there will be the very rare exemption from this rule.

Categories that use large non-polarised cylindrical capacitors are large household appliances, refrigerators, microwave ovens, electric tools, and luminaires. We determined the share of PCB-containing capacitors from these categories. The results are shown in Figure 5.

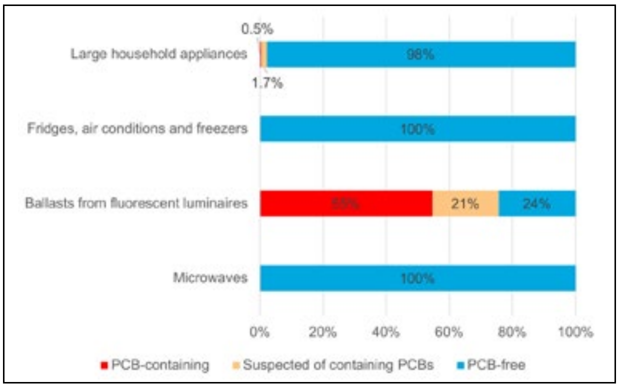

Figure 5: Share of PCB-containing capacitors within appliance categories in units

The orange columns show the proportions of capacitors suspected of containing PCBs. These are the capacitors which could not be classified as PCB-free or containing PCBs. These are capacitors which could contain PCBs due to their age but are not listed in the capacitor list [1] and their PCB content was not determined in a chemical analysis. The reported share of PCB-free capacitors should be seen as minimum values. In a best-case scenario – whereby all capacitors classified as being suspected of containing PCBs are actually PCB-free – the share of PCB-free capacitors would be 99.5 per cent for large household appliances and 45 per cent for fluorescent luminaires.

The share of PCB-containing capacitors in large household appliances and luminaires leads to an estimated annual PCB flow for Switzerland of 300-350 kg PCB/a. This flow compares to an estimated total emission of PCB to the atmosphere of about 400 kg/a [6] and a PCB flow in the river Rhine by Basel of about 30 kg/a. We conclude, that the PCB flow from WEEE is still well above the background flow and therefore still relevant.

5 Substances of concern in PCB-free capacitors

Substance lists of the known liquid substances of concern in capacitors can be created using the results of the chemical analyses and the literature research. The identified substances of concern are presented separately below by capacitor type. The tables contain all substances that were analysed in the GCMS laboratory analysis with a very good correspondence to the substance library. Substances from LCMS analysis are mentioned if their identity is confirmed or classified as likely. All substances mentioned in literature that we considered reliable are also listed. The tables indicate in the last column whether a substance was found in the GCMS or LCMS analysis of this study or if it is reliably mentioned in the literature.

In addition to the substances listed in Table 2, it has emerged from the laboratory analyses that boron-containing compounds are also found. The boron content in the samples was between 0.5 and 2.5 g/kg with regard to the coil mass. Furthermore, boric acid is described as a substance in aluminium e-caps multiple times within the literature.

The analysis results of the microwave capacitors show numerous biaryls, diarylalkanes or arylalkanes. Many of these substances are not present in Table 4, as they are described in little detail in the literature. A classification was not possible for these substances because no information on the toxicity of the substance could be found. For many of the observed substances in microwave capacitors, compounds with similar absorption spectra could also be present in the GCMS analysis. The consistency between the measured spectra and the spectra in the substance library is often only moderate.

Chemical designation	CAS No.	How was it found?
1-Methoxy-2-nitrobenzene or isomer	91-23-6	GCMS analysis
Boric acid	11113-50-1	Literature (and boron analysis)
Dimethylacetamide	127-19-5	LCMS analysis and literature
Dimethylformamide	68-12-2	LCMS analysis and literature
N-Methylpyrrolidone	872-50-4	Literature
Phenol	108-95-2	GCMS analysis

Table 2: Known substances of concern in electrolytic capacitors

Chemical designation	CAS No.	How was it found?
1-Chloronaphthalene (chlorinated naphthalenes)	90-13-1	Literature
1-Methylnaphthalene	90-12-0	GCMS analysis and literature
2-Methylnaphthalene	91-57-6	GCMS analysis and literature
Benzyltoluenes (p- and m-)	27776-01-8	GCMS analysis
Butylated hydroxyanisole	25013-16-5	Literature
Dibutyl phthalate	84-74-2	Literature
Diethylhexyl phthalate	117-81-7	GCMS analysis
Diisobutyl phthalate	84-69-5	Literature
Dinonyl phthalate	84-76-4	GCMS analysis
Naphthalene	91-20-3	Literature

Table 3: Known substances of concern in non-polarised cylindrical capacitors

Chemical designation	CAS No.	How was it found?
2,2',5,5'-Tetramethylbiphenyl or similar compound	3075-84-1	GCMS analysis
2,6-Diisopropylnaphthalene	24157-81-1	Literature
Benzyltoluenes (p-, m-, o-)	27776-01-8	GCMS analysis
Di-p-tolyl-methane or isomer	4957-14-6	GCMS analysis

Table 4: Known substances of concern in microwave capacitors

6 Mass fractions of substances of concern in capacitors

For the substances of concern determined through analysis, we know the approximate mass fractions in the analysed liquid from the laboratory analyses. To obtain the mass fraction of the substance of concern in the capacitor, we also need the liquid content of the capacitors. The mass share of liquids has been determined for all three capacitors categories by cutting the capacitors open, letting the liquid flow out and weighing solid and liquid contents after a shelf time of several weeks. This led to the numbers shown in Figure 6.

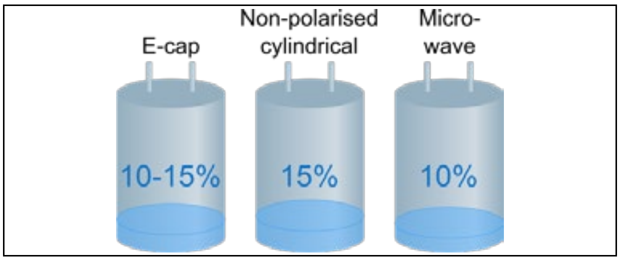

Figure 6: Liquid content of capacitors as determined by separating fluids from a small number of capacitors collected from WEEE

By multiplying the mass fraction found in the laboratory analysis with the liquid content of the respective capacitor category, the mass fractions in capacitors for some substances of concern could be estimated. The results are shown in Table 5 for non-polarised cylindrical, Table 6 for electrolyte and Table 7 for microwave capacitors.

Chemical designation	CAS No.	Estimated mass fraction [mg/kg]
1-Methylnaphthalene	90-12-0	750
2-Methylnaphthalene	91-57-6	1 200
Benzyltoluenes	27776-01-8	6 900

Table 5: Estimated mass fraction of substances of concern in non-polarised cylindrical capacitors

Chemical designation	CAS No.	Highest determined mass fraction [mg/kg]
1-Methoxy-2-nitrobenzene/2-nitroanisole	91-23-6	100
Phenol	108-95-2	50

Table 6: Estimated mass fraction of substances of concern in e-caps

The chemical-analytical determination of the main components was successful for the microwave capacitors. For the non-polarised cylindrical capacitors, all determined mass fractions lie below 2 per cent. The mass fractions of the determined substances in the liquid of the mixed samples are consistently below 1 per cent for aluminium e-caps. The analysis of single-model samples also did not reveal any main components of the liquids in non-polarised cylindrical capacitors.

Chemical designation	CAS No.	Highest determined mass fraction [mg/kg]
2,2',5,5'-Tetra-methylbiphenyl	3075-84-1	80 000
Benzyltoluenes	27776-01-8	4 600
Di-p-tolyl-methane	4957-14-6	500

Table 7: Estimated mass fraction of substances of concern in microwave capacitors

7 Substances of concern in recycling processes

The authors among other experts are currently looking into recycling processes to determine critical pathways for substances of concern in recycling processes. Some preliminary guidance can already be given. The main focus of our investigations lies on the spillage of liquids from damaged capacitors during mechanical treatment. These liquids will contaminate other fractions and reach final treatment processes as contaminations of the main materials.

An important question for this matter is the distribution of capacitors above the size limit for manual removal of 2.5 cm used today and below this limit. The data collected in our study allowed us to calculate the shares of capacitors bigger than 2.5 cm in at least one dimension and capacitors smaller than that. The results in Figure 7 show, that about half of the total capacitor mass is in capacitors smaller than the size limit.

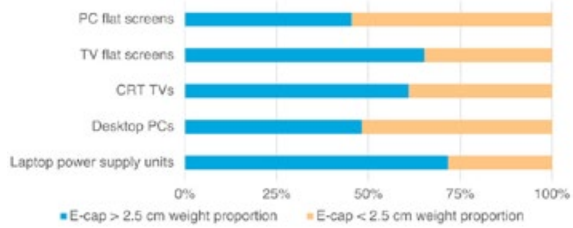

Figure 7: Shares of e-caps above and below size limit in IT equipment and consumer electronics

The substances of concern that we have found in our study are not readily biodegradable. However, they are not as stable or persistent in the environment as PCB are. We found by a literature survey and in dialog with experts for waste incineration processes [7], that all substances of concern could be safely destroyed in a municipal waste incineration, if they stick to combustible materials. We thus consider contaminations on fraction that are incinerated as not critical regarding the release of substances of concern to the environment. We also consider metal smelting processes as being safe. We conclude that the high temperatures arising in these processes also reliably destroy the substances of concern from capacitors.

Fractions that are processed in final treatments using cold processes and are then used as recycled material in new products constitute the most delicate pathway regarding the uncontrolled release of substances of concern from capacitor fluids. We are currently investigating different recycling processes and their mass flows to determine which damage rates of capacitors may be tolerated during mechanical treatment. Preliminary results show, that for IT equipment and small household appliances, a separation of electrolytical capacitors after mechanical treatment may be feasible.

8 Recommendations for environmentally sound processing of capacitors in WEEE

The removal requirement stipulated in the Directive 2012/19/EU of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE Directive) and the CENELEC standard EN 50625 should be revised to include all capacitors which contain liquids and are larger than 2.5 cm in at least one dimension. We recommend to reformulate the removal requirement as follows:

“Capacitors must be removed from waste electrical and electronic equipment if at least one of the following criteria is met:

- The capacitors contain liquid substances of concern.
- The capacitors contain polychlorinated biphenyls (PCB).”

The authors of the study didn’t reach a consensus, whether the size limit for capacitors containing liquids “(height > 25 mm; diameter > 25 mm or similar volume)” should be mentioned or not, for the reason that electrolytic capacitors smaller than the size limit contribute to half of the mass of electrolytic capacitors. The size limit doesn’t play an important role for the other categories with liquids, as they are always above the size limit.

PCB-containing capacitors, which are still found in large household appliances and especially fluorescent luminaires, must be removed prior to mechanical treatment. Capacitors in ballasts used in fluorescent luminaires contribute about 50 % to the total flow of PCB. Regarding the removal of PCB from WEE, it is important that capacitors from luminaires are properly removed and disposed of as PCB-containing capacitors.

Electrolytic capacitors may be separated after mechanical processing, if rates of total destruction are modest. They may contain substances of concern. But the concentrations found in our study have been very low. Also, electrolytic capacitors don’t lose their liquids easily. The removal should be carried out within a distinct stream that can be monitored as stipulated by the standard EN 50625.

Large capacitors in microwaves must be removed before mechanical treatment. They always contain liquids that flow out easily once a capacitor is damaged. This liquid may contain substances of concern in very high concentrations.

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10 Full reports

Please send an e-mail to the corresponding author to obtain the full report of the study.

Depollution and materials recovery from ICT products containing high-energy batteries

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Abstract

Increasing volumes of battery containing small ICT products such as smartphones, tablets as well as other products like small household appliances, toys or power packs are returned to the WEEE collection systems. The removal of these embedded high-energy batteries is quite challenging for the first treatment facilities due to the specific design of these items, in particular by sealed and rigid housings, glued batteries or pouch cells. The manual removal is quite time consuming and causes fire hazards when batteries are damaged or deformed.

Within the three-year project DISPLAY, an innovative process cascade was developed and up-scaled, delivering a solution for treating electronic display appliances, printed circuit boards as well as small battery-containing products. A technical solution for a material oriented disassembly was created by combining electrohydraulic fragmentation, spectroscopic sorting and the solvent based CreaSolv® Process. This cascade of innovative and developed processes will produce engineering plastics like PC-ABS and metal concentrates.

1 Challenges and aim

Half of the world's population is now online. In addition, users often own several information and communication technology (ICT) devices such as smartphones, tablets and laptops. The amount of obsolete devices is also determined by relatively short replacement cycles. As technologies change rapidly, many users change devices regularly and often before it is actually broken. This is also an indication of the growing amount of WEEE. Although data collected by Kantar World Panel indicate that smartphone users started delaying their cell phone upgrades between 2013 and 2015, the average lifecycle of smartphones in the U.S., China, and major EU countries is typically not more than 18 to 24 months [1].

Even if the above conditions can expect a high return on old devices, the return quantity of small battery-containing ITC products is relatively small in relation to the sales volume. ITC products are usually hoarded because there are concerns about the stored personal data and the space requirement is negligible. Smartphones and mobile phones contain a significant amount of precious metals which results in a high recovery potential. [2], [3], [4]

If the devices finally reach the first treatment facility, the disassembly is often extremely difficult due to the glued housing. In addition, the batteries are partially connected to the housing. Further, there is a high variation among the smartphone types which makes a dismantling by robots impossible. However, manual dismantling is time consuming and expensive and batteries can only be manually removed with great effort. There is also a risk of damage to the battery and thus ignition due to internal short circuits.

The aim of the DISPLAY project is therefore to upscale and to implement an innovative process cascade for the recovery of raw materials from electronic display devices such as smartphones and mobile phones as well as tablets. Increased benefit is achieved by avoiding manual processes and generating pure and high-quality plastic fractions. In addition, the electrohydraulic fragmentation enables extensive deletion of the data on the devices.

2 Overall process and key technologies

A processing cascade for smartphones was developed as part of the DISPLAY project. Smartphones from different producers were treated. As an example, the results from treating 31 kg of Sony Smartphones are described in this article. The overall process consists of three sub-processes: battery separation, material separation and recovery and plastic recycling (Fig. 1). The first sub-process enables the gentle opening of the smartphone housing - without damaging the batteries. For this, the shock wave technology electrohydraulic fragmentation (EHF) is used. The EHF treatment enables an automated crushing of smartphones without the risk of fire due to damaged batteries. After opening the housing, the smartphones are dried and the exposed batteries are removed manually. Unopened smartphones are treated again. All other smartphone components are completely crushed in the second subprocess with the help of an impact crusher and subjected to a sorting cascade using air and eddy current separators and colour sorting. In several passes, fractions with largely uniform material are generated from the material mixture. At the end of the second sub-process, the material is sorted into the following fractions: circuit boards, aluminum alloys and iron, glass displays and plastics. In the third sub-process, the CreaSolv® Process is used to produce new, high-quality plastics from the old smartphone plastics. The DISPLAY project focuses primarily on the production of recycled PC-ABS.

container wall for earthing. The temperature and the pressure inside the channel rise suddenly and compress the surrounding medium, which creates strong shock waves and hits the material to be fragmented. With this process, the material is loaded far more homogeneously than with comparable mechanical comminution processes, such as mills or crushers. Because of the homogeneous application of force to the material and the superimposition of pressure waves within the material, phase boundaries between materials with different acoustic properties are stressed (e.g. glass display and plastic frame). Material failure at the contact areas results in a selective separation.
The starting point for smartphone recycling was the pilot plant at the Fraunhofer IWKS. The system works in semi-automatic batch mode. A material-selective separation could be successfully proven here.

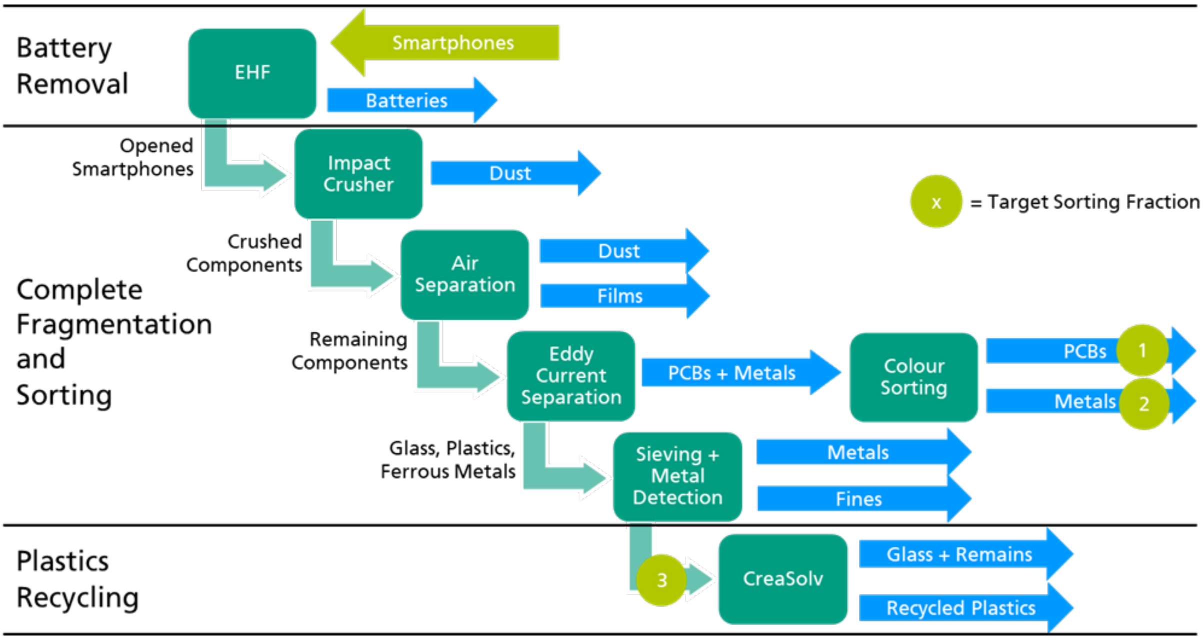

Figure 2: DISPLAY process chart - The overall process consists of three sub-processes: battery removal; complete fragmentation and sorting; plastics recycling.

All individual units already exist on the market at industrial scale, whereby specific systems like EHF, sensor based sorting and CreaSolv® components have so far been available on the market for other industrial-scale applications [5]. The developed process chain enables the handling of smartphones in mass flow and can therefore be scaled up accordingly.

2.1 Separation of the battery (Electrohydraulic Fragmentation, EHF)

Figure 2 shows the basic structure of an EHF system. First, capacitors are charged via the power grid. The electrodes are then connected to capacitors in an electrically conductive manner by means of a spark gap, so that the charges can suddenly flow off via a plasma channel through the carrier medium (water) and the

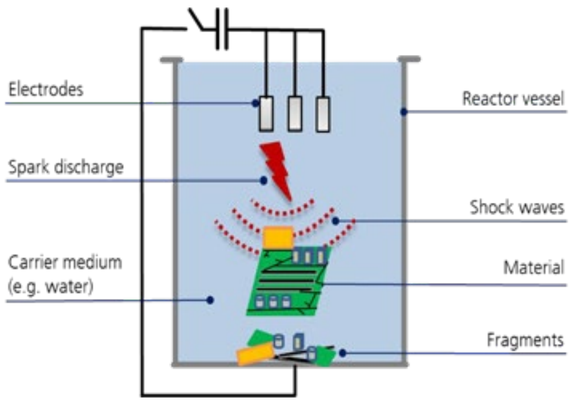

Figure 2: Principle of the Electrohydraulic Fragmentation

However, the targeted and gentle opening of the housing requires a targeted alignment of the shock waves on the smartphones. In cooperation with the company KLEIN Stosswellentechnik GmbH (manufacturer of

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industrial shock wave systems for cleaning cast components, primarily in the automotive industry), a device for the fragmented container of the EHF- was then designed. This ensures that the smartphone housing is opened successfully by optimally orienting the smartphone to the shock wave and at the same time allows automation of the EHF process (Figure 3).

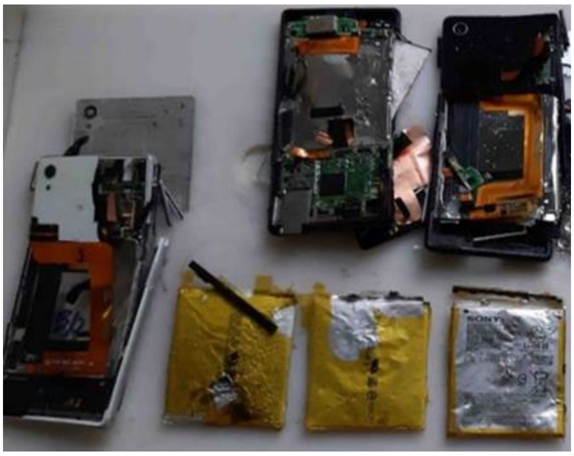

Figure 3: Sony smartphones after EHF treatment. The battery was separated without manual handling [6], [7].

2.2 Crushing, sorting and material recovery (Impact Crusher, Sensor based Sorting)

After removing the battery and drying the devices, the opened smartphones are treated with an impact crusher. With few strong hits by the hammers, the remaining connections between the different components are broken. The result is a mixture of mainly large component pieces, therefore minimizing the amount of electronic elements removed from the circuit boards. This is done to prevent valuable elements from being carried over to other fractions.

In an air separation process, dust and films are removed. The dust is mainly caused by the crushing step, while films are part of the liquid crystal displays and are separated from the glass likewise. Around 4.0 mass% (mainly display films) are separated during the air separation process step. The remaining components run through an eddy current separation, collecting circuit boards and light metals, such as aluminium and magnesium from the mix. To achieve a higher concentration of circuit boards in target fraction 1 (Figure 4, Figure 5), a sensor based colour sorting step is performed. By ejecting objects of low chromatic saturation, most of the mainly grey metals can be removed. (Figure 6, Figure 7) The golden hue of conducting tracks prevents the PCBs from being ejected.

Figure 4: Pass fraction of Sony smartphones after colour sorting

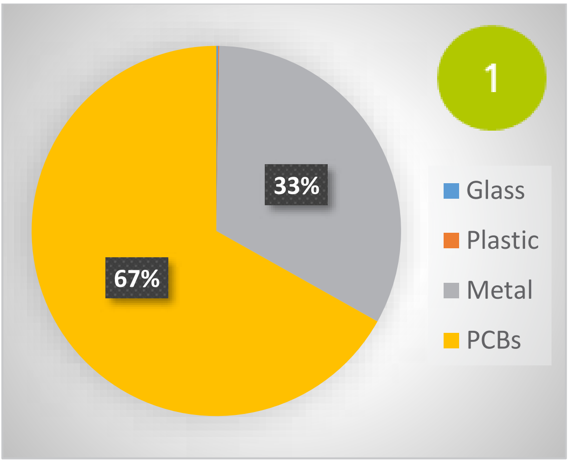

Figure 5: Pass fraction material share after colour sorting (number 1 corresponds to figure 1)

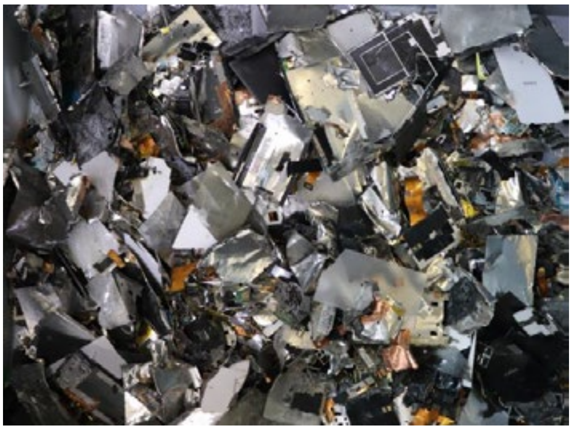

Figure 6: Eject fraction of Sony smartphones after colour sorting

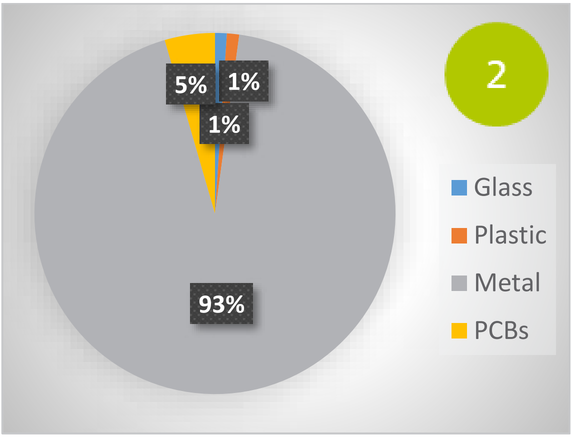

Figure 7: Eject fraction material share after colour sorting (number 2 corresponds to figure 1)

The remaining glass, plastics and mainly non-magnetic metal sheets leaving the eddy current separation are fed through a sieving and metal detection step. A flip-flow screen is used to provide the subsequent process with material in with a size above 5 mm required for the used sensor based sorting system.

Adjusting the system's sensitivity, the metal detection is adapted to detect larger metals parts, ignoring tiny screws in plastic casings. Thereby a fraction of high-alloyed ferrous metals is achieved. The glass and plastics are being concentrated in the pass fraction and would usually be considered as waste (Figure 8, Figure 9). From this stream, the CreaSolv® process is used to extract a high quality polymer.

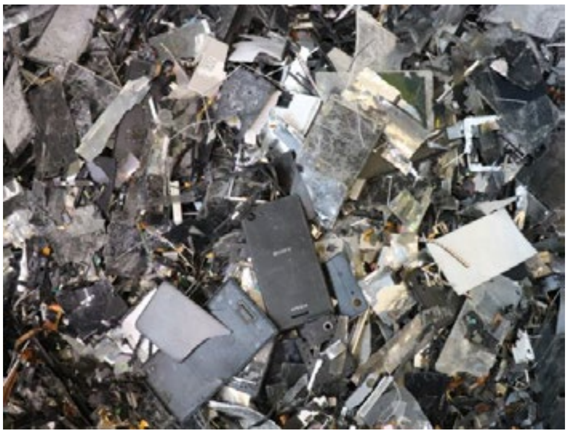

Figure 8: Pass fraction of Sony smartphones after metal detection sorting

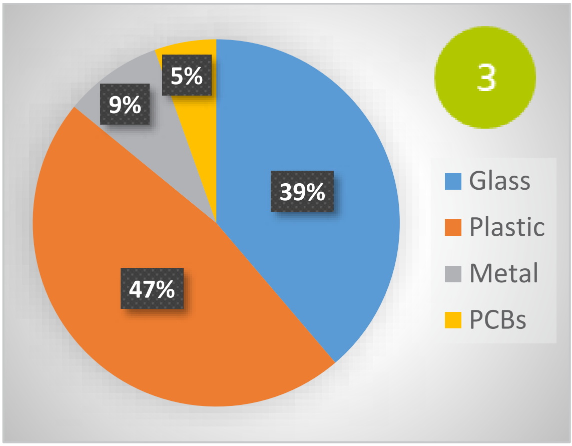

Figure 9: Pass fraction after metal detection sorting (number 3 corresponds to figure 1)

2.3 Plastics Recycling

The CreaSolv® Process developed by Fraunhofer IVV is a solvent-based recycling process, generating high-quality secondary plastics. It is based on the selective dissolution of a target polymer from a material mixture, in this case PC. The dissolved target polymer is separated from undissolved solid constituents by filtration, purified and finally converted to dried pellets of recycled polymers. Applied solvents are recovered and reused in the process, thus enabling an economic treatment. The properties of the PC recyclate produced in the DISPLAY project are shown in Table 1.

Parameter	Test conditions	Results
Melt flow rate	250°C / 5 kg	3.14 cm³/10 min
Tensile modulus	1 mm/min	1927 MPa
Tensile stress at yield	50 mm/min	44.16 MPa
Elongation at yield	50 mm/min	5.19 %
Elongation at break	50 mm/min	70.78 %
Charpy notched impact strength	23°C, notched	52.47 kJ/m²
Charpy impact strength	23°C, unnotched	Non break
Density	23°C	1.13 g/cm³
Vicat	50°C/h; 50 N	124.6 °C

Table 1: Properties of PC recyclate

3 Upscaling

According to an internal study on generated waste smartphones in France and Germany and an economic analysis of the overall process, the process was designed for a throughput of 500 tons of smartphones per year.

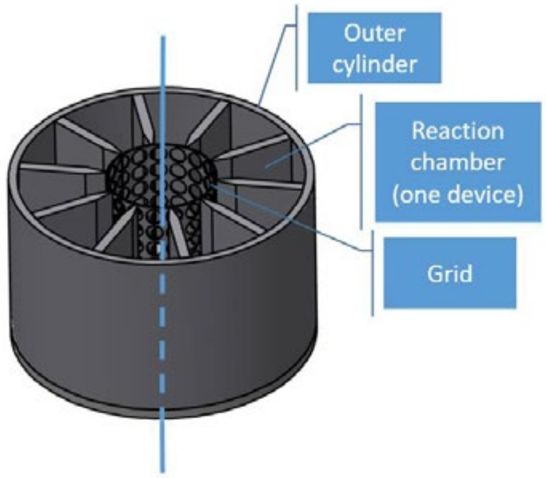

Figure 9: Optimized holding device for an automated EHF [6], [7]

A special holding device (Figure 9) was developed for this application. This holding device allows the simultaneous treatment of several smartphones, so that the energy input can be used efficiently, short cycle times are required and high throughputs can be achieved.
The concept of the recycling system for the automated opening of smartphones using EHZ technology is shown in Figure 10. The input material (smartphones with battery) is transported to the system by a conveyor belt. The holding device stands on a rotating table and is fitted with smartphones by one person. The table is then rotated so that a robot arm can place the loaded holding device in one of the two shock wave chambers filled with water. In the meantime, another holding device is loaded manually. The two shock wave chambers change position and the newly loaded shock wave chamber is closed so the smartphones can be treated with shock waves to expose the battery. After the treatment, the two shock wave chambers rotate and the robot arm takes the holding device together with the processed smartphones out of the shock wave chamber and places them on a second rotating table. The operator removes all exposed batteries in a few simple steps and puts them in a collection container. The smartphones without a battery are placed on a discharge conveyor belt by the robot arm. Smartphones with unexposed batteries are processed again.

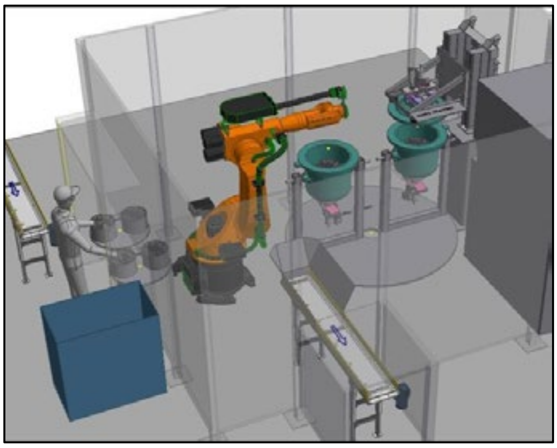

Figure 10: System concept for the mapping of the overall process [6], [7]

Even if the project focuses on smartphones and mobile phones, the DISPLAY process is easily adapted to a variety of small electrical and electronic appliances. The DISPLAY process provides answers to the demand of the WEEE recycling industry for an efficient and effective battery removal process.
A high level of occupational safety is guaranteed through the use of EHF, since there is no risk of damage to the battery due to manual dismantling. A treatment under water can also rule out a fire hazard if the battery is already damaged. At the same time, complete data deletion is achieved on the devices by destroying electronic components.

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[7] Image source: KLEIN Stoßwellentechnik GmbH

Initiating the human-robot collaboration during the WEEE management

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Abstract

The amount and variety of WEEE (waste electrical and electronic equipment) that is generated, in Europe and globally, has steeply increased during the last years. Adequate WEEE recycling enables both the recovery of valuable resources, creation of wealth and prevention of environmental issues. However, the recycling process for these complex products still significantly relays on manual work. In this context, the HR-Recycler Project (H2020 GA 820742) is developing a human-robot collaborative environment in which the replacement of tough, hazardous and time-consuming manual tasks by more automated and robot assisted procedures is studied to: i) reduce WEEE processing costs and increase quality of recovered fractions, ii) improve working conditions and job satisfaction of workers, iii) boost the competitiveness of the European robotic industry and iv) contribute to the European circular economy strategy. In this work is described the selection of the activities where human robot collaboration will be implemented based on: the current legal WEEE management practices, the demands of the professionals involved in WEEE recycling and, the choice of the most adequate waste types to test this novel alternative.

1 Introduction

Over the last decade, the continuous reduction in electronic devices manufacturing costs, together with an increase in their worldwide demand and the fast and continuous changes in the technologies, have resulted in shorter replacement cycles of these products [1]. This steep growth in the consumption pattern has led to a tremendous increase of both types and quantities of WEEE (waste electrical and electronic equipment) that are disposed every year [2]. WEEE contains scarce and valuable elements and hazardous components and materials that can have large economic, environmental and social impacts if they are not adequately handled.

Despite the huge efforts made by the WEEE recycling industry, processing this type of waste at large scale is an issue that still faces relevant limitations [2]. Essentially, the main stages that comprises the management of WEEE at plants are: (1) classification of devices by product category; (2) dismantling i) to depollute by removing hazardous components and substances, and ii) to reuse and recycle by separating reusable parts and added-value components; (3) sorting of pieces and materials in compatible fractions for the next processing and final recycling lines [3]. Until now, due to the features of WEEE, the recycling practices comprise extensive skilled and physically demanding manual work for their manipulation and processing, if compared to wastes that do not require depollution and that can be directly processed.

In this context, the H2020 Project HR-Recycler, "Hybrid Human-Robot Recycling Plant for Electrical and Electronic Equipment" (Dec'2018 - Nov'2022), was launched to develop human-robot collaborative environments that replace intensive, hazardous and time-consuming manual tasks of the WEEE recycling with correspondingly robot-aided and human-robot cooperative procedures, ultimately aiming to: (1) increase of process performance due to efficient collaboration of robots and human workers in the classification and dismantling steps, (2) improve working conditions in the factories as workers have less physical and mental stress, (3) introduce innovative processes based on robotic technology in the recycling industry, and (4) activate circular economy as the quantities and ratios of recovered materials are increased.

To achieve these objectives, innovative tools are being developed focused on five main features: (1) 3D object detection and manipulation, (2) human-robot social interaction, (3) robot motion planning, (4) human-robot communication, and (5) real time factory floor orchestration. Initially, system requirements, based on the functional specifications of the "end users" (i.e. industrial partners engaged in WEEE recycling), have been defined in detail. Next, real-world "use cases" (i.e. actual WEEE processing) have been identified and manual actions required to become collaborative described to guide the design and development of the system and eventually demonstrate its performance.

2 WEEE management

2.1 Legal framework

The original WEEE Directive provided a legal framework to structure the WEEE management, promote the recycling and avoid uncontrolled landfilling [4]. Later, the recast of the WEEE Directive [3] in 2012 encouraged the reuse, recycling and other forms of recovery to reduce the quantity of waste for disposal and to improve the environmental performance of WEEE recycling. Both texts emphasise the obligation of completing a selective removal of potentially hazardous substances, mixtures or components from the WEEE prior to its processing. They also group WEEE products into categories (now only six): C1 "temperature exchange equipment", C2 "screens and monitors", C3 "lamps", C4 "large equipment", C5 "small equipment" and C6 "small IT&T equipment", for which minimum recycling and recovery targets must be achieved.

2.2 Current recycling practices

The legislative requirements force recyclers to manage WEEE properly and guarantee the compliance of a set of basic principles: (1) the preservation, protection and improvement of the environment quality, (2) the protection of human health, and (3) the utilisation of natural resources prudently and rationally. Following these criteria, the recycling chain for WEEE consists of a sequence with three main steps:

1. Selective collection and safe transport to the treatment facilities
2. Classification, pre-processing and dismantling (including handling, depollution and sorting)
3. End-processing (including material separation or concentration and final waste disposal)

State of the art WEEE recycling processes at industrial scale offer limited automated solutions [5]. They still require expensive, extensive and time-consuming manual efforts for the classification, dismantling and pre-processing of the input materials.

WEEE products received at the recycling plants are categorized, usually by manual operation, due to their diversity. This step can be partially automated by using conveyor belts to feed the process and pneumatic manipulators for moving some specific items. The cost analysis of the operations, showed that the required effort for classification is 2.0-5.0 person-hour/t (200-500 kg/person-hour), being 12-37 % of the total recycling cost, depending on the device category and type [6].

The pre-processing tasks are mainly carried out by hand since the complexity of WEEE makes many of their components not readily accessible and, sometimes, their nature makes necessary handling them with care because they are fragile and can be easily damaged or broken. Additionally, the removal of hazardous components or substances for further selective treatment requires manual dismantling. Nevertheless, there are some semi-automated systems in the market, focused on specific devices, as displays and monitors, to help in the removal or depollution of components. Again, the cost analysis of the operations revealed that the needed effort for manual dismantling is 2.5-12.5 person-hour/t (80-400 kg/person-hour), being 48-68 % of the total recycling cost, by far the largest when compared to the costs associated to classification, human inefficiencies, power consumption or consumables usage [6].

Besides personnel costs, the manual activities associated to classification, pre-processing and dismantling of WEEE imply issues which demand a deep assessment to improve productivity and working conditions.

- Economic and productivity requirements: manual classification is applied since there are not automated systems able to sort the huge variety of electronic devices present in WEEE streams
- Safety and ergonomic requirements: manual classification and dismantling demand actions based on repetitive movements and gestures, handling and lifting of weights, forced postures and exposure to possible projections of scraps that could produce injuries

3 Opportunities of human-robot collaborative work

3.1 Demand of collaborative work

One important point to implement the human-robot collaboration is to determine which is its true demand. Besides the onsite collection of requests and ideas that the WEEE recycling companies do on steady basis, the focus group methodology was selected as dedicated tool. Its function was to bring people together to participate in the discussions for the validation and definition of the functionalities to be implemented in the human-robot collaborative environments.

A focus group is just a team of people, including participants that represent the overall population involved, in this case in the WEEE recycling activity, that meet ready for discussion. They are driven by a moderator that follows an agenda including explanation of basic purpose, open discussion using guided questions related to the solutions (robot types as automated vehicles or articulated arms) and their use (classification, transport or dismantling) and invite to fill a questionnaire.

The recording and subsequent analysis of the discussions contributes to the objective of the focus group that is gather good quality information to support decision making and integrate improved outcomes.

3.2 Roles and motivations

Two relevant roles involved in the WEEE recycling scheme, operators (workers) and supervisors (plant managers), were identified to select relevant human-robot collaborative actions based on their motivation and potential benefits.

The main motivations and goals of each role and the expected benefit from the human-robot collaborative solutions are summarised in Table 1 and Table 2.

Operator motivation	Benefit from solution
Reduction of labour hardness and times a movement is repeated	Lessening of physical weariness
Reduction of number and complexity of activities and tools	Lessening of mental weariness
Enhancement of security and healthy conditions at workplace	More secure environment
Flexibility and applicability of the robot	More opportunities for human-robot collaboration

Table 1. Description of motivations and benefits of solution for the operators (workers)

Supervisor motivation	Benefit from solution
Increase in efficiency	More productivity and better classification and dismantling results
Enhancement of security and health conditions at workplace	Less absenteeism and better work organisation
Comfortable workspace	Attractive work for operators and retention of skilled people
Return of the investment	Robot profitability and contribution to lower treatment costs

Table 2. Description of motivations and benefits of solution for the supervisors (plant managers)

3.3 Focus group sessions

The participants were recruited between operators and plant managers. The recruitment procedure included nomination of key people given their role or profile in the company and random selection of participants and volunteers through open calls. The participants were organized in groups with around 8-10 people and session duration was 90 min. The characteristics of the focus group were defined as follows:

- Age: adults (20-40, 41-50, 51-65 years old)
- Sex: men and women in an equally number of respondents (as much as possible, considering that most of the employees are men in two plants and all them women in another one)
- Expertise: novel, initiated, junior and senior (< 2, 2-5, 6-10, >10 years in the company)

3.4 Results of focus group sessions

The meetings were conducted in a friendly environment and participants were invited to share different points of view and introduce either positive or negative comments. Participants were informed of the existence of equivalent exercises in other WEEE recycling companies in Europe (Greece, Portugal and Spain). Data were processed in line with the European and Member States data protection laws. To preserve anonymity and confidentiality names were removed from reports and collected data were available only to the HR-Recycler consortium members and to the European Commission. The key findings were that:

- In general, and unexpectedly, participants agree with the purpose of using robots in WEEE classification, disassembly and sorting
- There is a generalised concern regarding the productivity of the robot at the disassembly area and how it will be combined with much higher productivity coming from the humans
- About the human-robot interaction, participants prefer the use of gestures and tactile screens than the use of augmented reality
- The navigation of the robots in a plant where there is circulation of humans, forklifts and lorries is a point of big concern

4 Selecting candidate products to test human-robot collaboration

4.1 WEEE flows at recycling plants

Three WEEE recyclers, “end users” of the solutions, located in different EU Member States, in alphabetical order BIANATT in Greece (#1-GR), INDUMETAL in Spain (#2-ES) and INTERECYCLING in Portugal (#3-PT), have completed a comprehensive analysis of the material flows at their plants considering the following streams: (1) total inlet WEEE, (2) WEEE stream destined to selective treatment, (3) fully manually dismantled WEEE in the selective treatment. Table 3 shows the total incoming WEEE that is processed by each recycler annually and the fraction that is manually dismantled. At least 66 % and up to 75 % of the WEEE reaching the plants is processed using a selective treatment. Some of them deviate to semi-automated lines part of the WEEE but, even not considering that flow, the percentage of WEEE treated by means of fully manual operations remains high and over 40 %.

Recycler	Total WEEE (t/year)	Treatment share		
		Direct	Selective	
			Automated (semi)	Manual (fully)
#1-GR	15,000	25 %	--- %	75 %
#2-ES	19,320	34 %	12 %	54 %
#3-PT	8,000	30 %	28 %	42 %

Table 3: WEEE flows at recyclers facilities according to the occurrence of disassembly operations (direct treatment is only applied to depolluted WEEE)

4.2 Occurrence of products in WEEE that demand selective dismantling

A deeper study of the inlet stream arriving to the plants has identified a wide number of products belonging to the different WEEE categories. As not every plant deals with all products in every category (i.e. one plant does not accept C1 "temperature exchange equipment") or some categories are wide and generic (i.e. C5 "small equipment" includes all appliances with no external dimension > 50 cm) a preselection of the representative products has been done considering a combination of: (1) annual incoming amount of each product, (2) legal requirements regarding the removal of a set component or material in that product, and (3) specific features related to the manageability of each unit (weight, accessibility, etc.) and working demand (intensity, repeatability, etc.) of the dismantling actions.

In addition to this basic analysis, the selection of individual waste streams at WEEE recyclers, have prioritized four "use cases" by applying the "multiple criteria decision analysis". This technique was developed by C.H. Kepner and B.B. Tregoe in 1965 in the context of business decision making but, nowadays, is spread and commonly used in the fields of research, technology and industry [7]. This technique provides a good compromise between intuition and objective analysis by using a systematic framework that evaluates, by scoring and weighting some identified criteria. Table 4 shows the different criteria applied to select "user cases" based on the motivation and goals of stakeholders in WEEE recycling plants.

Criteria	Justification for the scoring (applied weight)
Economic benefit / human labour (€/h)	Higher ratio, higher value (25 %)
Amount treated (t/year)	Higher amount of material, higher value (20 %)
Challenge for the robotization	More challenge, higher value (15 %)
Weight of the device	Higher weight, higher value (13 %)
Productivity (unit/h)	Low productivity, low value (9 %)
Complexity of the step	Higher complexity, higher value (8 %)
Number of elements to be removed	Higher number of elements, higher value (5 %)
Ergonomic requirements during the process	More complicated or hazardous for the worker, higher value (5 %)

Table 4: Criteria to select WEEE "user cases" and their scoring and weighting

The weighting of each criteria is defined based on existing information and knowledge of the process, i.e. the WEEE management industry and its technology, and the scores are ranged from 1 to 5 for each product class. The prioritisation outcome is the sum of the values resulting from multiplying the weights and the scores assigned by the recycling partners to each waste stream. This final numerical result incorporates all the criteria and allows ordering every "use case" by its relevance at every "end user" site and producing the final choice.

Table 5 shows the amounts of the four more interesting products to study that are selectively treated by each WEEE recycler: emergency lamps (EL), microwave ovens (MW), PC towers (PC) and flat panel displays (FPD). Each one represents interesting recycling challenges associated to the occurrence at plants, complexity of the recycling process and the toxicity or value of the components to selectively be extracted.

Recycler	Selective treatment WEEE (t/year)				
	EL	MW	PC	FPD	Others
#1-GR	100	750	300	300	9,800
#2-ES	1,002	469	1,288	370	9,622
#3-PT	< 1	20	50	220	5,310

Table 5: Breakdown by type of products of the selectively treated WEEE at recyclers facilities

4.3 Studying the current recycling of the candidate products

The WEEE recyclers have analysed in detail the classification, dismantling and pre-processing operations applied to the candidate products. Since classification and pre-processing follow almost identical patterns, the study has been focused on a comparative dismantling exercise that has been completed in the three recycling lines using actual units of the products found at their WEEE streams.

4.3.1 Dismantling emergency lamps (ELs)

An emergency lamp (EL) is a battery-backed light source that is automatically activated when a power outage creates low-visibility conditions in a workplace. This device is affected by the WEEE Directive, according to which the tube fluorescent lamp, battery and printed circuit board, must be separately collected and treated. Additionally, an EL contains further parts, as plastic covers and housing, that are also recovered.

The dismantling of an EL consists of 8-9 steps, including its opening, by removing the plastic cover, and the extraction of the tube fluorescent lamp, the battery and the electronic components that are separated from the housing, see Figure 1. The components are adequately sorted, by placing them in containers of appropriate sizes, for the next recycling stages. As the tube fluorescent lamp is very fragile, a critical point is its gently removal and handling to avoid breakage and prevent both the exposure of workers to mercury compounds and the contamination of other materials.

Figure 1: Opening emergency lamps and extracted tube fluorescent lamps (courtesy of INDUMETAL)

4.3.2 Dismantling microwave ovens (MWs)

Due to its size (no external dimensions > 50 cm) a microwave oven (MW) is a "small equipment". This appliance consists of a cavity inside which microwaves are generated, reflected and used to heat food or beverages. The device is affected by the WEEE Directive, according to which the electrolyte capacitor and printed circuit board, must be separately collected and treated. Also, a MW contains other valuable parts and components made of metals and plastics, such as a high-voltage power source, a cavity magnetron, a stirring fan, a metal chamber and a plastic housing, that are separated.

The treatment method applied to a MW is a full manual dismantling. From the analysis performed by the WEEE recyclers 8-12 steps have been identified in the disassembling of MWs, depending on the number of components targeted by them. Basically, internal glass plate is taken away, external cable is cut off, screws are loosened to remove the metallic back cover, interior is inspected to locate components and capacitor is accessed and carefully removed to prevent the release of the hazardous substances, see Figure 2. Finally, further valuables parts (e.g. magnetron, fan motor) are located, extracted and adequately classified.

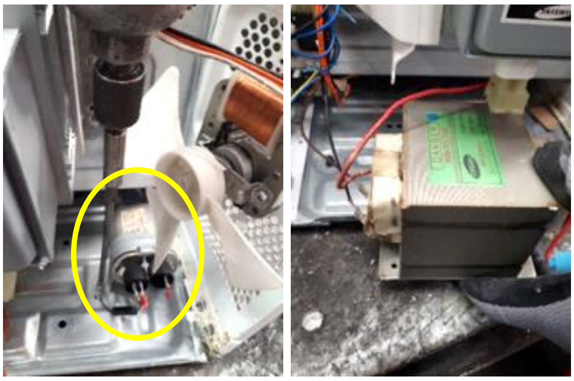

Figure 2: Accessing capacitor and extracting magnetron from a MW oven (courtesy of BIANATT)

4.3.3 Dismantling personal computer towers (PCs)

PC towers are very complex devices that typically consists of metal and plastic cases that hold a motherboard (with processor, graphics and sound cards, memories, battery, etc.), hard and optical disc drives, power supply, plugs, electric cables and wires and cooling fan.

In the dismantling of PC towers all the parts are separated manually in 7-16 steps, depending on the number of components targeted by the recyclers. Overall, PC towers are treated in order to selectively remove batterie, printed circuit boards > 10 cm^2, electric cables and plastics containing brominated flame retardants, and to recover valuable materials from the metallic and plastic parts.

Essential steps include pull out of external cable and plug, removal of screws, housing and front cover, extraction of power supply, removal of motherboard and electronic cards, and extraction of battery (see Figure 3) and valuable components (e.g. hard disk drives, optical disk drives). Some of the recyclers further dismantle motherboard by unscrewing and pulling apart processors, memories, connectors, etc.

Figure 3: Removing the power supply and motherboard from a PC tower without housings and extracting its battery (courtesy of INDUMETAL)

4.3.4 Dismantling flat panel displays (FPDs)

Flat panel displays (FPDs) are backlighted screens usually less than 10 cm thick. Although the newest FPDs use LEDs for backlighting, the units produced during the past decade usually implement mercury-containing cold cathode fluorescent light tubes (see Figure 4).

Figure 4: Opened FPD and extracted backlight lamps (courtesy of INTERECYCLING)

Treatments applied to FPDs by the WEEE recyclers comprises 10-15 steps, depending on whether they are fully dismantled by hand or by a combined manual and semi-automated mechanical treatment. In general, external cable is cut off, base is removed, back cover is pulled away manually loosing screws or cutting sides or semi-automatically by using a cutting machine. The frames are further dismantled to access the mercury-containing backlighting lamps that, due to safety concern, are always manually removed to avoid breakage. The displays, the printed circuit boards and the electrolytic capacitors are extracted. Finally, as for the other "use cases", additional components or materials as diffusers or plastic and metallic housings and screws are also recovered.

4.5 Analysing the dismantling

The highest priority components contained in the selected "use cases" are those listed in the Appendix VII of the WEEE Directive [3]: mercury-containing components as tube fluorescent lamps or backlight lamps, batteries, printed circuit boards > 10 cm^2, plastics containing brominated flame retardants, external liquid crystal displays > 100 cm^2, gas discharge lamps, electrolyte capacitors > 25 × 25 mm (> 12.3 cm^3) and cables.

Due to safety reasons, most critical steps during the dismantling are the extraction of lamps and capacitors, as they contain hazardous substances and are fragile. On the other hand, in order to recover value from the selected "use cases" the target components to extract are electronic boards, hard disk drives, power supplies, motors, cables, metallic or plastic housings and screws.

Considering the legislative framework, the current available technologies and the potential recycling and recovery alternatives, the components to be disassembled have been prioritized for the four "use-cases" as follows:

- Use case EL: Tube fluorescent lamp (fragile), Battery >> Printed circuit boards > Cover (plastic), Housing (plastic), Screws
- Use case MW oven: Electrolytic capacitor >> Printed circuit boards, Display > Cavity magnetron, Motor, Back housing and Fan (Metallic), Front housing (Plastic), Electric cables, Screws
- Use case PC Tower: Battery >> Printed circuit boards, Hard disk drives, Power supply unit > Cooling fan, Back housing (Metallic), Front housing (Plastic), Screws
- Use case FPD: Backlight lamps (fragile), Display, Electrolytic capacitor >> Printed circuit boards > Internal housing (Metallic), Back housing (Plastic), Diffusers, Screws

Additionally, the concerns associated with user needs regarding efficiency, quality and safety issues, have been identified for the different disassembling steps. The productivity study of the dismantling lines has given these results: ELs 180 kg/person-hour, MW ovens 400 kg/person-hour, PC towers 85 kg/person-hour, FPDs 75 kg/person-hour. As it can be seen, generally the manual dismantling of WEEE, with a lot of movements in short spaces, leads to low productivity rates. Then, an increase in the productivity by process automation is an essential demand. Moreover, some of the electronic components disassembled from printed circuit boards are the most expensive materials that are produced from the WEEE recycling. The reduction of sorting mistakes may also lead to savings by maintaining a constant and high quality for the sold products. Finally, attending safety concerns, it is desired to remove components containing hazardous substances avoiding worker contact and to assist heavy load lifting and handling to release physical stress.

5 Process definition and user requirements

5.1 Human-robot collaborative WEEE recycling process

In the envisioned HR-Recycler system, human workers and robots will share and undertake, in an open collaborative environment, tasks involved in the WEEE classification, dismantling and pre-processing steps, where most of the manual work is carried out.

In the initial classification of WEEE, robots designed to pick up WEEE and AGVs (Automated Guided Vehicles) able to carry containers on pallets will aid in selecting, categorizing and transferring devices from the storing area to the workbenches, where the recycling process starts. In this first step, the role of human workers will be to supervise robot operation to achieve a proper device classification and loading by the robotic arms and pick-and-place by the AGVs.

In the subsequent step, the containers transferred by the AGVs to the recycling area will be unloaded by robots that place the devices in the workbenches. There, the disassembly step will be initiated and robotic arms and human workers will collaborate in a joint and synchronized manner in dismantling the devices by releasing external screws to open the devices or cutting internal cables to extract hazardous and valuable components that may require particular treatment (as capacitors and copper coils from MW ovens, batteries or printed circuit boards from PC towers or lamps from ELs and FPDs).

This step will comprise the most challenging and innovative element of the overall system, as it requires extensive human-robot collaboration. Robust RGB-D visual analysis techniques will be development to detect and recognize the different WEEE objects types as well as their constituent parts. Advanced social capabilities will be incorporated to the robots to adapt their behaviour to individual human co-worker, ensuring user predictability and perceived safety. Interactive motion planning will be applied for humans and robots acting jointly in a common workspace as a single action pair. For human-robot communication, a new adaptive human-robot interface will be designed considering human cognition and behaviour factors in order to meet context and human restrictions.

In the last step of the process, AGVs with a robotic arm mounted on top will take part in the categorization and transfer of the different device components to the end of the recycling pipeline, where they will undergo further treatment. Involved AGVs will be able to pick the valuable/hazardous components in bins from the workbenches and adequately arrange them for dispatching.

5.2 User requirements in the collaborative WEEE recycling process

After a deep analysis of the recycling process including human-robot collaboration, up to 16 user requirements have been identified, from which 9 requirements were related to automation and robot integration and 7 to human-robot interaction.

All these requirements have been extracted based on the feedback collected during the focus group sessions and based on the responses to the questionnaires. The requirements have been prioritized considering the percentage of positive answer: with more than 75 % of positive feedback, the requirement is classified as MUST, between 65-74 %, the requirement is classified as SHOULD, and between 50-64 %, the requirement is classified as COULD.

The list of requirements related to automation and robot integration prioritized as MUST are:

- Use robots (AGVs) to transport devices from the WEEE classification area to the workbench, to move devices between the workbenches and to move sorted parts to the end-processing areas
- The AGVs in charge of transport have to be capable of avoiding obstacles in the plant, adapting to different distribution of workbenches and navigating safely close to workers by detecting their presence and keeping a security distance
- Use robots (lifting arms) to perform an initial classification of the WEEE devices and to load and unload the AGVs with devices in the classification and dismantling areas
- Use robots (collaborative arms) to automatically remove external cables, open devices or extract internal parts

The list of requirements related to human-robot interaction prioritized as MUST are:

- Provide workers with visual information of the current status of the robot (e.g. the action or movement that is performing) as well as its

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expected next steps (e.g. a list of planed actions or movements) to ensure safe operation and reinforce trust

- Robots detect the presence of workers and know their distance to avoid accidents and guarantee trust
- Capability of collaborative robots to adapt to the specific preferences and skills of individual workers to help them in the most suitable manner

6 Conclusions

During the initial stages of the HR-Recycler project a comprehensive analysis of the current WEEE management practices has been completed in order to introduce human-robot collaboration actions during recycling.

The processes in three running WEEE recycling plants -BIANATT in Greece, INDUMETAL in Spain, and INTERECYCLING in Portugal-, the "end users" of human robot collaboration, have been studied. Material flows and main operations performed at the facilities, as device classification, dismantling for selective removal of hazardous components and sorting of valuable parts, have been analysed. Special focus has been put in the tasks associated to those operations that demand manual activity regarding the performance (productivity and efficiency) and the skill, safety and ergonomic requirements demanded.

Two relevant stakeholders, operators (workers) and supervisors (plant managers) have been identified at WEEE recycling plants. In order to discuss, validate and define human-robot collaboration in practice several interviews have been conducted with them. The proposal of using robots has been well received by both workers and plant managers to perform actions in the classification, indoor transport, disassembly and sorting of WEEE components. Gestures and tactile screens have been selected by workers as the preferred options to communicate with robots. Main concern of plant managers is associated to the expected productivity of robots at the disassembly area compared with the human while main concerns of workers are associated to indoor navigation of robots where people, forklifts and trucks also move.

The specific features at every WEEE recycling plant, such as the managed amount (t/year), the share of treated products (%) among WEEE categories, type of devices and the way of running the plant (specific technical treatments and physical arrangements of working places) at every "end user" site have been assessed. After that study, each "end user" has combined that information with a "multiple criteria decision analysis" including 8 criteria associated with manual classification, dismantling and sorting operations that have been weighted and scored. This has resulted in the selection of four "use cases" (Emergency lamp, Microwave oven, PC tower and FPD) to develop and test human robot collaboration. A detailed study of the individual process steps has been completed in every "use case" in every plant, resulting in the selection of manual tasks to be transformed into human-robot collaboration.

After interviews with partners, recycling professionals and technology providers, up to 16 user requirements (9 related to automation and robot integration and 7 related to human-robot interaction), to be considered by the designers of the human-robot collaboration, have been identified and rated using design thinking methodology.

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Circular Economy in practice: The FENIX project. Additive Manufacturing Pilot Plant

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Abstract

The current global warming and resource depletion are alarming. It is imperative that the scientific community and, mostly, those who work in production processes take actions with responsibility. Material production is currently an important factor, not only for concerning resource depletion, but also energy consumption (45% of the final cost of aluminium production is energy). This makes circular economy, defined as a restorative economic system, one of the solutions to these problems. However, being able to fully manage and control the entire life and end-life of a product is still today a material and technological challenge especially for modern EEE (Electric and Electronic Equipment) which miniaturization has led to the complicated entanglement of different materials in the same product. This article exposes the development of means, both technological and in terms of business models, developed within H2020 Fenix project giving a special focus in the development of an additive manufacturing method in order to provide a second life to recovered Copper which represent a special challenge.

1 CIRCULAR ECONOMY in a nutshell

1.1 The Four Drivers of CE

A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times. [1]

This economic system is an alternative to the current unsustainable linear economy, with the aim of minimizing waste and turning goods in their end-life service into resources by recycling the materials, closing loops in the ecosystem. Based in reuse, repair, recycle and remanufacture the maximum goods.

Apart from individual actions, innovation and research are key role to transform the end-life goods materials into a new product with a significant added value.

The change from a linear economy system towards a circular one will be for four drivers: [2]

1.Economical: Due to a growth of production activity and savings in the net cost of used materials mainly. The Ellen MacArthur Foundation, SUN, and McKinsey have identified that by adopting circular economy principles, Europe can take advantage of the impending technology revolution to create a net benefit of €1.8 trillion by 2030, or €0.9 trillion more than in the current linear development path [1].

2.Environmental: A reduction in emissions and also in the use of primary materials will be a must to create a sustainable ecosystem and to reduce waste. Consequently, it will increase the productivity of the lands and create a friendly environment.

3.Business: The demand for new business services will be increased due to new technologies that will be developed to facilitate the resource optimization and will make remanufacturing, recycling and recovery processes much more sustainable.

4.Individual: Connected to social and environmental awareness, as customers, they will prefer environmental friendly products. Transition to “pay-per-one” to “pay-per-use”.

1.2 Circular Business models

To get a circular economy business model the most relevant aspect is to change the way a company manages its resources, how makes and uses the products and last but not least, what does with waste and materials.

It is necessary to transform the take-make-waste of a linear system into a circular one with a close loop. For this transformation, it is important to analyse and take action in the flow circularity. According to Fenix project four principles support the circulatory system. The first one consists in reducing the use and minimizing the resource requirements. The second consists in recycle materials, reuse and energy recovery. Here will start the circularity of the system in the business model and will directly affect to the first principle helping to need less. The third one is to generate circularities due to the opportunity of the outcome product to be recycled and reused and the waste to be recovered. The last one is the use of renewable energy and sustainable and environmentally friendly processes. There are 5 business models [3] according to the mentioned principles:

1. Circular supply model: Using renewable resources like energy or materials.
2. Resource recovery model: Obtaining energy or resources from waste.
3. Product life extension model: Making long-life cycle products by repairing and reselling them.
4. Platform sharing model: Encouraging collaboration between users to share resources.
5. Product as a service model: Customers rent the product, use it and return it for another customer.

1.3 Real implementation of a business model based in circular economy

Fenix project is based in an aforementioned resource recovery model and has developed an efficient process in different pilot plants to make final output products from electronic waste with a sustainable process and a key technology explained below called DIW (Direct Ink Writing) 3D printing.

Electronic waste refers to discarded electrical and electronic equipment that is at the end of its economic life and no longer used by consumers. It is commonly shortened as e-waste, and referred to as WEEE (Waste Electric and Electronic Equipment). [4]

Due to the small size of their components, modern electronic equipment like smartphones are extremely difficult to recycle. Separating the different element requires to chemically separate each atom.

In circular economy, there are some CMB (Circular Business Models) based in three perspectives of sustainability (economic, environmental and social ones). Fenix project partners has done a study to define the suitable ones for the project. The result was to focus on three CBMs: 1) result-oriented e.g selling capacities or services like disassembly, additive manufacturing and 3D scanning services, 2) use-oriented e.g selling the access to the pilot plant and 3) product-oriented e.g selling the pilot plant or a final product like metal powders, 3D printing products. The majority of them can be focused on the pilot plant (process-oriented) or the final outputs (product-oriented).

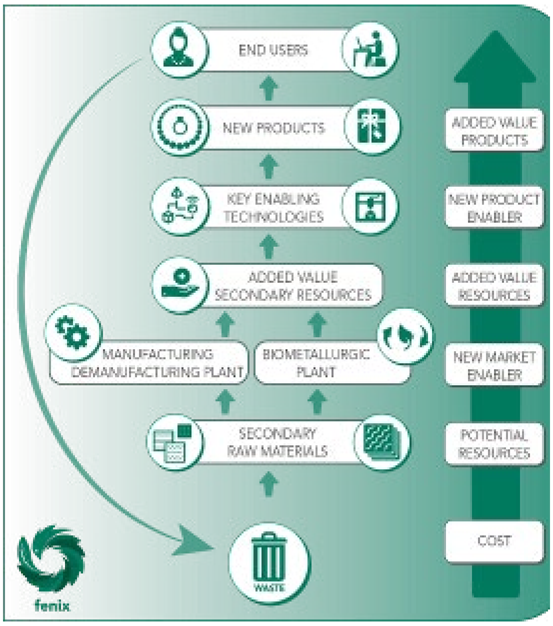

Figure 1: Fenix project concept.

2 Case study: Fenix Project

2.1 Electric and Electronic devices are collected from waste

In a nutshell, Fenix project's aim is the recovery of Au (gold), Ag (silver), Cu (cooper) and Sn (tin) from the surface of the WPCBs (Waste Printed Circuit Boards) and revalorizes and reintroduces this recovered material into the market.

To know more about the materials and the quantities in which they can be found, the table below shows a comparison between the amount of recoverable metal per smartphones and their market prices.

Comparison Value/ Price of the recovered metals					
Recovered Metal	Indicative market price €/Kg (2020)	g/smartphone	Value/ smartphone	% Weight	% Value
Au	49.000,00€	0,038	1,86€	0,25	89,32
Cu	5,80€	14	0,08€	91,58	3,90
Ag	500,00€	0,249	0,12€	1,63	5,97
Sn	17,00€	1	0,02€	6,54	0,82
	Total	15,29	2,08€	100	100

Table 1: Comparison between Value and Price of the recovered materials.

It is worth to highlight the asymmetrical relation between copper and gold's respective proportional weight and value. The fact that gold is almost 90% of the value of the recovered metals explains the traditional focus on the existing gold inside WEEEs, and that the recovery of copper is not a usual priority for recyclers. On the other hand, giving a profitable output for recycled copper would increase the total mass of recycled material by a factor of 10 with all the implications in terms of environmental impact.

Even if the output for the gold is already clear, its profitability can also be improved. In this study, we are going to focus on how to give to the recovered copper an output.

To give the best possible profitability of the recycled materials, several principles are going to be followed:

-Usage in AM (Additive Manufacturing) because it is low amount of waste, give the best possible value to the material.

-A business model involving the control of the full supply chain from extraction to the consumer in order to limit the cost of intermediaries.

- The focus in low production, high added value parts because of the low quantities of extractable material and to allow AM to give its full potential.

2.2 The Bio-Hydrometallurgical pilot plant

this study will analyse the recovery process once the metals are collected and separated,

For the metals recovery, a Bio-hydrometallurgical process has been used. It is much more environmentally friendly than the current ones, which use metallurgical-based operations, like pyro- and hydro-metallurgical processes, which are efficient for the recovery but have huge requirements in terms of energy, equipment and investment and generate toxic emanations.

Hydrometallurgy has advantages over pyrometallurgy such as lower toxic residues and emissions, and higher energy efficiency. However, this process still poses a threat due to the use of large amounts of toxic, corrosive and flammable reagents and the generation of high volumes of effluents and other solid wastes [4].

The bio-hydrometallurgical process is the "greener" option that FENIX consider, because it is central to preserve quality of water, safety and economical convenience of the treatment. Disposal of wastes also has a significant role in sustainability [5].

The complete recovery process, shown below in Fig. 2, use biological reactions that allows the thrift and regeneration of H2SO4 and Fe2+. Both will be reused in the oxidation leaching process.

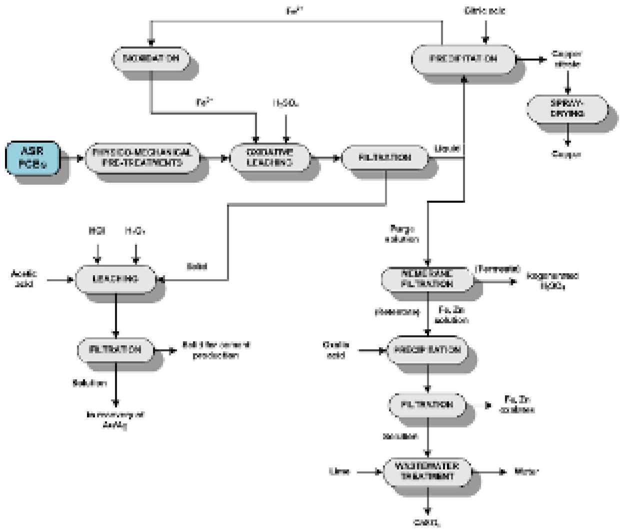

Figure 2: Bio-hydrometallurgical process in the recovery of metals.

The Bio-hydrometallurgical process (Fig. 2) principle is the following:

- The WEEEs are first mechanically crushed and then leached in a solution of ferrous ions and Sulphuric acid (H2SO4).
- The solution obtained is filtered. The solid part is then leached again with hydrochloric acid, acetic acid and hydrogen peroxide and then re-filtered to

recover silver and gold.

- The solid part of the initial leaching contains the copper.
- The ferrous ions are then recovered by bio-oxidation and the sulphuric acid is also regenerated.

The outputs of this process are the following:

- Almost complete separation of fibre glass was obtained by the treatment of solid residue of the WPCBs leaching process with N Methil Pyrrolidone.
- Metallic Sn powder with a purity of 95% was obtained by cementation with Zn (zinc) metal.
- Organic acids (citric and oxalic acids) production was achieved by bio technologies.
- Bioleaching process had as result recovery of 94% of the Cu from WPCBs.
- Ag was recovered as AgCl at a purity of 70%.
- The Au recovery from solution can be successfully recovered by its reduction with ascorbic acid. In this way, the cost of the process and environmental impact have been significantly reduced.

In order to increase the added value of the extracted Au, a line of jewellery has been designed. The idea is to offer to those consumers the possibilities of personalization of AM, and print a mould in wax and then cast with recovered Au. By controlling the full supply chain from extraction to the final product all the benefits go to the recycler and the customer can be assured on the "green" provenance of the precious metals.

Figure 3: Customized and personalized 3D Printed/casted jewels.

Considering the presented results above, there is possible to draw the followings conclusion:

- The Bio-Hydrometallurgical process allows to recover metals from WEEEs.
- The impact of this process is low due to the regeneration of most of its reactive.
- The gold output is directly usable.
- The copper output is not directly usable

2.3 Chemical composition of the material

The recovery of copper is more problematic. The direct usage of the powder from the bio-metallurgy plant is too coarse and too oxidized to be used as it is in AM processes (and in powder metallurgy in general) moreover the high level of impurity of the material further restrict its usage. In fact, the extracted copper comes with 5% of Sn which makes it closer to a low alloyed bronze than an impure copper.

The electrical conductivity of this material is unknown but a similar material the EN CuSn6 has a conductivity of 15.5% IACS (International Annealed Copper Standard).

This means that the market price of the extracted material is even lower than the one mentioned in Table 1.

The proposed solution is to use this impure material as a component of a ferronickel alloy that already has Cu and Sn. This adds value to the copper by decreasing the price and reducing the impact of the ferronickel alloy with no additional refinement process required to separate Cu from Sn.

The composition of the developed material is detailed in the table below (Fig. 4).

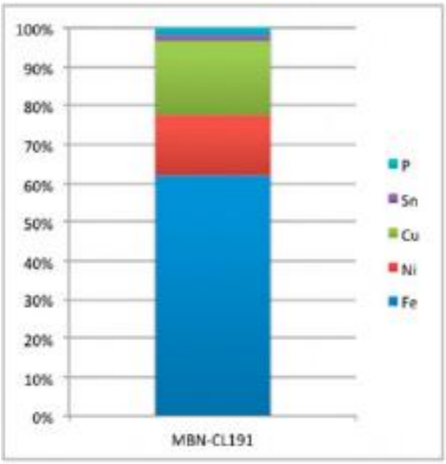

Figure 4: Composition of the material

2.4 Key Technology DIW

DIW 3D printing consists in depositing layer by layer an ink composed of particles of a solid component and a binder that gives it a pseudoplastic behaviour. This method has several advantages compared to FDM (Fused Deposition Modelling), it allows to manufacture metallic or ceramic parts and compared to powder bed fusion methods SLS (Selective Laser Sintering), SLM (Selective Laser Melting), EBAM (Electron Beam Additive Manufacturing), it allows to build a parts with a fraction of the input material required for the above mentioned techniques. This is because powder bed fusion requires to fill the batch of the machine with an amount of material ranging from 10 to 100 kg depending on the powder and the machine. With the DIW technique the minimum required is a full 3ml syringe, making the amount of required material much smaller. This makes of DIW a candidate for research applications where the material is very expensive or available in very small quantities.

Thus, this process is well adapted to circular economy models due to the amount of material is low and the profitability depends greatly on the capacity to give the maximum added value to the extracted material.

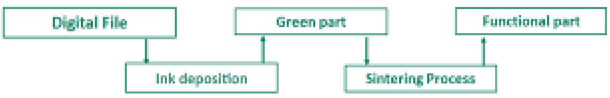

Figure 5: DIW Technology workflow. [6]

The established workflow in the printing process is shown in the Fig 5. It starts with a digital file from a 3D part, traditionally in STL format. This file is used to print the part thanks to a generated G-Code which is defined by printing parameters like the layer thickness, the diameter of the tip, the printing speed, and the desired infill, among others. Then, the green part is printed and subsequently it is submitted to a thermal process consisting in the burning of the binder (debinding) and the soldering of the solid particles (sintering) that consists on the application of a thermal cycle determined by the ink used.

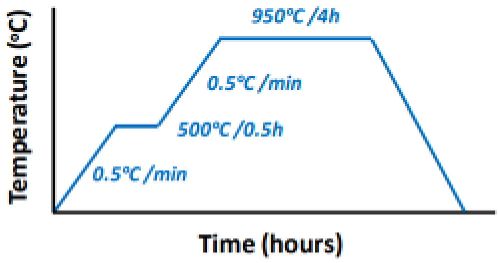

Figure 6: Thermal process

The result is a solid part exclusively composed by the material of the solid component. Finally, the metal functional part is obtained.

2.5 Increasing material density

A typical application of the technology is within the biomedical field. The ability to make porous parts, both at macro and micro scale using biocompatible metals and ceramics, makes of DIW one of the most promising technology in tissue engineering.

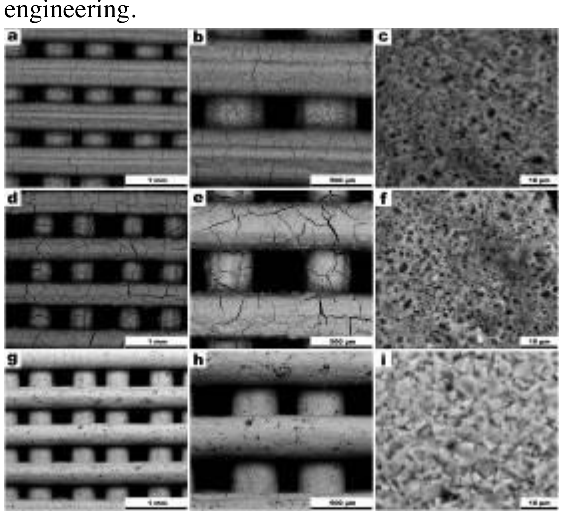

Figure 7: SEM (Scanning Electron Microscopy) of Akermanite scaffold Silicate based bioceramic. [7]

In Fig. 7 images a, d and g shows the macro porosity of a scaffold part in the order of magnitude of the mm. In addition, porosities can also be observed in the micron scale images (c, f and i).

As the ferronickel alloy is not a biocompatible material, the alternative application will be low cost small steel parts. In order to maximize their mechanical properties, the goal will be achieving minimal porosities inside the part.

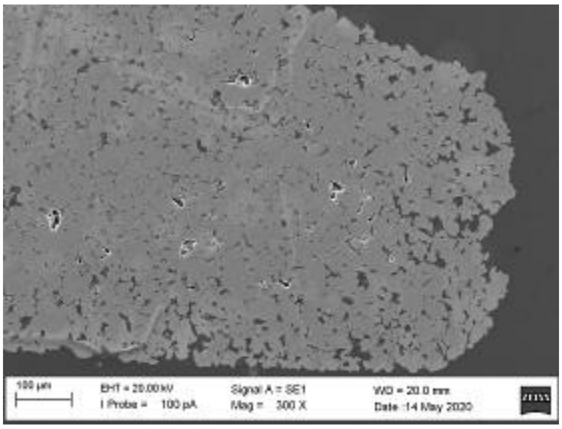

Figure 8: SEM image of a DIW printed sample using a monomodal powder.

Fig. 8 shows the internal structure of a sintered sample printed with a monomodal ink. As expected, a high porosity is observed and this will reduce the mechanical properties due to the creation of stress concentrator.

In traditional sintering, density can be improved by increasing the pressure in the mould, but this is impossible with AM due to the absence of mould. The solution is to work on the particle size distribution of the powder and its morphology.

The maximum packing density achievable for an assembly of spheres of the same diameter is $\frac{\pi}{3\sqrt{2}} \simeq 0,74$ % (Gauss, 1831).

In order to increase this density, it is necessary to change to a bimodal distribution of the particles.

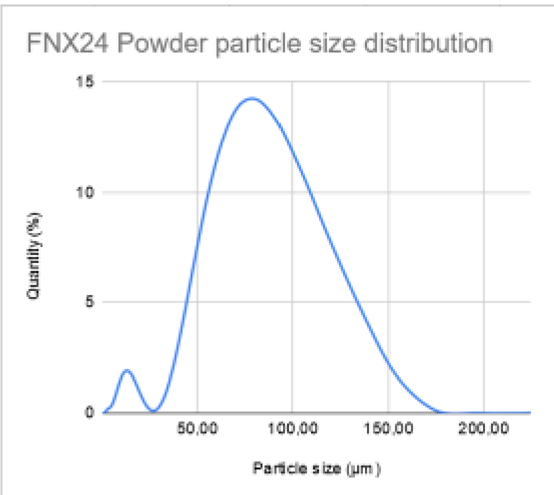

Figure 9: FNX24 Bimodal particle distribution.

The powder FNX24 developed within Fenix project is a bimodal powder with the main particle size of 82μm and the secondary particle around 12μm. Their radius ratio is 0,146% half from the theoretical maximum of 0,29 %. However, this maximum values are given for perfect spheres and in this case the sphericity of the particles is very poor as shown in the Fig. 10 below making orientative those values.

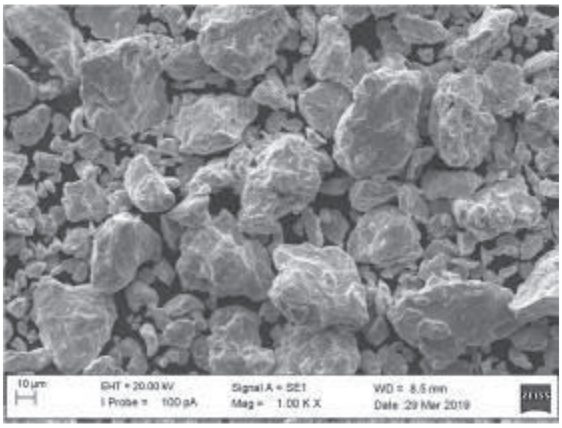

Figure 10: SEM of FNX24 powder.

The table below shows, that a bimodal repartition clearly increases the tapped density of the powder, not only in absolute terms, but also compared to the apparent density of the particles. Bimodal powders double the difference between densities.

Powder ref	Powder type	Particles Tap Density (in g/cm3)	Particles Apparent Density (in g/cm3)	Difference
FNX11	Mono	4,01	3,44	16,6%
FNX20	Mono	4,08	3,48	17,2%
FNX24	Bi	4,83	3,67	31,6%
FNX31	Bi	5,43	3,97	36,8%

Table 2: Comparison between different densities of powders.

The important factor here is that the final tapped density of the bimodal powder is closer to the final density of the metal (8,13g/cm3) leaving less space to be filled during the sintering process.

The result is a sintered part that show a clear increase in density.

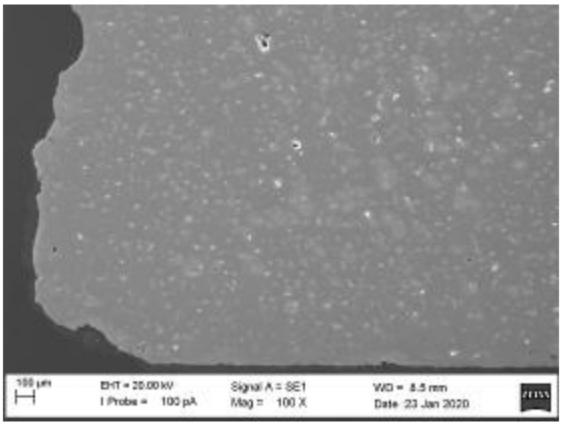

Figure 11: SEM image of a DIW printed sample using a bimodal powder.

2.6 Final Product & User involvement

Once the whole process is done, the last step is to focus on the end-user. The project employs two business models, B2B and B2C, in this way it will interact with major players, producers, customers and service providers depending on the outcome, product or service they need.

As designed recovered materials have good properties and with the DIW process it is possible to design and manufacture a wide range of metal products, almost everything needed from customers or the industry can be done. From gears to a milling tool, all of them highly functional and with the opportunity to obtain personalized products.

Both, customers and industry, are those that are going to make Fenix circular system possible, because they are the ones that will provide Fenix with obsolete electronic devices to restart the process. Fenix will cross information from both to get a good management of waste. This cooperative work will provide the right tools to monitor waste material, to predict possible consumption and production behaviours among others.

To conclude, the end user is probably one of the most important roles in this circular economy model, not only because without its cooperation waste couldn't be collected but also because is the customer the one that will use the new products or services closing the circularity of the system. So customer interaction and loyalty are a must.

3 Conclusions

What does the change from linear economy towards a circular one creates? It is not just one thing, but several.

It has created new business in those settle companies with fixed customers. Now they have another way to generate a business unit just reconfiguring their pilot plant, as seen in the case study above.

It also has created new products and as a consequence, new markets. For example, WEEE is one source of materials to make jewels, 3D printing metal powders and 3D printing filaments. As consequence, three different markets are created.

Due to the implemented circular system, a new supply chain is created, where industries and citizens are a fundamental element to guarantee the supply from their own obsolete devices.

Savings are included in the improvement because of the cheaper resources and manufacturing lines, due to the re-adaptation of the current ones.

Based in the study case, it is also possible to conclude that it will help to the environmental footprint of WEEE, transforming them to a sustainable resource to make environment friendly products. It is important to mention that a circular economy model reduce the obsolescence of the new products built-to-last or to be recycled. During the process, the greener technologies will be implemented.

4 Acknowledgements

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B.2
CIRCULARITY OF PLASTICS

Recycling WEEE Plastics – Closing the Loop in Times of Changing Chemicals Legislation

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Abstract

As it is one of the fastest growing waste streams in Europe, WEEE recycling practices should face additional scrutiny. Despite considerable ecological potential, WEEE plastics recycling rates are significantly lower, compared to other waste streams. WEEE plastics is hindered by past use of brominated flame retardants (BFRs), which are now restricted under European chemicals legislation. This article briefly summarizes the development of relevant restrictions that currently affect recycling and which recycled plastics can be used in new applications. The anticipated ban of tetrabromobisphenol A (TBBPA) under RoHS and lowering of PBDE thresholds of POP Regulation may affect the future of WEEE plastics recycling. Analyses of plastics from select WEEE groups with high BFR levels anticipated showed especially high concentrations of TBBPA and decabromodiphenyl ether (decaBDE). In order to achieve effective BFR separation long term, developments of recycling technology and capacity is needed. German Environment Agency developed recommendations to increase demand for and supply of recycled plastics.

1 Introduction

In Germany, 853,124 tonnes of Waste of Electric and Electronic Equipment (WEEE) were collected and 841,062 tonnes treated in 2018 [1]. The total amount of WEEE collected in Germany and the EU has been increasing continuously since 2015 (see table 1) making it "one of the fastest growing waste streams in Europe" [2]. The increase is attributed to a rising penetration of households with information and communication technology (ICT) and consumer electronics and increasingly short product cycles [3].

	2010	2015	2016	2017	2018
Germany	777	722	782	836	853
EU-28	3,526	3,886	4,519	4,572	n/a

Table 1: Total WEEE collected (*kt*) in Germany and the EU-28 [4]

In the 2000s, plastics content in WEEE was found to be around 20 %, though varying widely among the different types of equipment [3][5][6][7]. It was expected to further increase, [3] even assumed the total WEEE plastics to roughly double from 2005 to 2015. A more recent study estimated plastics content to amount to 180,000 tonnes in Germany in 2013 [8], thus assuming an increase to roughly 25 %. Total WEEE plastics in collected WEEE amounts to 209,000 tonnes in Germany for the year 2017 [9], this equates to 1.1 million tonnes in the EU-28.

Recycling of WEEE plastics bears a significant potential to reduce greenhouse warming potential (GWP) of related industries. In a life cycle assessment, energy recovery of plastic rich WEEE shredder residue was found to be four times as GWP intensive as material recycling [10]. The impact of virgin plastics production on GWP was even six-fold compared to production of recycled WEEE plastics. With GWP of production of 1 tonne of the most prevalent polymers in WEEE [11] ranging from 1.63 t CO_{2eq} to 3.10 t CO_{2eq} (see table 2), recycling can play an important role in European efforts to reduce greenhouse gas emissions.

	PP	ABS	HIPS
GWP [kg CO_{2eq}/kg]	1.63	3.10	2.43

Table 2: GWP cause by virgin materials production of most common plastics types found in WEEE [12]

Despite the environmental benefits, recycling rates of WEEE plastics are comparatively low. 47 % of plastic waste is recycled in Germany, whereas only 21 % of WEEE plastics were recycled in 2017 [9]. High complexity of electronics and the large variety of materials contained hamper production of marketable recycled plastics [9]. Separation processes are geared towards metal separation, as metals are responsible for most of the revenue and recycled mass, with plastics remaining as part of shredder residue [13].

Owing to the wide application and multiple uses, different polymer types and additives used pose another obstacle to processing of the plastics fractions [11]. Flame retardants and other pollutants are often found in WEEE shredder residue and plastics, further impeding recycling [13]. In recent years, several substances have been banned from use in electric and electronic equipment (EEE) placed on the market in the EU, potentially facilitating future recycling operations. In the meantime, removal of regulated substances from the waste stream is required, in order to close the loop for EEE plastics.

Brominated flame retardants (BFRs) come under scrutiny, due to their possible effects on health and the environment [14]. Therefore, governments implemented restrictions of several substances within this group, though many still occur in the waste stream [15]. Some substances have effectively been eradicated from the waste stream, such as polybrominated biphenyls (PBB) [16] or are mainly used in other applications such as hexabromocyclododecane (HBCD). This article will focus on the group of polybrominated diphenyl ethers (PBDE), tetrabromobisphenol A (TBBPA), 1,2-bis(2,4,6-tribromophenoxy)ethane (BTBPE) and decabromodiphenyl ethane (DBDPE), as those substances exhibit the highest concentrations in WEEE plastics [15][16].

In polymers, BFRs are typically used in single- to lower double-digit percentages. Common loads of decabromodiphenyl ether (decaBDE) are 10 to 15 %, usually involving the use of antimony trioxide (ATO) [17], a synergist amplifying the effect of the flame retardant.

In this article, we will analyse recent developments in legislation governing the use of hazardous substances impacting the recycling of WEEE plastics. We will then present analytical results testing BFR content of potentially highly contaminated WEEE conducted for German Environment Agency (UBA). Finally, legislative measures, proposed by UBA for the national legislation will be discussed as well as a research approach for developing separation strategies for recyclable plastics from WEEE.

2 Legal framework

As relevant European legal framework regulating the use of BFRs in EEE and recycled plastics, REACH Regulation (Regulation (EC) 1907/2006), the Regulation on Persistent Organic Pollutants (Regulation (EU) No. 2019/1021, POP Regulation) and the European Directive on the Restriction of the use of Certain Hazardous Substances in Electrical and Electronic Equipment (Directive 2011/19/EU, RoHS Directive) were identified. REACH provides the general framework for production and use of chemicals in Europe, among others, restricting and authorising their use. As a party of the Stockholm Convention on Persistent Organic Pollutants, EU realised its obligations under the POP Regulation. As some BFRs occurring in WEEE plastics are identified as persistent organic pollutants (POPs), POP Regulation is relevant for their recycling, as it is regulating both, the waste management and placing on the market of mixtures and substances containing POPs. RoHS Directive may be viewed as *lex specialis* concerning restrictions of use of hazardous substances in EEE. Recycled plastics derived from WEEE may not be in the scope of RoHS if placed on the marked as such, thus necessitating the inclusion of POP and REACH Regulations in this analysis.

2.1 RoHS

RoHS Directive banned the use of PBDE when restrictions came into effect in 2006. Concentrations up to 0.1 % by weight (1,000 mg/kg) in homogenous materials are tolerated under RoHS. One notable exemption in effect until 2010 applied to the use of decaBDE in polymeric applications. The use of decaBDE in electronics was effectively banned from July 2008, though, due to a ruling of the European Court of Justice [18].

2.2 POP Regulation

Internationally, widely used PBDE have been added to Annex A of the Stockholm Convention. Tetra-, penta-, hexa- and heptaBDE were listed for elimination in 2009, decaBDE was added to Annex A of the Convention in 2017. From 2010, production and placing on the market of tetra- to heptaBDE were banned in the EU above a concentration of 10 mg/kg in substances, preparations, articles. To allow for recycling of plastics containing PBDE, articles and preparations containing PBDE under a threshold of 0.1 % by weight each were exempted from this ban. Use in EEE falling under RoHS was also exempted from POP Regulation, as the substances are banned under this directive (cf. 2.1).

Waste management provisions under POP Regulation demand the destruction or irreversible transformation of banned substances. A threshold of 1,000 mg/kg as the sum of the four listed PBDE was established in 2015 for this requirement, making pre-treatment of waste intended for recycling necessary, to eliminate PBDE above this concentration.

The ban of decaBDE was implemented in the recast of the POP Regulation in 2019. As no exemption for decaBDE in mixtures and articles containing recycled materials was included in the Stockholm Convention, a different approach was chosen to ensure recycling of WEEE plastics containing BFRs remains possible: The trace contamination threshold for the now five banned PBDE – including decaBDE – was specified at 10 mg/kg in substances, whereas trace contaminations of up to 500 mg/kg of the sum of all five PBDE are tolerated in mixtures and articles (see table 3). The exemptions for tetra-, penta-, hexa- and heptaBDE in recycled materials were dropped in the POP recast. Concerning POP destruction in waste management, decaBDE was included in the existing threshold of 1,000 mg/kg for the sum of PBDE.

	RoHS Directive (Annex II)	*POP Regulation (Annex I and IV)*			*REACH Regulation (Annex XVII)*
	Threshold concentration for EEE	Tolerated traces in substances	Tolerated traces in mixtures or articles	Threshold for destruction or irreversible transformation	Threshold for restriction in substances, mixtures and articles
tetraBDE	1,000 mg/kg as the sum of PBDE	10 mg/kg	500 mg/kg as the sum of tetraDBE, pentaBDE, hexaBDE, heptaBDE and decaBDE	1,000 mg/kg as the sum of tetraDBE, pentaBDE, hexaBDE, heptaBDE and decaBDE	–
pentaBDE		10 mg/kg			–
hexaBDE		10 mg/kg			–
heptaBDE		10 mg/kg			–
decaBDE		10 mg/kg			1,000 mg/kg
octaBDE		–	–	–	1,000 mg/kg

Table 3: Threshold values for restricted and banned PBDEs relevant for recycling of WEEE plastics in EU legislation. Exemptions for certain uses apply

2.3 REACH

Production and placing on the market of pentaBDE, octaBDE and decaBDE as a substance and in other substances, mixtures and articles with a threshold value of 0.1 % by weight (1,000 mg/kg) were also restricted under REACH Regulation. PentaBDE and octaBDE were added to Annex XVII in 2009, though the pentaBDE restriction was deleted from REACH in 2011, following the substance ban under POP Regulation. The restriction for decaBDE is in place since 2019, but will be deleted in the near future since it is now regulated in the POP Regulation. Among others, an exemption for EEE within the scope of RoHS Directive as *lex specialis* is in place.

2.4 Further developments

PBDE thresholds under POP Regulation, both for placing on the market and waste management of the substances, are to be evaluated by July 16, 2021. This might entail further lowering of current limits, as thresholds are viewed as compromise between European Parliament and Council [19]. Lowering the threshold for destruction or irreversible transformation of waste for the sum of PBDE to 500 mg/kg is to be evaluated.

The restriction of TBBPA use in EEE under the RoHS directive is currently evaluated. The RoHS Annex II Dossier for TBBPA restriction conducted by Öko-Institut recommends inclusion of TBBPA as an additive in the list of restricted substances with a limit value of 0.1 % per weight [20]. Restriction of antimony trioxide is also currently considered. The respective RoHS Annex II Dossier does not recommend restriction of ATO but rather a combined assessment of halogenated flame retardant–synergist systems [21].

DBDPE and TBBPA were added to the Community Rolling Action Plan (CoRAP) in 2012 and 2015 respectively. DBDPE and TBBPA are under assessment for their PBT (persistent, bioaccumulative and toxic) properties, TBBPA is also screened for its properties as endocrine disruptor. The assessment might lead to further measures taken, to mitigate their potential adverse effects.

3 BFR analysis in WEEE plastics

For the analysis of BFRs in WEEE, we selected six groups of EEE with high levels of BFRs anticipated. Based on a review of available literature, the following groups of WEEE were identified:

- printers, scanners and photocopiers,
- electric tools,
- consumer electronics,
- telephones,
- personal computers and docking stations and
- kitchen tools [8].

Based on a first screening for tetraDBE, pentaBDE, hexaBDE, heptaBDE, octaBDE, decaBDE as well as TBBPA, BTBPE, DBDPE and HBCD the following BFRs were chosen for a more in-depth analysis:

- decaBDE,
- TBBPA,
- BTBPE and
- DBDPE.

TetraDBE, pentaBDE, hexaBDE, heptaBDE, octaBDE and HBCD only occurred in quantities lower than or close to the limit of quantification and are thus viewed as being of minor relevance for recycling of WEEE plastics. Methods and detailed results are published separately [8][22].

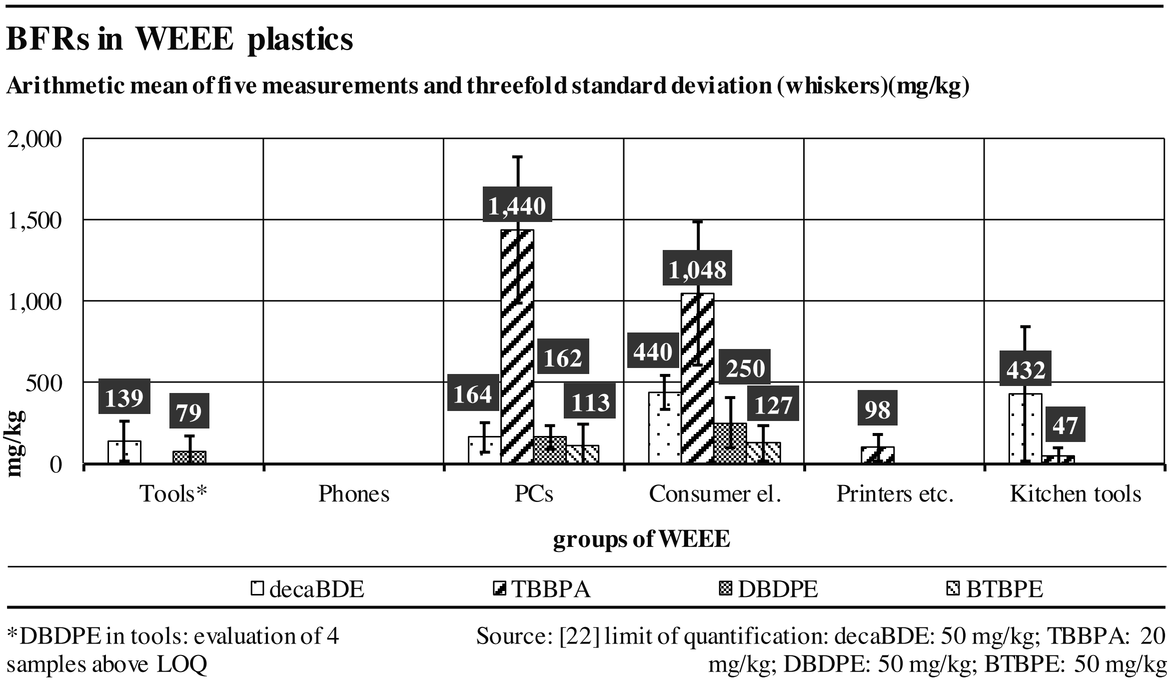

Figure 1: Analysis of BFRs in dismantled plastics of select WEEE groups with high BFR levels anticipated

3.1 Results and discussion

From 17 tonnes of separately collected WEEE, equipment of the identified groups were separated manually. Plastics fractions were generated my manual dismantling. Consequently, mixed plastics were shredded an representative samples were generated for BFR analysis.

The analysis shows, that PCs and consumer electronics show the highest BFR loads (see. Figure 1). All four BFRs tested occurred in these groups of EEE. In phones, none of the BFRs analysed were found and only TBBPA was identified in printers. Electric tools and kitchen tools both contained decaBDE, with DBDPE in the tools group and TBBPA in the kitchen tools group present.

The highest amounts of currently regulated BFRs was found in plastics of consumer electronics and kitchen tools, with both 99.7 % confidence intervals reaching above the 500 mg/kg threshold for decaBDE in mixtures placed on the market. The highest occurrence of any substance was observed for TBBPA with average concentrations reaching 1,440 (± 449) mg/kg and 1,048 (±442) mg/kg in PCs and consumer electronics respectively (printed circuit boards were not part of the plastics analysed). Average DBDPE and BTBPE levels were all relatively low compared to the other BFRs with a maximum concentration of 250 (±155) mg/kg of DBDPE and 127 (±108) mg/kg of BTBPE in consumer electronics.

None of the WEEE groups analysed exceeded POP Regulation Annex IV thresholds for POP destruction. Still, removal of BFR containing plastics during WEEE treatment is required by Directive 2012/19/EU (WEEE Directive). As BFRs are typically used in concentrations much higher than average values found in this analysis, it can be assumed only some plastics, with BFRs intentionally added, contain flame retardants while a large fraction is mostly BFR free. High variance in BFR distribution was also found for other WEEE plastics [23]. Consequently, removal of plastics with intentional BFR use is necessary to ensure requirements of POP Regulation for tolerated PBDE trace concentrations are met by all recycled plastics.

The commonly used technique for separating BFR-free plastics from the plastics-rich shredder residue from WEEE treatment is density separation [23]. The higher density of BFR containing plastics allows for sufficient reduction in BFR content in float fractions to comply with applicable thresholds [24]. In some BFR systems, this is further aided by higher density synergists such as ATO [21].Though density separation is suitable to allow for recycling of WEEE plastics under the current legal framework, the possible addition of TBBPA to RoHS restrictions and the lowering of threshold for PBDE in POP Regulation may increase market pressure on recyclers. It is thus crucial to develop strategies for even more effective BFR separation from WEEE plastics to ensure closed-loop recycling remains viable and avoid introduction of contaminated recycled plastics in other applications [25].

4 Closing the loop

Recycling of WEEE plastics bears the potential to reduce adverse environmental effects of WEEE disposal. Production of recycled plastics has a lower impact on greenhouse gas production than virgin plastics production, though separation of BFRs is necessary to ensure environmental and health safety as well as compliance with relevant waste and chemicals legislation. Past developments in relevant restrictions of placing on the market of flame retardants used in EEE raise some concern about appropriate applications of recyclates derived from WEEE. To avoid any contamination of other products with substances primarily found in EEE that may be identified as hazardous in the future, closed-loop recycling should be preferred.

In recent years, some manufacturers of electronics have increased their efforts to use recycled plastics in their products. Environmental awareness amongst consumers and the political efforts against climate change have brought effects of our consumption habits to the attention of the general public. Though exchange with industry shows, the use of recycled plastics is limited by the availability of suitable recyclates – concerning quality, quantity and reliability of supply. To effectively close the loop in EEE plastics, the appropriate legislative framework needs to be developed and issues of quality and quantity of recyclates need to be solved.

Recycling of WEEE plastics requires appropriate waste treatment and technology. EERA assumes total capacity for recycling of WEEE plastics to be around 250,000 tonnes, equating to roughly one fifth of arising WEEE plastic waste [26]. Reliable input into European recycling facilities and reliable demand for the recycled plastics produced are a prerequisite for investments into additional recycling capacity. To create a suitable environment for development of recycling infrastructure, German Environment Agency recommends to include recycled content in criteria for public procurement and the introduction of recycling targets for WEEE plastics.

4.1 Requirements for recycled materials in public procurement

To generate reliable and steady demand for recycled plastics, recycled content needs to advance as relevant factor for purchasing decisions. Information on recycled content is sparse, though some environmental certificates for EEE require recycled plastics content. A suitable measure to increase demand for recycled WEEE plastics is the introduction of requirements for recycled content in public procurement.

The German transposition of the recent amendments of the European Waste Framework Directive include the requirement for the federal administration to give, among others, preference to articles containing recycled materials. Similar requirements for procurement should be implemented on all levels and in other states alike. Only by increasing demand will recycling of WEEE plastics gain traction.

4.2 Recycling targets for WEEE plastics

One of the issues frequently brought up in discussions by EEE manufacturers is the lack of reliable supply of appropriate recyclates. Availability and cost can most likely not be separated completely in this reasoning, nevertheless, supply needs additional consideration by the legislator. The export of a considerable portion of plastic waste, mainly to Asian countries, has posed an obstacle for the development of plastics recycling in Europe. Due to recent amendment of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal in 2019, most WEEE plastics will be classified as hazardous in the future, leading to a decline of plastics exported overseas. To ensure this will result in a reliable supply of recyclates, German Environment Agency proposes the introduction of plastic recycling targets.

These targets should be implemented under extended producer responsibility (EPR) schemes. As demand for recycled plastics is influenced by the cost of virgin plastics uncertainty poses an obstacle for the necessary investments to raise total recycling capacity in Europe. The framework of EPR is designed to ensure viability of recycling operations during fluctuating markets for virgin and recycled plastic. This should create the appropriate environment for investments in technology for WEEE plastics recycling to ensure proper separation of regulated substances and the production of quality recyclates in the long term.

Based on literature review, plastics content of WEEE categories and data on pollutants and other barriers for recycling and research conducted for the German Environment Agency [8], we derived the following proposals for recycling targets:

Category (Annex IV of WEEE Directive)	Average plastics content	Recycling target
1. Temperature exchange equipment	15-20 %	10 %
2. Screens (only LCD)	25-35 %	10 %
4. Large equipment	20 %	10 %
5. and 6 Small equipment (IT and telecom.)	25-45 %	10 %

Table 4: Recommended proportion of plastics to be recycled (percent of total WEEE mass) by category

Though ambitious, these recycling targets can be achieved using state of the art technology. Increased availability of recycled plastics combined with an increased demand can contribute to closing the loop in WEEE plastics.

5 Conclusion

The changing legal framework concerning WEEE plastics recycling and production of recyclates creates an environment of uncertainty. At the same time, investments in treatment and recycling technology is needed to increase capacity as tighter regulation for exports of plastics containing BFR come into effect and RoHS Directive and POP Regulation will likely raise the bar for depollution of plastics, in order to comply with expected TBBPA and PBDE thresholds. The increasing pressure from chemicals legislation may not seem indicative of recycling targets and use of recycled plastics. To the contrary, we believe recycled content criteria for public procurement and plastics recycling targets for WEEE can play an important role in creating an environment for investments in recycling technology.

Recycling bears a significant environmental potential compared to the *status quo*, thus recycling of WEEE plastics is desirable for legislators. Failure to timely challenge the exposition to equal market pressures of recyclates and virgin plastics may cement the prevalence of energy recovery for this waste stream. Differentiation between the two is necessary due to the different environmental burdens linked to their production.

To address issues of hazardous substances in WEEE plastics, additional research concerning effective separation and safe destruction is needed. In a research project commissioned by the German Environment Agency, long-term strategies for removal of current and possible future restricted substances are being developed. Results of this study will be used to develop additional recommendations for legislation in order to ensure both, a high level of protection from hazardous substances and reduce the environmental impact of EEE manufacturing.

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Design for and Design from Recycling: The Key Pillars of Circular Product Design

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Abstract

The annual global plastics production increased from 1.5 million tons in 1950 to 348 million tons in 2018. While society has benefited tremendously from this plastics revolution, the negative environmental impacts are becoming increasingly visible.

As a consequence, the European Commission adopted a Europe-wide Strategy for Plastics in the Circular Economy in January 2018. The Strategy has the ambition to transform how plastics and plastics products are designed, produced, used and recycled in the future and it comes with challenging targets for the next years. One of its goals is to ensure that all plastic packaging put on the market is recyclable by 2030 (design for recycling). Another target is to “ensure that by 2025 ten million tons of recycled plastics find their way into new products on the EU market” (design from recycling), against less than 4 million tons in 2016.

The main goal of this paper is to present design strategies that can help increase the uptake of recycled plastics in product design. It focuses on the sector of electrical and electronic equipment and the results are the outcome of ongoing work of the H2020 project PolyCE.

The paper is organized in three parts. First, it presents the main challenges for recyclers and designers to improve the circularity of plastics. Specific challenges at each step of the development process are highlighted. The second part of the paper introduces the new Drop-In Approach™, which provides a practical three pillar tool for product developers to start designing with recycled plastics. A complexity flowchart helps designers to focus on priority parts and a six step material approval approach allows them to gradually reduce the risk that is linked to using recycled plastics. The Look & Learn pillar shows the power of small-scale demonstrators. The last part of the paper puts theory into practice and presents case studies that were developed within the PolyCE project and follow the design strategies.

1. INTRODUCTION

The first synthetic plastic, the so called Bakelite, was produced in 1907 [1]. It is believed that this has marked the birth of the global plastics industry. However, it was not until the mid of the 20th century that massive plastic production really took off. The annual global plastics production has increased from 1.5 million tonnes in 1950 to 348 million tonnes in 2018. Today, the European plastics industry has a yearly turnover of more than 350 billion EUR and employs more than 1.5 million people [2].

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Society has benefited tremendously from the plastics revolution and the large amount of functionalities that this material offers. Nowadays, plastics can be found in all sectors and in countless applications. They help us preserving our food, contribute to weight reduction in new cars and are used as robust housings for consumer electronics or as insulating materials in the building sector.

While innovation in the plastics industry makes it possible to use less materials for the same functionality, the increased diversity and complexity of plastics used in modern applications has a huge downside at the later stages of the product's lifecycle.

In December 2015, the European Commission (EC) presented its first Circular Economy Action Plan with the ambition to close the loop of product lifecycles through more sustainable production, distribution, consumption and waste management.

As one part of the implementation of the Action Plan, the EC adopted a Europe-wide Strategy for Plastics in the Circular Economy in January 2018 [3]. This Strategy has the ambition to transform how plastics and plastics products are designed, produced, used and recycled in the future and it comes with ambitious targets for the next years. One of the main targets is to ensure that by 2025, ten million tonnes of recycled plastics will be integrated into new products on the EU market [3]. These figures contain all plastics in all sectors.

Since stakeholder engagement will be crucial to reach the targets, the EC announced on 11th December 2018 the launch of the Circular Plastics Alliance (CPA) that gathers public and private stakeholders in the plastics value chain to promote voluntary actions and commitments for more recycled plastics. Within the CPA, over 175 stakeholders from different sectors pledged to use or produce more recycled plastics [4].

A first assessment of the pledges in March 2019 showed that while the European recycling industry could theoretically deliver around 11 million tonnes of recycled plastics by 2025, the pledges from the demand side reached only 6.4 million tonnes and would therefore miss the target by 3.6 million tonnes [5].

However, many of the pledging brand owners indicated that they could substantially increase the pledged amount, if a suitable quality of recycled plastics would be available at a competitive price. These quality requirements are multi-dimensional and can be linked to different steps in the overall design process, such as the material choice, geometry, moulding and the production process.

Indeed, most of the recyclates coming out of European recycling plants are nowadays used in the building and construction sector, mainly for quality reasons [6]. In order to increase the share of recyclates in higher-value applications, such as electrical and electronic equipment, guidelines and standards on responsible design and minimum quality standards are needed [7].

2. KEY CHALLENGES

One well-known prerequisite for closing the gap will be to switch from linear to circular thinking throughout the entire value chain. However, this transition comes with major challenges, since two different "worlds" that nowadays operate independently most of the time, need to be connected: The world of product development and the world of material recovery. The world of product development consists of product designers, moulders, manufacturers and consumers. The world of material recovery starts at a product's end of life and involves waste collectors, pre-processors, recyclers and compounders. The following Figure illustrates the relationship.

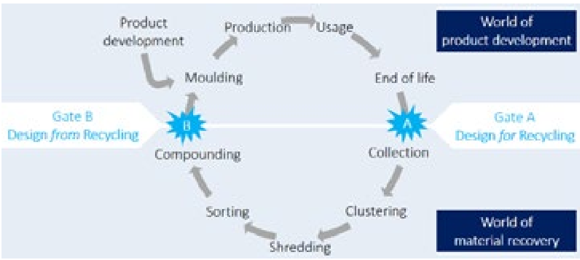

Figure 1: Bringing together the world of product development and the world of material recovery (Pezy Group)

In order to bring these two worlds together, it is particularly important to focus at the "gates" linking one world to another. In Figure 1, these two gates are illustrated as Gate A and Gate B. Gate A shows the missing link between the state of a product at its end of life and whether it is properly designed for the world of material recovery (design for recycling) and Gate B represents the missing link between the output of material recovery (recycled materials) and the input requirements of product designers (design from recycling).

While this relationship holds for all sectors, this paper focuses on the sector of electrical and electronic equipment.

Challenges for recyclers

More than 80% of the environmental impact of a product is determined at the design stage [8]. Products that are easy to recycle at their end of life can not only improve the yield of recyclers, but also help delivering the quality required by OEMs. For this reason *design for recyclability* is a particularly important part of the EU plastics strategy.

Recyclers of plastics from waste electrical and electronic equipment (WEEE) face a broad variety of challenges. As an example, the presence of many different polymers in the collected WEEE makes it difficult for recyclers to separate all of them correctly and cost effectively. One of the main polymer separation techniques is the sink-float separation, which relies on the different density properties of polymers. However, the more different polymers are present in the waste stream, the more difficult the separation can become because of density overlaps. For this reason more sophisticated techniques are often added as an extra step to improve the overall yield. Since these techniques come at additional investment costs, they are less likely to be deployed by smaller recyclers with limited capacities [9].

Some plastics can be particularly problematic for recyclers. As an example, chlorinated materials such as Polyvinylchlorid (PVC) can release hazardous hydrochloric acid fumes or dioxins. Furthermore, PVC is corrosive and can cause a quicker deterioration of the recycler's machinery. Another polymer that can cause issues for recyclers is Polyoxymethylen (POM), since it can lead to the release of toxic formaldehydes when heated above 220°C [9].

The occurrence of glass or carbon fibres can also be problematic for recyclers, since they cannot be recycled mechanically and can deteriorate the machinery [9].

"Legacy" substances (e.g. heavy metals, flame retardants, etc.) and other impurities from non-plastic materials (wood, glass, paints, coatings, etc.) present another technical challenge [9]. Colour can be another issue for some sorting technologies such as near infrared (NIR) scanners that are unable to identify polymers with carbon black.

Challenges for designers

Virgin polymers can be engineered in a complex way and for specific and demanding applications. To satisfy the requirements, a large variety of different thermoplastics such as styrenics (PS, HIPS, ABS, SAN), polyolefins (HDPE, LDPE, PP), different engineering thermoplastics (PC, POM, PUR, PA) are used. A broad variety of additives (organic & inorganic) are added before processing that can change material properties such as colour, melting point, flammability, and density, for legal, design and/or cost purposes. These additives may be pigments (e.g. TiO_2, ZnO, Cr_2O_3, Fe_2O_3, Cd), flame retardants (often brominated organics combined with Sb_2O_3 or polychlorinated biphenyls (PCBs)), and stabilizers or plasticizers (e.g. compounds of Ba, Cd, Pb, Sn and Zn, or PCBs) [9].

Achieving the same target properties can be very challenging with recycled plastics, since the collected material can suffer from limitations with respect to mechanical properties, colour or purity. These limitations can reduce the area of applications for recycled plastics. Since it cannot be categorically ruled out for certain waste streams that they contain impurities (incl. substances of concern), they cannot be used in products with food contact, toys or medical devices.

Product designers follow a product and material strategy which varies from one company to another. Main assessment criteria such as desirability, profitability and feasibility [10] (Figure 2) are driving the innovation processes and determine successful products.

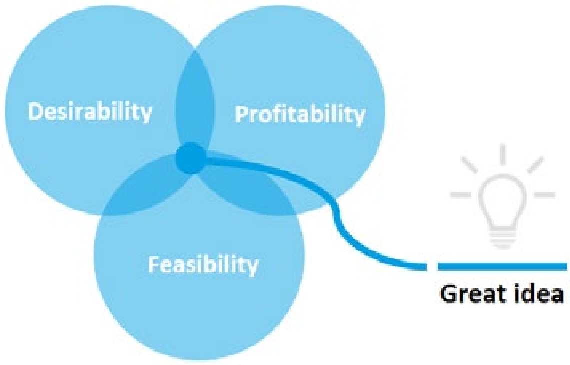

Figure 2: Venn diagram of a 'great idea' according to Pezy Group

In practice, any design option needs to be justified by short or mid-term commercial benefits and only few companies integrate sustainability aspects systematically in their product strategy (e.g. through a cradle-to-cradle certification [11]) without specific profitability requirements. Changing the materials used for an existing product can increase the project risk if the materials are not proven over time. The choice of materials is therefore mainly driven by technical and legal requirements as well as cost considerations.

As a consequence, integrating recycled materials in new products should not negatively impact any of these assessment criteria, but rather enhance them. In general, designers would voluntarily consider the integration of recycled plastics in new products, as long as this change improves at least one assessment criteria without impacting the others in a negative way. As an example, it would be possible to imagine the substitution of virgin resins by recycled polymers in a new product, if the profitability of the product would increase (e.g. through lower material costs) without harming the desirability (e.g. smell, aesthetics, function, etc.) and feasibility (e.g. technical requirements like robustness, etc.) of the initial product

Since recycled plastics are often new to designers and OEMs, the final outcome comes with much uncertainty. This lack of knowledge and increase of risk is one of the major barriers for companies to use more recycled plastics. A comparison of main technical and economic attributes for virgin and recycled plastics is presented in Table 1 [12].

Table 1: Attributes for virgin and recycled plastics (adopted from [12])

		Virgin Plastic	Recycled plastic
Technical	Quality	Constant	Quality variation based on used source
	Availability	High	Limited PCR (PP, PE, HIPS, ABS, PET)
	Surface	Good surface finishing quality	High gloss surfaces difficult to reach
	Colour	Flexibility in colouring	Transparent natural color barely available, mainly black and grey colours
	Olfactory performance	Good	Can be very smelly, depending on the source
Economic	Supply chain	Limited number of suppliers and availability of second source	Complex supply chain
	Support	Strong technical support through the application chain (selection, technical data, part design, mould design, moulding)	Low level of technical support
	Price	Highly vulnerable to oil price	Price is less vulnerable to changes in oil price High quality recycled grades are priced as virgin material

Challenges during the development process

Designing a plastic product involves four different product parameters that together define the properties on behaviour and looks:

- Material (plastic grade)
- Geometry
- Mould
- Production process

The sequential order as described above defines the process a designer follows to create a good product. It is called the development waterfall (Figure 3).

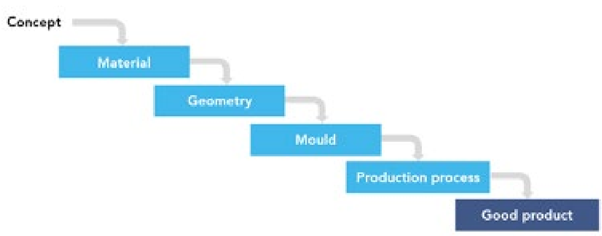

Figure 3: Development waterfall of plastic parts

These four product parameters are in balance with each other, which means that changing one parameter will very likely have an impact on the final result.

Every plastic grade has its own properties impacting the mechanical or aesthetical behaviour. Recycled plastics are not the same as virgin plastics which means that shifting from virgin plastics to recycled plastics implies a change of at least one of the four product parameters and will affect the end result.

The real or perceived lack of performance of the recycled plastics can be related to all aspects of the product parameters. Specific challenges for each parameter are summarised in Table 2.

Table 2: Challenges related to recycled plastics in the development waterfall

Parameter	Challenges
Material	• Portfolio needed from supplier • Lack of material & application know-how at supplier's • Limited colour options • Quantity availability over time
Geometry	• No part specification (upper/lower limits of mechanical properties unknown) • CP/ CPk values uncertain (i.e. tolerances uncertain) • No moldflow data (i.e. less predictability than with virgin)
Mould	Risk of mould damage due to: • Contamination in general • Blocked hot runner • Surface contamination due to outgassing • Extra wear on texturing and high gloss • Blocking of air venting (requires extra cleaning)
Production Process	• Variation in processing conditions • Limited acceptance by moulders related to risk of using recycled materials • Full size new process release needed • Lot-to-lot stability unknown or unproven

Drop-In Approach™

In order to integrate recycled plastics in new products and to reach the required properties, the recycled material needs to be perfectly understood. Generally, designers deal with two main uncertainties at the starting point:

1) Translation of the requirements and functions into the product to-be developed
2) The unknown plastic properties

By 'dropping in' recycled plastics into the moulds of an existing product, designers can learn about the performance of the recycled material. The parts made from recycled plastics can then be compared with existing parts made from virgin plastics. This approach allows to get acquainted with the possibilities of the material for future purposes.

Learning about the possibilities of PCR plastics by using and comparing them with virgin product parts is done step-by-step. First, simple shapes can be used to determine certain critical properties. Once more confidence is reached, the designer can try more complex shapes. This step-by-step approach helps to determine if the performance is comparable to virgin materials, what needs to be adjusted and whether the material or geometry can be fine-tuned.

This approach is not only the beginning of the development process for new products made from recycled plastics, but can be the start of in-house capacity building. New knowledge about the performance of recycled materials will shape the knowledge database, which can be a valuable input for future projects.

3. THE KEY PILLARS OF CIRCULAR PLASTICS DESIGN

The Drop-In Approach™ was developed within the H2020 PolyCE project and is built on the following three key pillars:

1) Drop-in complexity level tool
2) Six step material approval approach
3) Look & learn

The drop-in approach starts with applying the drop-in complexity level tool, followed by a six step approval approach which guides the designer through the complete process from material selection to mass production with parts made from recycled plastics. The Look & Learn pillar consists of demonstrators that provide a physical proof of mechanical and aesthetical properties and the process. The three pillars are described in more detail in the following sub-chapters.

Drop-in complexity level tool

Once a company makes the strategic choice to use recycled plastics in new products, it is important to define a starting point. Companies often have a wide range of products within their portfolio and each product consist of different plastic parts. All these parts need to fulfil their own specific requirements (e.g. mechanical, aesthetical, and legal) which define the complexity level for the integration of recycled plastics.

Building up material application knowledge from scratch comes with hurdles. For this reason it is advisable to start with parts that have relatively low technical and aesthetical requirements and are therefore relatively easy to manufacture from recycled materials.

By evaluating the product portfolio and classifying the product parts from ‘low hanging fruit / feasible’ to ‘the cream of the crop / at this moment not feasible’ a roadmap including the starting point can be defined (Figure 4).

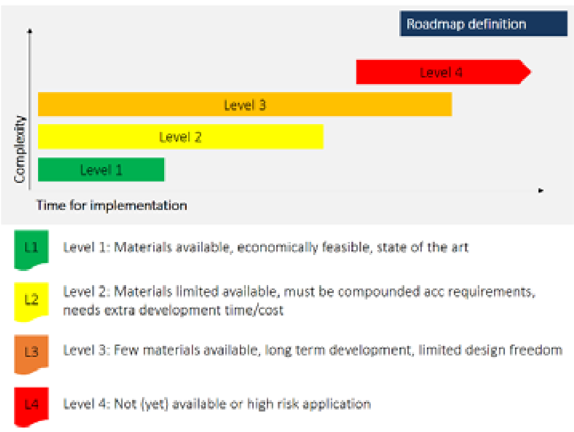

Figure 4: Recycled plastic implementation roadmap

Aspects to consider are for instance the availability (quantity and quality) of recycled materials, design freedom, aesthetic properties, mechanical and legal complexity, etc. These can be assessed trough a complexity level tool in form of a decision tree. An example of such a decision tree is shown in Figure 5.

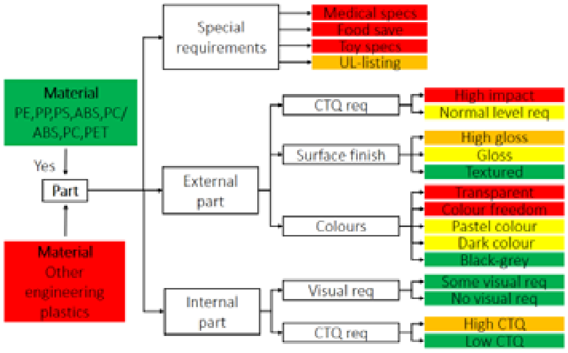

Figure 5: Example of a complexity level tool

A decision tree guides the designer step-by-step through the process. In this example, first the polymer type is assessed. If it is a polymer that is usually recycled (e.g. PE, PP, PS, ABS, PC/ABS, PC, PET) with existing recycling processes, the second step is to evaluate if it is an external or an internal part and if the part has special requirements or specific applications. It is usually easier to substitute internal parts with recycled materials, since they come with less visual requirements (e.g. high gloss). Specific applications, such as medical products, food contact, toys, etc. are not (yet) suited for recycled materials.

Six step material approval approach

After having chosen the part that will be made with recycled plastics, the development process starts. Based on the initially used virgin plastic type and the specific requirements, suitable suppliers need to be identified. It is crucial that suppliers provide detailed information and samples of the materials which can be tested on a small scale. Mechanical and aesthetical properties of the recycled plastics need to be tested first. The results give an indication where and to what extent the recycled material deviates from the initially used virgin plastic. The selection of potential materials should focus on the most promising one(s). Only then a pilot moulding should follow.

The following steps focus on the details for the specific application. The design might require some changes along the way to match the requirements with the recycled plastic properties. Possibly, the product architecture and part design can be changed to reduce the complexity and to increase the room for more recycled material use.

All sorts of uncertainties such as cost, availability, colour stability, lot-to-lot stability and process capability need to be reduced to a minimum to proove that the recycled material fits the business case and the technical needs of the product. Only then it will be possible to move towards large mould trials, product assembly and finally to mass production. The six steps are summarised in Figure 6.

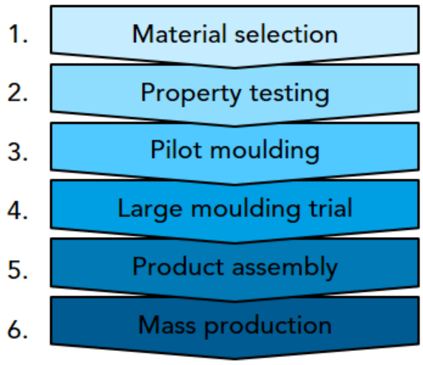

Figure 6: The six step approval approach

Look and learn

Look & Learn is the third pillar of circular plastics design. Demonstrators provide physical proof of mechanical and aesthetical properties and the process. First, simple moulds can be used to make tensile bars or to perform a spiral flow test. Furthermore, simple shapes with textures or curved surfaces in combination with available colours can give designers an indication of what can be reached with the recycled material. Physical evidence is a powerful and convincing way to guide the process and to show the full potential of the material.

Once enough confidence for the material is built up with all stakeholders, more complex shapes can be made. Used moulds of existing products are usually an effective way to move forward with the new material without additional costs for new dedicated tools.

Besides demonstrating the feasibility of the new recycled materials, the built up learnings are an important part of the complete process of complementing the virgin plastics knowledge base with the recycled plastics knowledge base.

Figure 7: Look & Learn - Start with simple shapes and increase complexity once confidence is built

4. CASE STUDIES

This final chapter presents selected case studies from the H2020 PolyCE project that follow the approach described in the previous chapters.

Wisensys

The Wisensys is a measuring device that was made from recycled plastics for the company Wireless Value. The comfort sensor is measuring humidity, CO_2, light, movement and temperature and transmits data to a base station. Based upon the generated data, the environmental conditions can be adjusted to fit the desired living environment.

Figure 8: Exploded-view of the Wisensys

The three key pillars from the drop-in approach were used in the development process for this product. Once the adequate recycled plastics was found on the market and aesthetical and mechanical tests were performed on a small scale, the designers were assigned with specific design rules. Following these rules, a design was developed that created a balance between the assessment criteria desirability, profitability and feasibility presented earlier in the paper (see Figure 2). All plastic parts were made from recycled plastics and the product was designed in a way that it can itself be again recycled (design from and for recycling).

Senseo Viva Café Eco

The coffee department at Philips was challenged to develop a sustainable Senseo coffee machine by closing the plastics loop without compromising product design and coffee taste. Based upon the design of a Senseo machine already on the market, different possibilities to implement recycled plastics in the product were evaluated following a complexity level analysis. Materials were scouted, tested for technical

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and feasibility properties, moulded in the housing parts and tested on the market. Demonstrators helped building up confidence in all participating departments. The final result exceeded initial expectations and was a good showcase for the integration of recycled plastics in new products.

Figure 9: Senseo Viva Café Eco with recycled plastics

5. CONCLUSIONS

This paper had the objective to present design strategies that can help increasing the uptake of recycled plastics in product design. The core of the paper is the Drop-In Approach™ that was developed within the H2020 PoyCE project and which consists of the three pillars:

1) Drop-in complexity level tool
2) Six step material approval approach
3) Look & learn

Following the Drop-In Approach™ can help designers to mitigate different risks related to the use of recycled plastics by first building up material knowledge and then using this knowledge in new products and projects. Starting with easy to implement steps and growing to more complex applications by means of the complexity level tool can build up trust and confidence in using recycled materials. Demonstrators are very useful to convince stakeholders about the desirability, profitability and feasibility of the product and to lead by example other market players to follow the path.

If design for recycling becomes a norm, more high-quality feedstock material will be available for recyclers, which would increase the quality of PCR plastics without increasing its costs. This quality improvement could trigger an increase in demand for PCR plastics and help to ensure that by 2025 ten million tons of recycled plastics find their way into new products on the EU market.

6. ACKNOWLEDGEMENTS

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Using Post-Consumer Recycled Plastics in new EEE: A promising Circular Business Model for the Electronics Sector

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Abstract

This paper promotes the use of recycled plastics in new electrical devices against the background of economic, technical, political, and environmental drivers and obstacles. The paper will guide interested manufacturers and take a company perspective, where technical insights are provided on how minor changes in product design can facilitate the use of recycled plastics. The article will illustrate what is possible with modern recycling technologies in terms of quality and color and technical properties and identify the remaining barriers. Besides looking at the economic advantages of lower commodity prices and more flexibility in material choices for electronic manufacturers, the paper also looks at how the targeted recovery of the plastic fraction could bring considerable environmental benefits and thereby add value to the company profile. Practical examples from the H2020 Project PolyCE with strong industry participation will be presented to showcase how a paradigm shift in material use can be achieved away from virgin plastic use into a more sustainable product design.

1 Introduction

At the end of their lifespan, electrical and electronic equipment (EEE) could act as an urban mine for a large amount of valuable resources. While many metals are already being economically recovered, recycling of the high-quality polymer fractions from electronic waste is still lagging behind. The content of recycled plastics in new EEE today is below one percent [1]. For this reason, it is important that a sales market for this valuable resource flow is created in order to close material loops in the future and thereby work in line with the current European circular economy action plan. Political winds are addressing the problem of the low recycling rates of plastic fractions from Waste Electric and Electronic Equipment (WEEE). The European Commission is trying to counter the problem by launching the first EU Plastics Strategy in 2018 Europe. Among other things, the EU Plastics Strategy states that at least 10 million metric tons (Mt) of recycled plastics should find their way into new products on the EU market by 2025. As a response, more than 175 companies and business organizations joined together to form the Circular Plastics Alliance and published individual voluntary targets for the uptake of recycled plastics in future products [2].

With increasing consumer concern for sustainability issues, companies see the need to engage in more sustainable practices affecting their business model, product design and materials used. The use of post-consumer recycled (PCR) plastics offers a number of advantages to companies. Prices of PCR plastics are less vulnerable to changes in crude oil price. Life cycle analysis shows that PCR plastics have less environmental impacts compared to their virgin counterparts by a factor of 4 [3]. Research commissioned by Unilever among 20,000 consumers in five countries found that 33 % choose brands claiming social or environmental practices and 21 % choose brands promoting sustainability [4].

However, recycled plastics are often new to many designers and original equipment manufacturers (OEMs) and the final outcome comes with much uncertainty. This lack of knowledge and increase of risk is one of the major barriers for companies to use more recycled plastics. This paper provides a valuable PESTLE analysis shaping a thorough business case for the integration of PCR plastics into new electric or electronic products. The paper examines the enabling factors for including more recycled plastics into new electronic applications, considering internal and external aspects such as political winds and technical developments. The paper also provides a step-by-step approach for companies considering to start using recycled plastics.

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2 Current e-waste arising

The section below provides an overview of the current e-waste development with a market overview and examples of companies using PCR plastics in their products.

2.1 Overview of WEEE generated

WEEE is one of the fast-growing waste streams with an estimated annual growth rate of 3-4 % [5]. In the year 2019,approximately 53.6 Mt of e-waste were generated globally [6]. In contrast to the generated amount of 44.7 Mt of WEEE in 2016, the waste stream grew by 8.9 Mt [5]. The European amount of generated WEEE was 12.0 Mt in 2019, which accounts for approximately 22.3 % of the worlds e-waste generation [6].

When it comes to plastic fraction in electrical and electronic equipment, the total quantity in Europe amounts to some 3 Mt per year, whereas only 1.2 Mt mixed WEEE plastic finds its way back to the separate collection of WEEE in Europe [7]. According to current polymer prices (about 900 – 1500 € per ton) this is an estimated value of PCR plastics from WEEE of about 1.13 billion Euro [8].

2.2 Opportunities for business

The successful application of circular economy principles in companies is closely related to the profitability of circular resource use, the companies' capacity to change their business models into sustainable and competitive ones, and the companies' capacity to respond to market demands, meaning to meet the customers' needs and expectations [9].

A market review indicates that leading market players already design their products by using recycled plastics. For instance, the Swedish home appliances manufacturer Electrolux uses 55 % recycled Polypropylene (PP) in vacuum cleaner (Electrolux Ultra Silencer vacuum) with savings over 2 liters of crude oil and 80 liters of water per unit as well as reduced manufacturing energy consumption by 90 % [10]. The German brand Grundig designed a vacuum cleaner made of 90 % recycled plastics originating from WEEE [11]. Philips designed a steam iron made of 30 % recycled plastics, a vacuum cleaner with 25-47 % recycled PP and a coffee machine with 13 % recycled plastics, while 90 % recycled Acrylonitrile-Butadiene-Styrene (ABS) is in the baseplate and 40 % PP in the frame [12].

These examples show that it is technically possible to replace a significant part of virgin plastics with PCR plastics. The transition of gradually replacing virgin plastics with recycled plastics can be seen as a shift from linear to a more circular business model and can at the same time demonstrate diversity and creativity as for instance in the new design of new Senseo Viva Coffee Eco machine by Philips with a recycled look in the top lid [13]. It is thus also an opportunity for a gradual transformation into more a sustainable company profile.

3 PESTLE analysis

A PESTLE analysis is a tool used by companies to track the environment they are operating in or are planning to launch a new project, product or service [14]. PESTLE is a decision-making tool that provides the macro-environmental impacts, including political, economic, social, technological, legal and environmental

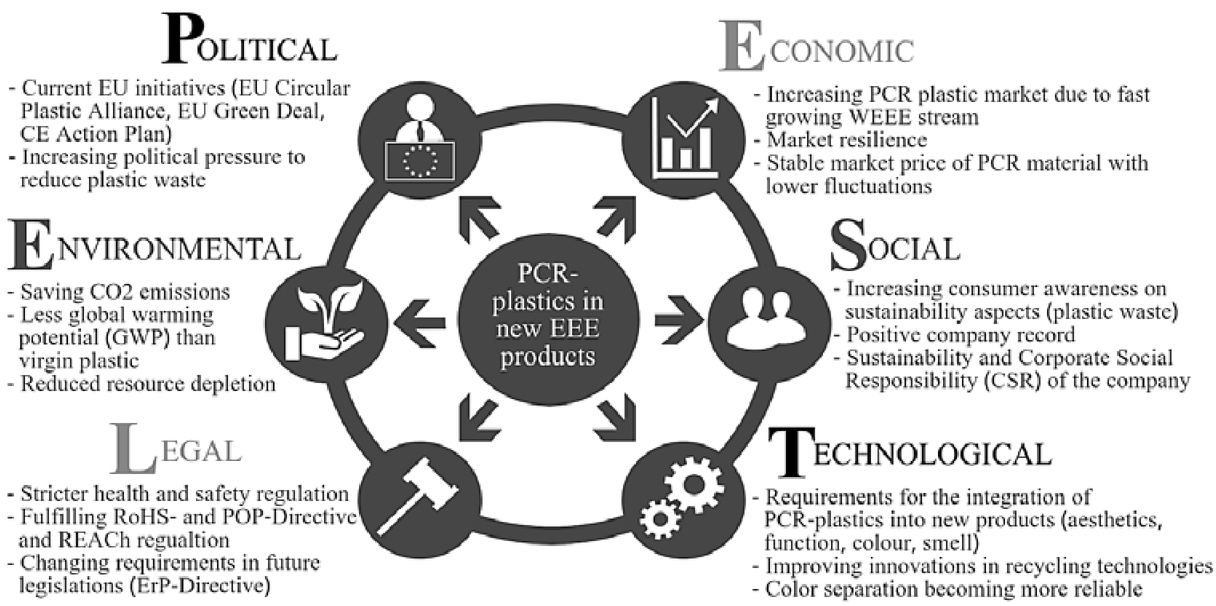


Figure 1: Influencing factors of PESTLE analysis regarding to PCR-plastics

aspects that are crucial for the successful implementation of a new project or a service [14].

The different factors associated with a shift from using exclusively virgin plastics to integrating PCR plastics are elaborated here to provide companies with an overview on the expected macro environmental aspects related to this strategic decision, see Figure 1.

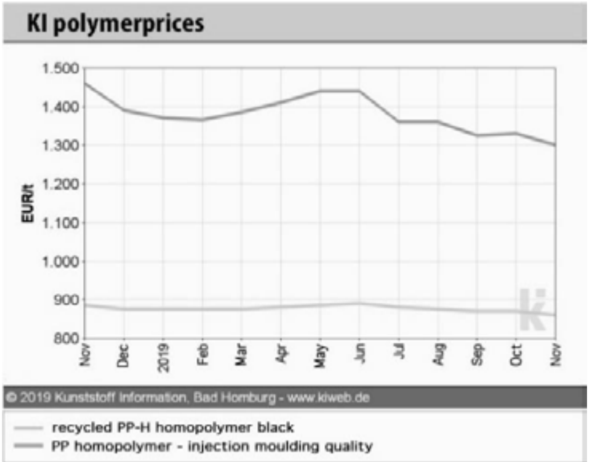
3.1 Political factors

The European Commission set higher collection and recycling targets to increase the amount of WEEE to be treated which will lead to a situation where more WEEE plastics are potentially available for recycling. From 2019 the minimum collection rate rose from 45 % to 65 % [15]. In addition, large amounts of WEEE plastic must be treated in Europe, since the china ban prohibits the import of plastic waste [16].

The European Federation of Waste Management and Environmental Services is continuously advocating for concrete and strong policy measures, such as mandatory green public procurement, binding recycled content in certain products, reduced VAT for products composed of recycled content, and eco-design aspects [17]. Vice Commission President Frans Timmermans argues that an EU-wide tax on virgin plastics will be extremely difficult to establish pinpointing to the fact that some plastic use is indispensable. However, through incentives and innovations, but also through prohibitions, Brussels wants to make plastics not only better: the only long-term solution Timmermans sees is to reduce plastic waste by increasing its recycling and reuse [18].

The European strategy for plastics in a Circular Economy, published in January 2018, aims to push the EU to a circular plastic economy, to support more sustainable production patterns for plastics, to support the reuse, repair and recycling of products as well as to reduce marine litter, greenhouse gas emissions and dependence on imported fossil fuels [19]. To push the uptake of recycled plastics, Annex III of this strategy includes voluntary pledges of more than 175 companies and business associations defining their contribution with a goal that 10 million tons of recycled plastics find their way into new products by 2025 in the EU [19].

In December 2019, the European Green Deal was announced which aims for no emissions of greenhouse gases until 2050 and to decouple the economic growth from resource use [20]. One of the main blocks of the Green Deal is a Circular Economy Action Plan, which was published in March 2020 and provides a future-oriented agenda for achieving a cleaner and more competitive Europe. The Action plan announces initiatives along the entire life cycle of products, targeting the design of sustainable products, promoting circularity in production processes, supporting sustainable consumption and aiming to ensure that the resources used are kept in the EU economy for as long as possible [21]. One of the strategies to increase the uptake of recycled plastics could go along a requirement for minimum recycled content in new products as well as waste reduction measures. Current and future political initiatives are very much in line with the strategy that support the integration of recycled plastics into new electronics applications. Thus, manufacturers that chose this path are actively supporting the current political circular economy initiatives in Europe and could gain a competitive advantage in the long term over companies that chose to remain in a linear business model.



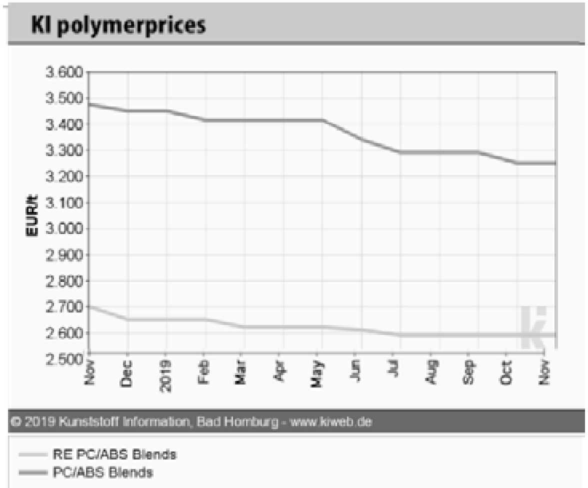


Figure 2: Polymer costs of recycled PP and PC/ABS and virgin equivalents [8]

3.2 Economic factors

A decisive advantage for using PCR plastics from a manufacturers' point of view is the more stable market price with lower fluctuations. Figure 2 shows the monthly data from "Kunstoff Information" with two commonly used types of plastic, Polycarbonat (PC)-ABS and PP. The graphics clearly show that in 2019

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recycled plastic equivalents had a market price around 30-50 % below the price of primary plastics and show fewer price fluctuations. Both observations are of interest to companies. Case studies have shown that the use of plastic recyclates can be profitable for companies, especially in the long term, with increasing experience and if PCR plastics remain below the virgin plastics price [22]. It remains to be seen whether a future increase in demand for plastic recyclates would result in rising prices and if a drop in oil prices could change the price advantages of recycled material. Lower price fluctuations mean increased planning security on the cost side in the long run in line with more market stability.

In their strategic decisions, OEMs depend on input factors such as quality, quantity and price of the raw material. Lower raw material costs consequently result in lower manufacturing costs and can lead to a higher profit rate. Since the recycling industry can meet the quality requirements for many electronic applications, certain plastic components can be replaced by recycled equivalents in the future. However, it must be emphasized that the quantities that are currently on the market do not provide a substitute for primary to secondary plastics as a mass scenario yet, and that a significant increase in secondary plastic material in adequate quality will be necessary in the future.

3.3 Social factors

Investigations conducted on the consumer side have revealed that the most relevant social aspect affecting the low demand for EEE containing recycled plastics is the lack of knowledge and lack of awareness by consumers regarding recycled plastics in electronic devices. However, a consumer survey conducted in the framework of PolyCE, revealed that consumers are becoming more aware of the positive aspects of adopting circular consumption models, especially when it comes to the negative effects related to the plastic waste problem.

A social experiment was conducted in the course of the PolyCE project, as part of a consumer awareness raising campaign to highlight the benefits of recycled plastics in electronics. The experiment took place on the streets of Brussels, in June 2019, whereby random passers-by were approached and asked to compare two vacuum cleaners displayed on a stand on the street and find differences in their appearance and functionality. They were given information on their components and technical specifications. Participants were faced with two vacuum cleaners looking the same, the only difference being the plastic components (one with- and one without recycled content). Consumers did not notice a difference, moreover many were stating their readiness and willingness to purchase a vacuum cleaner containing recycled plastics if available in the shop. When asked to guess the amount of recycled plastic content in current electronic products, many where shocked to find out that the overall percentage is still only around one percent today. It seems that consumer awareness, especially amongst young adults, is changing into more environmental conscious buying behaviour that would be in favour of product containing recycled plastics. [23]

The uptake of recycled plastics into new electronic products is not only a choice for sustainability- it provides a company with a competitive advantage over market players who remain linear acknowledging the raising environmental awareness of consumer to help fighting the global plastic waste problem. The company could get a positive record by actively contributing to a more sustainable production strategy and demonstrate Corporate Social Responsibility (CSR). CSR is a voluntary contribution of the company to sustainable development, which goes beyond the legal requirements and includes among other issues such as environmental protection, environmentally responsible production and procurement [24].

3.4 Technological factors

When it comes to technological factors, it is important for manufacturers to know the challenges and possibilities of PCR plastics for their products. An important challenge at the downstream stage are the requirements for the integration of PCR-plastics into new products like aesthetics, functional properties, colour or smell. Plastics used in specific products have to fulfil target properties for the application which differ from one company to another. PCR plastics have to meet these technical requirements in order to enable its future uptake. When it comes to aesthetical challenges of PCR-plastics, a high-quality visual appearance including colour and surface properties (gloss, matt, etc.) pose some of the major challenges for manufacturers and designers working with recycled plastics. Since the visual appearance is a key priority for electric and electronic goods, it is necessary to fulfil these requirements with recycled materials when applied for visible parts [25]. There are several factors which pose a challenge for recycled material returning from the WEEE stream. First of all, the broad variety of coloured PCR plastics is a limiting factor for specific colour requirements. However, it has been proven that the quality of recycled plastics is improving rapidly and compounders are able to produce a broad spectrum of coloured and high gloss parts also with recycled materials. [25]

When it comes to material properties of PCR plastics, the material tends to change during recycling. The polymer itself and the conditions during its lifetime and processing determine which material properties are being altered more and which less. Therefore, a good knowledge about the degradational effects of the individual polymer is crucial. As an example, ABS is one of the most effectively recycled polymers within WEEE recycling. However, it is sensitive to degradation. Mostly affected are impact strength and ductility. In this case, destabilization through adding virgin material or additives like impact modifiers are promising solutions to overcome this barrier. [26] This holds for most polymers, just the type and amount of virgin material and additives varies dependent of the polymer and the final product specifications.

In case of material characteristics, four types of PCR plastics can be effectively recycled from WEEE namely Polystyrene (PS), PP, ABS, and PC-ABS. Each plastic type has its own characteristics which have to be taken into account during the moulding in production process.

When it comes to the processing of PCR plastics in the production process, injection moulding represents the technique mostly used to produce polymer formed components. When the company progresses towards introducing recycled plastics in their products, companies should ensure that the mold is optimized for the material properties [27]:

- Do ensure good venting of the mold
- Do not go for very thin walled mold design
- Do consider texturing parts to mask visual limitations of recycled plastics

In comparison to virgin plastics there are several crucial differences which left uninvestigated and could lead to defects in the final product. First, it is important to keep in mind that PCR plastics come with technical data sheets, however only showing the general properties (this is the same for virgin). Specific material properties are requested by the manufacturer who will do material property testing on product level. During the process itself mild processing is the key for a good result. Whilst virgin material can be processed at higher rates, pressure, temperature etc. for high efficiency and still obtain the desired quality, PCR plastics are more sensitive. High screw shear forces, temperatures and pressure can further degrade the recycled polymers [28].

The production of odorous substances can stem from a variety of sources. External contamination of the plastic in its previous use is perceived as the main cause for smell but also the production of odours during processing poses a challenge. It is self-evident that a product cannot be sold holding these bad smell characteristics [29]. Momentarily there are several existing methods to counteract this problem and many more are in development. Known methods for odour reduction in recycled materials are contacting PCR plastics with hot gas under vacuum, the addition of further substances or stripping of volatiles [30]. Furthermore, a gentle reprocessing could reduce the smell of recyclates at least for PE [31].

Since PCR plastics could contain certain impurities including a low percentage of substances of concern, applications for food contact, toys or medical devices are not suited for PCR plastic uptake [32]. It is advisable to start the replacement of virgin components with recycled equivalents for non-visible inner parts. With increasing testing and technical experience, manufacturers can in the longer run also replace outer, visible parts with PCR plastic material.

3.5 Legal factors

When it comes to legal factors, several regulations are in place for EU actors, like the Restriction of hazardous substances (RoHS), the WEEE-Directive as well as the REACH and Persistent Organic Pollution (POP) Regulation. By this regulatory requirements, WEEE recycling facilities and EEE manufacturers are often faced with difficulties like dealing with plastics parts that contain brominated flame retardants (BFR). The EEE industry is meanwhile generating a limited amount of plastic products with BFR which have to be properly separated by pre-processors and recyclers to enable the re-use of PCR plastics in new products. However, recycling technologies today are increasingly being developed to detect and remove substances of concern (SOC) from the plastic waste streams, followed by a secure elimination to remove SOC from the value chain. Furthermore, pre-processors and recyclers are widely aware of the waste stream categories and even the plastic parts that need special handling to avoid SOC entering the mix of materials to be recycled.

Today, there are still WEEE plastics which contain restricted BFR. However, a minority of these plastics actually contain POP substances. By far the majority of the WEEE plastics does not contain brominated flame retardants and of the approximately 5-10 % that do contain BFRs, only approximately 30 % consists of POP BFRs (see Table 1) [33].

ABS	24 %
HIPS	27 %
Polyolefines	7 %
PC and PC-ABS	7 %
BFR containing plastics	5 %
Other plastics	24 %
Other contaminants	6 %

Table 1: Average composition of WEEE plastics [33]

Regarding the design for recycling approach, there are currently no significant considerations to use PCR plastics in the manufacturing of new products within the legal framework 2009/125/EC Energy-related Products (ErP) Directive [34]. Focus of this directive is to reduce the environmental impact caused during the manufacturing, use and disposal of products as well as general requirements on energy consumption [16]. Nevertheless, discussions are ongoing whether a minimum recycled content for plastic should be introduced in new products to stimulate secondary plastic markets. Experts claim that it might only be a matter of time before recycled content is implemented in legislation e.g. in form of a minimum recycled content for new EEE products. Companies that deal early with the integration of PCR plastics in new products would be well prepared for this change and can deal with the implementation of the new recommendations more easily and quickly.

3.6 Environmental factors

Compared to virgin plastics, the recycling of plastics is saving large amounts of CO_2 emissions and energy [7]. An estimated CO_2 reduction of the compliant recycling of all plastics from WEEE in Europe according to the standard EN 50615-1 is about 2.5 million mega tonnes of CO_2 per year [7].

A study in 2015 concluded that PCR plastics have less than 20 % of the global warming potential (GWP), compared to virgin plastics from the primary production [3]. A life cycle assessment (LCA) conducted within the PolyCE project compared virgin and PCR plastics. The environmental performance of the virgin production of 1 kg of PP was compared with the production of the same amount of PCR PP from large household appliances following recommendation from the PolyCE project (PolyCE Scenario). The LCA showed that the GWP of 1 kg PCR PP is 75 % lower compared to virgin PP (see Figure 3). Furthermore, the need of water for the production of PCR is 53 % lower and the abiotic resource depletion potentials (ADP) is 91 % lower than the virgin production. [35]

4 First steps for companies transform towards circular economy

In order to integrate recycled plastics in new products and to reach the required properties, the recycled material needs to be perfectly understood. Learning about the possibilities of PCR plastics by using and comparing them with virgin product parts is done step-by-step. The following steps shown in Figure 4 are intended to provide companies with a guideline on how to start integrating PCR plastics.

The first step aims to gain a good understanding of the overall need for plastic types in the company and to identify the parts that are suitable for replacing with recycled plastics. In the next step, concentrating on large-volume polymers and invisible parts is advisable since they have relatively low technical and aesthetical requirements and are thus relatively easy to manufacture from recycled plastics. Applications such as medical devices and toys, and visible plastics with high color requirements and skin contact are not yet suited for recycled plastics. The next step is to get in touch and identify suitable suppliers. Provision of detailed information and samples of the materials are crucial. Small scale testing delivers important information if the material fulfills the desired requirements, such as mechanical and aesthetical properties. It is useful to use primary plastics as a reference. Scaling up the successfully tested and approved recycled plastics into the products also requires contracts with recyclers regarding quantity agreements and other relevant information [22]. As a final step, a decision must be made to communicate about the use of recycled plastics, as consumer acceptance of recycled plastics remains a challenge.

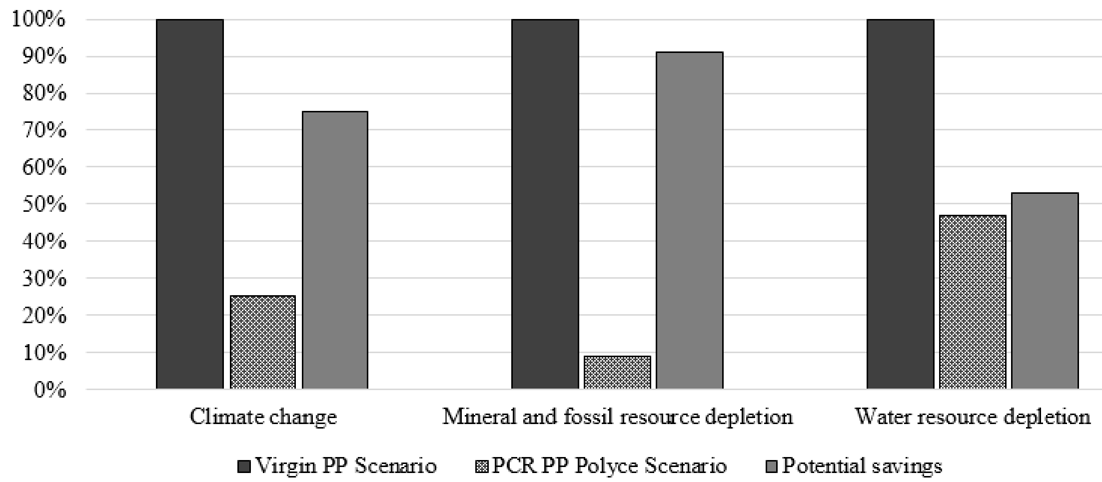

Figure 3: LCA results of using recycled instead of virgin plastics from WEEE according to [35]

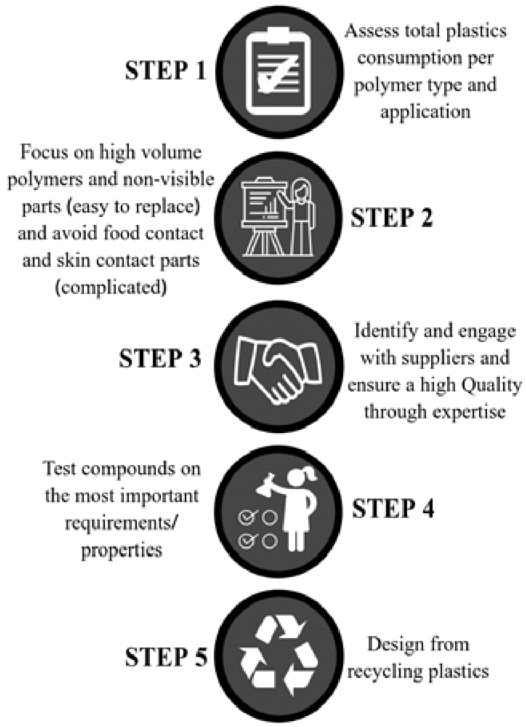

Figure 4: First steps integrating PCR-plastics

Once the process of material selection is completed and new business partners are identified, the integration of recycled plastics in new product parts can be scaled up.

5 Conclusion

The PESTLE analysis gives a good overview of the advantages and disadvantages for an uptake of recycled plastics in new EEE products and describes the opportunities and the remaining challenges. The main advantages by using recycled plastics in new EEE products are avoiding dependency on oil shortages due to market resilience, respond to rising consumer demand for sustainable products which stands for brands value as well as environmental benefits like saving greenhouse gas emissions of 75 %. The company could take on a pioneering role for environmental regulations which means a compliance with current and future policy. The uptake of recycled plastics into new electronic products is not only a choice for sustainability- it can improve competitiveness along the value chain and provides a company with a competitive advantage over market players who remain linear.

Remaining challenges in the use of PCR plastics are plastics with food contact, applications with specific requirements such as medical devices and toys as well as visible plastics with high color requirements. These applications require further research and trials as well as political solutions to overcome these challenges and to push the uptake of PCR plastics even more.

Acknowledgement

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Plastics Recycling for Waste Electric and Electronic Equipment: Key insights and challenges

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Abstract

Research into plastics recycling has gained widespread attention in recent years. Particularly for the treatment of waste electric and electronic equipment (WEEE), governments' ambitious recycling targets require innovative plastics recycling strategies. This is due to the diversity of polymers present in WEEE as well as hazardous materials. In this paper, insight is provided into the status quo in WEEE collection and WEEE plastics (WEEEp) recycling. For this purpose, an overview is provided of the compositions of various WEEE streams at the collection stage. Additionally, mechanical sorting technologies are considered, along with optimization methods to make the most efficient use of them. A case study is used to illustrate how strategic considerations along the value chain can increase the profitability of recycling facilities, as well as WEEEp recycling rates.

1 Introduction

In the European Union, an estimated 25.8 million tonnes of plastic waste is produced annually. Plastics from Waste Electrical and Electronic Equipment (WEEE; WEEEp for "WEEE plastics") account for roughly 8wt% of this overall annual figure, or 2.1 million tonnes [1]. The European Commission aims for a WEEE collection rate corresponding to 65% of the average weight of the EEE placed on the market in the three preceding years. An alternative target collection rate is 85% of the WEEE generated on the member state's territory in the given year. Targeted recycling rates for WEEE depend on the specific waste category, but are generally at least 70% [2]. These ambitious targets require that the plastic content of WEEE is also recycled.

The aim of this paper is twofold. Firstly, it will concisely survey the collection and recycling stages of the current WEEE(p) value chain in the European Union (EU). Emphasis is on the WEEEp from the small household appliances (SHA) category, as this is the least homogeneous category in terms of polymeric composition and the category richest in plastics. Secondly, the insights hereby obtained are used to evaluate WEEEp treatment strategies. In particular, the added value of isolating items that classify as SHA in the collection phase is addressed. This approach can make subsequent recycling steps more targeted. Its merits are evaluated from an economic as well as environmental perspective. The case study will help assess if an integrated approach with cooperation between pre-processors and recyclers can help achieve ambitious recycling targets.

2 WEEE Collection

2.1 Categorisation

While WEEE collection is formally the responsibility of original equipment manufacturers and distributors, in practice this task is delegated to or organized through dedicated institutions. In Directive 2012/19/EU (recast) [2], WEEE is classified into ten categories. These are listed in Table 1, along with the relative mass percentages at collection of each stream according to various sources. As WEEE statistics tend to be sensitive to geographic location, distinct regions are considered (as indicated by two-letter country codes).

Due to the presence of hazardous substances, fluorescent coatings in monitors and screens are considered substantial pollutants and are typically removed. Likewise, gasses from refrigerator circuits have to be extracted and mercury from luminaries must be removed. Furthermore, the division between SHA and CE is hard to maintain in practice and the relative rarity of products from the tools, toys, MD, MC and AD categories results in collection in six strata in most Member States, for instance in DK: [3], BE: [4], IT: [5]. This is illustrated in Figure 1. Note that the "other"-category in Figure 1 is nearly identical to the aggregation of the SHA and CE categories due to the negligible nature (in terms of mass percentage) of the other categories that constitute it.

Category	Abbreviation	[6](EU)	[7](ES)	[3](DK)	Target recovery (recycling) rate [2]	Proportion of plastics [8]
Large household appliances	LHA	53%	58%	56%	85% (80%)	15%
Small household appliances	SHA	10%	14%	8%	80% (70%)	20%
IT and telecom. eq.	IT&Tel	14%	7%	8%	- (80%)	20%
Consumer eq.	CE	15%	21%	22%	85% (80%)	20%
Lighting eq.	LE	-	-	-	75% (55%)	20%
Electrical/electronic tools	tools	-	-	-	- (80%)	
Toys, leisure, sports eq.	toys	-	-	3%	- (80%)	5%
Medical devices	MD	-	-	1%	- (80%)	20%
Monitoring/control eq.	MC	-	-	-	- (80%)	5%
Automatic dispensers	AD	-	-	-	- (80%)	5%

Table 1: WEEE categories according to directive 2012/19/EU with mass percentages at collection and recovery and recycling rates.

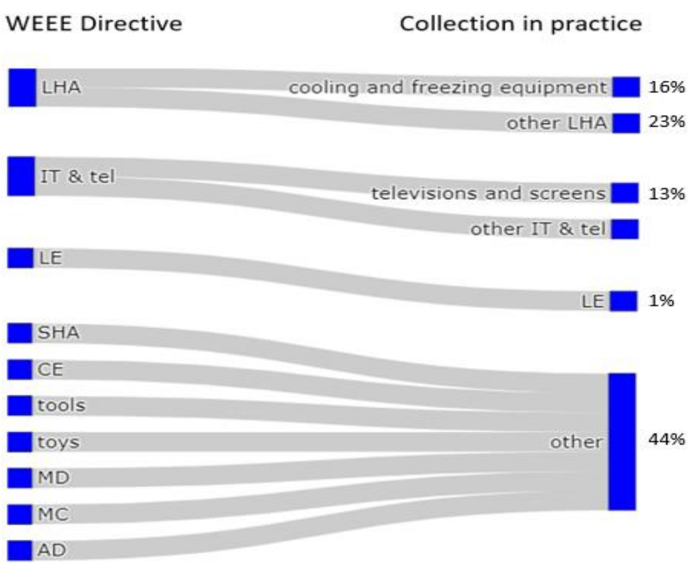

Figure 1: WEEE categories according to Directive 2012/19/EU and collection categories in practice. Percentages indicate mass percentage at collection and are obtained from [6].

In [9], methods are proposed to further separate the WEEE categories at the collection stage. Doing so can help avoid overly complex mixtures of polymers at the recycling stage. By identifying and isolating potential sources of contamination, legal issues can be avoided prior to mechanical recycling. Furthermore, by grouping together products containing either the same materials or materials that are easily separable from each other, the recycling rate of plastics can be improved. In section 4, such clustering strategies are illustrated in a case study with a small number of product categories classified as SHA. The methods in [9] are much more versatile and applicable on large data sets of product compositions if available.

2.2 Compositions of WEEE categories

In [5], the mass distribution of products in the categories *cooling and freezing equipment*, *other LHA* and *televisions and screens* were inferred from the ProSUM database [10]. This database is representative for the EU as a whole. This inspection showcased that one product type typically accounts for over 70% of these streams (for instance, 93% of the products in the *cooling and freezing equipment* category by mass are refrigerators). The SHA stream was an exception to this rule and deemed too complex to obtain a distribution of this type. Only a few recent publications are available that provide detailed quantitative insight into this stream, as summarized in Table 3. Figures in this table are inferred from graphical material and therefore ballpark estimates. Note that distributions of products in collected WEEE are time and location dependent.

Product type	[11](IT)	[12](ES)	[13](DK)
Coffee maker	3%	4%	15%
Desktop PC	<3%	11%	-
Keyboard	<3%	2%	-
Printer	8%	11%	-
Radio	<3%	7%	-
Clothes iron	<3%	14%	10%
Vacuum cleaner	4%	5%	50%
Microwave	<3%	17%	-

Table 2: Mass percentages of products in the SHA stream.

Regarding Table 2, reference [11] took random samples at a large WEEE treatment plan in the Milan metropolitan area. Among SHA, no products other than coffee makers, printers and vacuum cleaners occurred with a mass percentage of over 3%. Reference [12] took a total of 4,861 samples (pieces of SHA) from nine WEEE collection sites in a medium-sized city in Spain. The reference goes on to quantify the relative frequency of the products, their material composition (percentages of metals, plastics, etc.) and ease of disassembly. In reference [13], a total of 4,704 kg of "household WEEE" was gathered from a WEEE collection site in a medium-sized city in Denmark. The paper evaluates the economic potential lost in small WEEE, both in terms of potential for reuse and material recovery. The paper stresses the current lack of knowledge regarding SHA WEEE composition and the stream's economic potential.

Discrepancies persist in WEEEp polymeric composition quantification. It is, however, widely accepted that the most common WEEEp polymers are PP, PS, HIPS, ABS, PC, PC/ABS and PA [14, 15]. Table 3 provides an overview of WEEEp polymeric compositions according to various references published between 2013 and 2020. The general uncertainty regarding these compositions is highlighted in [16], in which samples taken from three distinct plants led to very distinct analysis results. In Table 3, note that some authors have reported HIPS and PS under a joint single name. Table 3 summarizes polymeric composition of WEEEp as a whole. WEEEp originating from products that fall in the SHA category tend to contain significantly more PP (see Figure 2 and, for instance, [12, 17, 18]). The SHA stream is also the richest in plastics of all the categories in Table 1. Its total material composition is depicted in Figure 3.

Ref.	PP	PS	HIPS	ABS	PC	PC/ABS
[5](EU)	25%	20%	-	22%	2%	-
[19](EU)	5%	-	27%	24%	-	7%
[15](-)	5%	-	27%	6%	6%	-
[20](-)	8%	3%	25%	30%	10%	9%
[8](Nordic countries)	18%	22%	-	33%	10%	-
[17](DK)(a)	10%	42%	-	38%	-	1%
[17](DK)(b)	1%	11%	-	18%	7%	32%
[17](DK)(c)	15%	21%	-	23%	5%	3%

Table 3: Polymeric distribution of WEEEp. Note that "PS" and "HIPS" are sometimes used interchangeably.

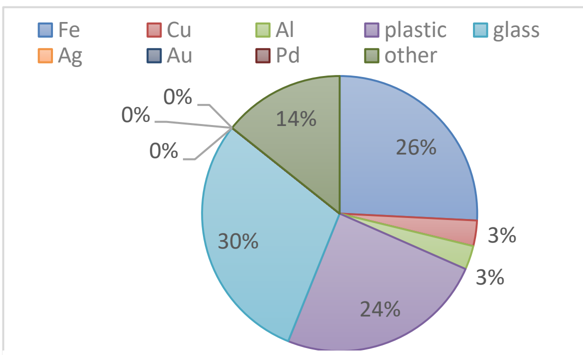

Figure 2. Polymeric composition of WEEEp from the SHA category [18].

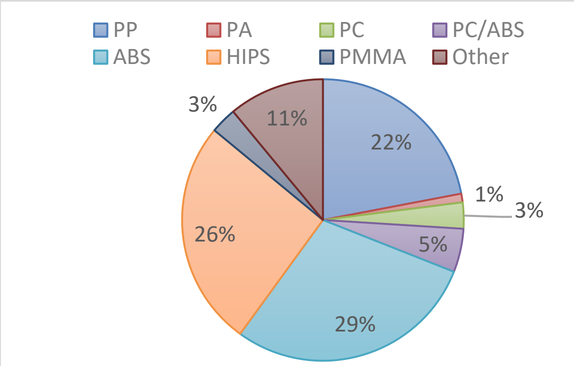

Figure 3. Composition of the SHA category [21]

Annex V of Directive 2012/19/EU prohibits particular brominated flame retardants (BrFR) from entering the EEE market [1]. The mass percentage of plastics containing BrFR in the SHA stream at intolerable levels is estimated to be 4.5% [22]. The only method to detect BrFRs that is generally accepted is X-ray fluorescence (XRF) [8, 14, 22, 23]. Unfortunately, this technique cannot be applied on an industrial scale. Therefore, a detailed account of the role of BrFR in WEEEp is beyond the scope of this article.

3 Mechanical Recycling of WEEEp

3.1 Mechanical recycling technologies

Material recycling facilities (MRFs) are companies that obtain collected waste streams and aim to harvest raw materials from them that can subsequently be sold. The core processes of an MRF revolve around depolluting, size reduction and material separation. MRFs specialized in WEEE typically first target metals using magnetism (for ferrous metals) and eddy currents (for non-ferrous metals), as these are valuable, easy to extract and prevalent (varying from roughly 30w% in SHA to 65w% in LHA [21], see also Figure 3). In consequence, plastics are commonly targeted in later stages of recycling, in the form of electronic shredder residue [14].

The most commonly used separation processes targeting plastics in practice are manual sorting, density-based sorting and spectroscopic methods [14, 24, 25]. Reference [14] is a patent for the theoretical structure an MRF can take on and focusses on electronic shredder residue from WEEEp. This means that other classes of raw materials (e.g. metals) are already removed. Furthermore, the size is already significantly reduced by the shredding operations. Reference [24] is a broad overview of challenges surrounding WEEEp treatment. Reference [25] addresses mainly municipal waste, but the insights carry over to other classes of waste involving large amounts of plastics as well.

Manual sorting is simply the identification and isolation of different materials by MRF employees with a "trained eye". The materials are identified using a code or specific characteristics of the plastics. For this method to be successful, products or components thereof still need to have a recognisable shape and size. Given these requirements, the method is reliable, though typically carried out under poor working conditions. A properly trained workforce can also neatly disassemble products and sort their components, so that contaminations with non-plastics can be avoided at later automated sorting steps. This is particularly desirable as the geometry of many products do not allow for easy mechanical disassembly [26].

Density-based sorting (DBS) methods are, as the name suggests, methods that rely on the difference in density between different materials to separate them. The most straight-forward implementation of DBS is the float/sink method. The density of the medium used in this process is in between that of the materials that are separated, so that the lighter fraction will float, whereas the heavier fraction will sink.

While the float/sink method is very intuitive, some ostensive material properties are directly related to the material's density that can also be exploited. For instance, the settling velocity of materials when put into motion is directly related to their densities. This observation is exploited by the so-called centrifuge [27] and hydrocyclone [28], both installations that create a stirring motion in a liquid in order to separate distinct materials. While the aforementioned DBS methods require a wet treatment, dry DBS methods also exist, such as the dry jig (or shaking table), which essentially is comparable to the float/sink method, but with pressured air as a medium rather than a chemical reagent [28]. Dry separation methods are more energy-efficient as no drying step is required afterwards [25]. As surface shapes can affect floating behaviour and settling velocity, the size of the particles has to be sufficiently small for DBS to be reliable.

DBS methods are among the most cost-efficient and most commonly adopted separation processes in practice [14, 25]. It has also been suggested that DBS can successfully be applied for the removal of brominated flame retardants from a plastic waste stream, as these tend to increase the density of a polymer [23, 24]. A problem with DBS is that densities of polymers are not fixed, but located on a spectrum [29]. This is due to differences in molecular mass (especially in lower quality materials where polymer chain lengths can vary widely), the presence of additives and even small differences in chemical built. Figure 4 shows the density ranges of a wide collection of polymers. Figure 5 shows how these techniques are incorporated in practice.

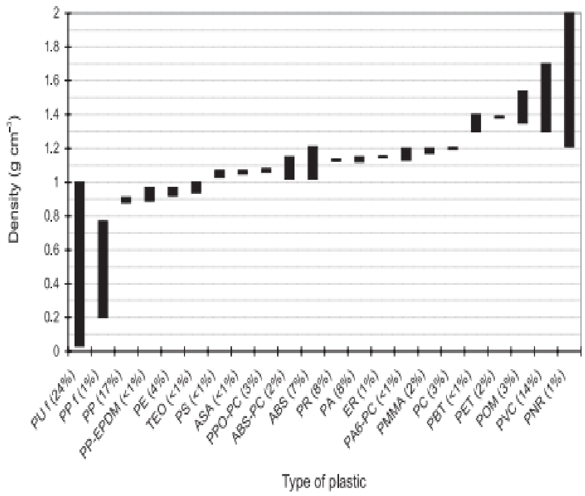

Figure 4. Density ranges of various polymers [29].

Spectroscopic methods use light absorption to determine the polymeric makeup of a sample. Light is emitted on the sample. The frequencies of the absorbed wavelengths are then recorded. The obtained spectra are unique for each material type. By comparing obtained spectra to a library of idealized spectra, an algorithm can quickly classify the sample's material composition. In MRFs, spectroscopy is usually carried out on a conveyor belt. The measurement spectrum of a sample is obtained and analysed while the sample is on the belt. At the end of the belt, the sample ends up in one of two containers; one for the targeted material (for instance, PS), and one for all other materials.

Spectroscopic methods are classified by the range of wavelengths they target. Near-Infrared Spectroscopy (NIR) (targeting wavelengths of 14,300 – 4,000 cm^{-1}) is the most commonly adopted method in practice. Due to the set-up with the conveyor belt, samples have to be sufficiently large to facilitate a realistic throughput. NIR performs poorly for dark-coloured plastics. Furthermore, dust may affect the performance. Each NIR process requires exactly one target material, so that more refined separation requires cascaded interconnections of NIR installations [25]. Estimates of the effectiveness of NIR range from output purities of target materials of 80% to 99.9% [30, 31]. These figures depend on the target material, the other materials present in the mix and colours and other epiphenomenal qualities of surfaces.

Research into alternative separation methods has a long history. Methods relying on surface treatment are sometimes considered promising. Flotation is such a method. It exploits hydrophilic properties of materials [32, 33]. Through a chemical reagent, air particles can be made to attach to specific polymers only, making them float on a liquid (typically just water), while other polymers with a similar density will not exhibit this behaviour and sink. Particular combinations of polymers can be targeted through specific reagents. For instance, sodium lignin sulfonate was shown to be highly effective (with purities of close to or over 99%) for the separation of PP and PE as early as 1979 [34]. To the best of the authors' knowledge, flotation has not yet been widely adopted on an industrial scale. Similarly, electrostatic sorting (sometimes referred to as triboelectrification) is a surface-based method in which distinct materials are separated using the triboelectric series [35].

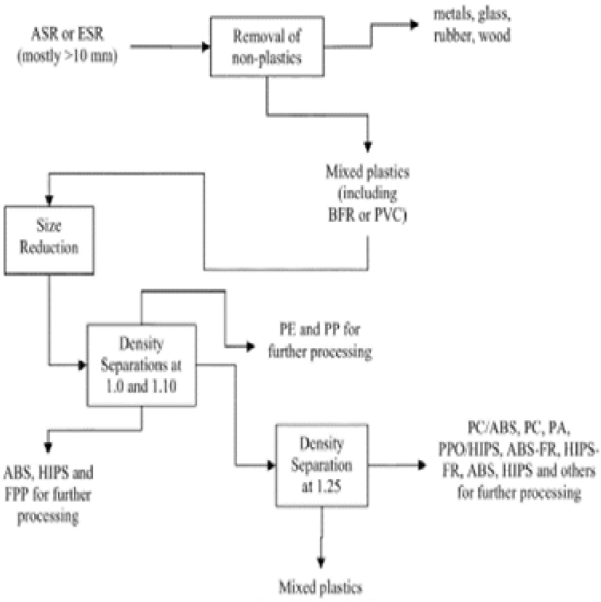

Figure 5. Structure of a material recycling facility [14].

3.2 Optimization of material recycling facilities

Prior research into the optimization of recycling facilities mainly outlines what recycling technologies to apply and in what order for a given input stream of unseparated materials. Optimization objectives reflect key performance indicators (KPIs) of material recovery facilities (MRFs). Notable are the works of Gutowski et al. [36] and Wolf et al. [37, 38, 39]. The graphical representations presented in these works (as exemplified in Figure 6), as well as the linear programming formulations contributed greatly to the study of material recycling facility optimization in an organized quantitative fashion. However, the objective functions

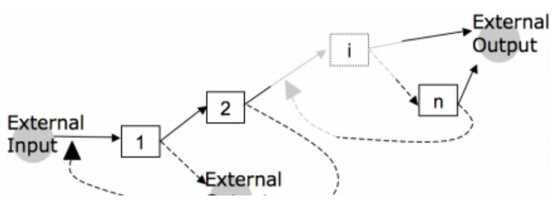

Figure 6. Graphic representation of MRF taken from [38]. Each numbered block represents a mechanical separation process of some MRF. Arrows indicate how waste streams flow through the MRF.

are only proxies of MRF KPIs (total throughput as an indicator of energy consumption; purity and yield in a multi-objective optimization problem as a proxy for profitable output).

In [40], a more realistic objective function was obtained by modelling the unit resale price of a recycled plastic as a linear function of its purity once a fixed purity threshold is reached. This allowed for the optimization of a profit-function that more realistically represents the Pareto-front between yields and purities of sets of output materials. However, this refinement also increased the problem's complexity significantly. In consequence, the MRF optimization was carried out with a meta-heuristic rather than an exact method. The mechanical separation processes are treated in a very abstract manner in the aforementioned references, typically as one fixed matrix of parameters per process. Furthermore, the objective function still cannot accurately reflect the complex WEEEp market, in which factors such as availability and qualitative reliability are perhaps as important as the purity of the involved materials. A detailed account of considerations relating to the WEEEp market can be found in [41, 42].

In [43], a meta-heuristic was proposed that was suitable for optimization of cascaded density-based sorting methods that took into account much more of the actual mechanical process. The method also extended on work by Sodhi et al. [44] to efficiently compute the optimal order of cascaded separation processes, given that their energy consumption is mass-dependent. In [11], this method was extended through the incorporation of heuristics and neighbourhood structures for spectroscopic methods based on the parameters estimated based on [30, 31].

4 Case Study: SHA WEEEp

A case study is presented that assesses the impact of an integrated approach where pre-processors and MRFs further sort sub-categories ("clusters") of the SHA category prior to carrying out mechanical recycling techniques. FTIR analyses of plastic flakes from the three main constituents of the SHA stream (in accordance with [11]) were carried out on 237 samples (printers: 69; coffee makers: 63; vacuum cleaners: 105). The results are depicted in Figure 7. Consistent with the considerations presented in Section 3.1, it is assumed that the MRF relies on manual sorting, density-based separation methods and NIR. Further assumptions are as follows:

- The MRF optimizes its use of sorting technologies through the methods outlined in Section 3.2; output streams of insufficient purity are incinerated;
- Unit operation costs for the operations of an MRF are: 150€/tonne for density-based sorting, size reduction and incineration; 200€/tonne for NIR;
- Each cluster requires a dedicated line; the implementation of such a line incurs a one-time cost of €30,000 with annual set-up costs of €500. Labour cost for the sorting and clustering process is 15€/tonne;
- An additional 180m^2 of industrial space is required for clustering activities and waste storage until a critical mass is reached suitable to undergo treatment (as clusters may be gathered in small volumes). At €125/m^2, this equates to a one-time investment of €22,500;
- The unit resale prices of recycled polymers are as follows (based on [41, 42]): PP: €900/tonne; ABS: €1670/tonne; PC: €2145/tonne; PE: €710/tonne; PS: 400/tonne; HIPS: €980/tonne;
- NIR has a 90% accuracy (in terms of purity) when targeting any of the aforementioned polymers; this estimate includes impurities resulting from NIR's inefficiency when applied to black plastics;
- The experimental results documented in Figure 7 form an accurate depiction of the polymeric compositions of the involved products in the EU in 2020. Likewise, the data in Fig-

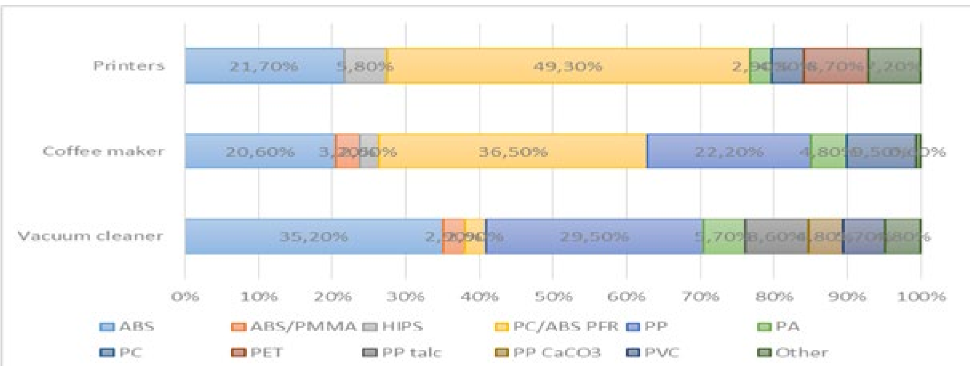

Figure 7. Polymeric composition of most frequent SHA products

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ure 3 are an accurate depiction of the SHA category as well as the “other”-category on the right-hand-side in Figure 1;

- The categories “unknown”/”other” in Figures 3 and 7 are negligible and can be ignored in the computational process;
- When removing products from the SHA waste stream for treatment in a separate cluster, the polymeric composition of the large SHA stream remains unaltered (due to the small percentages in Table 2).

By treating SHA as a whole, a unit profit of €278.32 per tonne of incoming SHA WEEEp can be obtained by applying two steps of NIR, targeting PC and PP and subsequently applying density-based sorting at density value $\rho = 1.05 g/cm^3$. Output materials that do not require incineration under this strategy are PP, PC and ABS. This approach can be outperformed by isolating only vacuum cleaners from the incoming SHA waste stream. This clustering strategy is summarized in Table 4. The unit profit of this strategy is €297.89 per tonne of input waste. The net difference is €19.57/tonne, thus €4.57 per tonne after adjusting for the €15 in additional labour costs for clustering per tonne. Assuming that the throughput of an MRF specializing in WEEEp from SHA is $25 \cdot 10^3$ tonnes per year, the annual net profit becomes €114,250, placing the break-even point in the second quarter after the investment. By isolating the vacuum cleaners, a larger fraction of ABS can be recovered.

	Cluster 1	**Cluster 2**
Products	Vacuum cleaners	Other SHA
NIR targets	PA	PC, PP
Density values [g/cm^3]	1.00; 1.09	1.05

Table 4. Clustering strategy

5 Conclusion

An overview of the status quo in WEEE(p) collection and recycling was provided. This showed that the complexity of polymeric compositions of WEEE categories was significant. The category of small household appliances contains the most plastics by weight and these plastics have to be considered to reach the ambitious WEEE recycling targets put forward by the European Commission. The idea of further stratifying the six collection categories of WEEE at the pre-processing stage to facilitate easier mechanical recycling in a later stage was raised.

Insight into the WEEEp recycling was provided through a survey of available mechanical separation technologies. Manual sorting, density-based methods and spectroscopy proved to be key sorting processes in a realistic, generic setting. Light was also cast on theoretical methods designed to allocate the right processes to the right waste streams, optimizing material recycling KPIs.

These insights were applied in a case study involving the most frequently occurring items in the small household appliances waste category. It was then shown that by isolating one of these items prior to treatment, a recycling facility could improve its performance. Thus, this case study showed in a concrete manner the use of integrating the collection and recycling stages of the WEEEp value chain by means of product clustering.

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Marine Plastic in Electronic Products

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Abstract

Plastic waste has surpassed climate change as the current principal environmental issue. Plastic waste is flowing into the ocean at increasing rates and is the environmental issue individuals feel they can address. Marine Plastic (i.e. plastic retrieved from rivers, oceans, and beaches as part of a cleanup exercise) poses a challenge to recycling due to material degradation from UV rays and other contamination from the collection and cleaning process. In collaboration with material suppliers Microsoft, developed a viable alternative to our current PC/ABS resin that incorporates Marine Plastic. I will walk through the material development and qualification process sharing the issues we encountered and how we solved them along the way.

1 Scope and Definitions

Plastic waste is a growing environmental issue. Every year, about 8 million metric tons of plastic ends up in the ocean. There are now five huge patches of plastic debris covering large swaths of the ocean [1]. The one between California and Hawaii is the size of the state of Texas [2]. Many companies have adopted policies surrounding the use of Post-Consumer Recycled (PCR) plastic materials. In the last 10 years, the technology for PCR plastics have improved and many plastic companies have PCR versions available, that are comparable in mechanical properties, to their virgin counterparts. However, the PCR grade of plastic resins used in consumer electronics incorporates very "clean" sources for the PCR material, such as 5-gallon Polycarbonate water bottles and CDs which are also comprised of polycarbonate.

Marketing campaigns for sustainable products are being published for items ranging from jewellery and clothing, to electronics and cleaning supplies. Based on the limited source of PCR material to be used in electronic plastic resins, the PCR material will become difficult to acquire for a consistent supply chain. These "clean" PCR sources aren't solving the real environmental issue waste plastics in our water ways, oceans and beaches. A small team at Microsoft wanted to challenge plastic resin suppliers to develop a material that incorporated a more difficult PCR material, marine plastic waste. We set a target of leveraging marine plastic waste to create a viable plastic resin, which could be used in a consumer electronic application, in this case a keyboard.

The intent was to integrate the degraded marine plastic waste collected from beaches, waterways, and the ocean(s) into a new resin for use in electronics. For this project, marine plastic (MP) is defined as plastic retrieved from beaches, ocean(s) or waterways as part of a clean-up exercise. The post-consumer recycled plastic resin portfolio controls the quality to function like a virgin plastic resin, but this project was to determine how much contamination or degradation of the recycled plastic material could be integrated and still meet the functional properties for a Microsoft keyboard.

2 Project Overview

Microsoft approached our plastic resin partners with this challenge and were able to engage with four suppliers for the development of an MP resin. Each supplier was challenged with finding a source of MP and develop their own MP-based plastic resin blend. The material properties would be compared to Acrylonitrile Butadiene Styrene (ABS), used in the top case and keys, and high impact polystyrene (HIPS), used in the bottom of a black wired ergonomic keyboard. Due to time constraints, moulding trials for each of the developed plastic resins would take place on the existing ABS/HIPS tooling respectively while the end product would be compared to the standard ergonomic keyboard moulded with original plastic resin.

2.1 Establishing a baseline

The selected keyboard device for this project is currently in production and thus the baseline plastic material properties and tooling data were leveraged to engage with the plastic resin suppliers. The first step for each supplier was to work with the Mechanical Engineering team to select a standard plastic resin grade from their current portfolio to establish a baseline. The MP material identified for this project was the PET, thus the MP blend from each supplier would also be a Polyethylene terephthalate (PET) based plastic resin material, which has significantly different properties than ABS and HIPS. The intent of the supplier proposing a standard PET-based plastic resin material from

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their current portfolio was to troubleshoot a known material and its properties before adding another variable to the equation in the form of MP. The supplier selected grade of plastic resin was then used in a moulding trial to determine compatibility with the existing tooling which was designed for ABS/HIPS.

The first trial conducted in December was intended for the suppliers to try their standard plastic resin material in the ABS/HIPS tooling. By doing this, they could determine which of their plastic resins moulded best as a baseline and could be used as a base for the MP PET blend. Only two suppliers conducted moulding and reliability trials in December on their baseline resin. The other two suppliers conducted their baseline trials as part of a moulding trial in March.

The testing identified for this project, to determine how the plastic resin material performs compared to ABS/HIPS, included testing the performance and moulding capability in areas such as durability, material properties, and chemical compatibility.

All results for these baseline resins can be seen in Table 1 below.

Supplier	**1**	**2**	**3**	**4**
PET Blend	PC	PBT	ABS	PC
Top	Shrink & stress marks	Shrink marks	Shrink & stress marks	-
Bottom	Gate & stress marks	Gate marks	Gate & stress marks	Unable to mould
Tilt	-	-	Gate & stress marks	-
Palm Rest	-	-	-	-
Keycaps	-	-	Stress marks	-

Table 1: Baseline resin inspection notes after moulding

Based on the results shown above the baseline plastic resins displayed cosmetic issues such as stress marks, gate marks, and shrink marks during moulding. Reliability wise, the three suppliers that were able to produce enough samples for the trial saw spacebars popping out and tilt pillars broken during drop, as well as key abrasion failure after thousands of cycles. In addition, there were some chemical failures when substances, such as sunscreen, were applied to two of the samples. The failures were noted as part of the baseline but not a huge concern moving forward. Finally, two of the samples can attribute their failure due to shrinkage in the mould which was expected based on the material properties and the moulding tool being designed for different material properties. Despite the cosmetic and reliability issues seen the suppliers were comfortable moving forward with the baseline results demonstrating their material could be processed through the existing tooling moulds.

2.2 Incorporation of Marine Plastic

Once the partner plastic resin suppliers determined the appropriate PET-based material, and Microsoft had completed the baseline moulding trial, it was clear that the tooling should be designed for the PET-based resin properties if this was to be implemented in a production environment. However, with this in mind we proceeded with the project to document the viability of the MP material, in the ABS/HIPS moulds, based on the comparison with the baseline data established. As a parallel activity during the baseline trials each of the resin suppliers were challenged to identify and source MP, essentially establishing their respective supply chains, for this new material being developed.

Due to challenges faced by the resin suppliers in identifying and sourcing the MP material, Microsoft assisted by partnering with an MP supplier and sourced the MP material to as an option for the resin suppliers to use for this project. The MP supplier Microsoft partnered with has a standard MP material and supply chain which supplies pelletized MP PET (a PET material which is a blend of 50% curbside recycled and 50% MP). Each supplier was allotted enough MP-PET from this MP supplier to incorporate into their plastic resin blend. The project parameters set by the Microsoft team specified the final material must consist of a minimum of 10% MP content.

The following two trials would act as an opportunity to incorporate the MP-PET into the baseline plastic resin, and secondary moulding trials to adjust the formulation as needed. A final (fourth) moulding trial would be reserved for July to build a large number of keyboards for extensive reliability testing of most promising MP plastic resin.

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3 Technical Findings – First MP Trial(s)

All four plastic resin suppliers approached the task of developing a mouldable resin differently. The majority of the plastic resin suppliers leveraged the technical knowledge and experience of mechanical recycling, but that is where the similarities end.

- Supplier 1 utilized straightforward mechanical recycling with a Polycarbonate (PC) based resin but found their own source of 100 percent marine PET as opposed to the 50/50 from the MP supplier provided by Microsoft.
- Supplier 2 chose to develop their resin using a chemical recycling process and sourced their own marine PET.
- Supplier 3 utilized the 50/50 blend from the MP supplier provided by Microsoft in an ABS blend but chose to add additional curbside recycled PET to increase the overall recycled content of the material.
- Supplier 4 chose to use just the provided 50/50 blend from the MP supplier provided by Microsoft in a PC material through mechanical recycling.

Supplier	1	2	3	4
MP PET Blend	PC	PBT	ABS	PC
Drop	Fail	Fail	Fail	-
T0 Rocking	-	Pass	-	-
Thermal	-	Fail	-	-
Key abrasion	Fail	Fail	Pass	-

Table 2: Reliability test results for plastics containing marine content

Out of the parts moulded, the bottom case proved to be the most challenging with only the chemically recycled PBT material able to be moulded, most other test devices were moulded with HIPS for testing purposes. It is believed that this is due to tooling design and flow properties of the MP material(s). Supplier 4's PC mechanically recycled material had the most issues throughout the trial and, as a result, no devices were built for reliability testing. On the other end of the spectrum, Supplier 2's chemically recycled PET/PBT blend was the easiest material to mould in the current tooling, closely followed by Supplier 3's ABS/PET blend with additional curbside recycled PET.

3.1 Tool compatibility

Throughout the trials, all the plastic resin suppliers saw issues moulding their MP resin blends with the tooling designed for ABS/HIPS. One of the most evident issues was the material sticking to the mould. In some cases, a mould release agent had to be used every time to allow the removal of the moulded parts. To remedy this, the moulder suggested that the plastic resin suppliers add more mould release additive to their MP resins for future trials.

Figure 1: Examples of moulding issues and failures due to tooling

3.2 Cosmetic Issues

There were also issues with cosmetics, such as weld marks, sink marks, gas marks, and drag marks. These marks were expected due to the MP source is heavily contaminate and the tooling was not optimized for the resins trialled, the cosmetic issues are less of a concern to the viability of the MP resin. Looking at the reliability results there were other issues with MP moulded parts as well, such as keys popping out during drop (likely due to shrinkage), chemical, and abrasion. However, the issues reported with the MP resins were similar to the baseline trial issues performed in in the initial phase of the project.

Figure 2: Examples of cosmetic issues due to material processing

4 Material Reformulation and Additional Trial(s)

After the initial MP moulding trials and reliability testing, the plastic resin suppliers were asked to optimize their MP materials for an additional moulding trial. To accurately assess the feasibility of MP plastic blends in the identified keyboard project the results from the May trial (MP material) need to be compared to the baseline testing completed initially on the virgin resin. The tables below show the differences between each plastic resin that can be attributed to the incorporation of MP material. *Note: Supplier 4 has been removed from future Table(s) as they were unable to mould parts successfully in either of their trials*

The Tables 3 and 4 show that the moulding and reliability impact due to the incorporation of MP PET throughout the three plastic resin suppliers would not result in a drop-in replacement for the original resins which the tools were designed, nor be able to pass Microsoft standards. Specifically, there are higher portions of the part sticking to the mould, drag marks, gas marks, ejector pin marking, material processing differences, and mechanical part compatibility. Some samples showed differences in rocking and thermal cycling, and the material flow properties were not compatible with the tooling and manufacturing process for the ABS/HIPS tooling. Overall, the plastic resins incorporating MP PET were more difficult to mould than the baseline resins, especially the mechanically recycled resins, and demonstrated differences in material properties such as higher rates of shrinkage which resulted in a more brittle material. This brittleness is more evident in the selected product design because the tools were tailored to the ABS/HIPS moulding properties, i.e. thin walled parts, which can be compensated for if the tooling was designed with the PET-based resin properties.

	Supplier 1	Supplier 2	Supplier 3
Blend:	PC + MP PET Mechanical Recycled	PBT + MP PET Chemically recycled	ABS + MP PET+ Additional Curbside PET Mechanically recycled
Top Case	Drag Marks, Ejector Pin Marks, release agent used every shot	Drag marks	Drag Marks, release agent used every 3 shots
Bottom Case	Alternative PCR resin used	Breakage on Tap, sink marks	Alternative Resin Used
Front Tilt	Gas Mark, Weld line	Shining mark	Gas mark
Palm Rest	Part sticking to mould	Marks showing, but not a cosmetic part	Marks showing, but not a cosmetic part
Keycaps	Sink marks, gas marks, stress marks, high shrinkage	Part sticking to mould, sink marks	Sink Marks

Table 3: Mould comparison results

	Supplier 1	Supplier 2	Supplier 3
Blend:	PC + MP PET Mechanical Recycled	PBT + MP PET Chemically recycled	ABS + MP+ Additional Curbside PET Mechanically recycled
Drop Test	More tilts broken and spacebar pop out than baseline	More Spacebar pop outs than baseline, no tilts broken	More space bar pop outs than baseline
T0 Rocking Measurement	N/A (Bottom case not moulded)	Pass (Baseline did not pass)	Good on corners, middle out of spec (Baseline passed)
Non-Op Thermal Cycling	N/A (Bottom case not moulded)	Failed at 100 Cycles due to excessive rocking (baseline also failed)	Pass
Key Abrasion test	Failed (Same as baseline)	Failed (Same as baseline)	Pass (baseline resin not tested)

Table 4: MP reliability testing results

4.1 Comparing Material Properties

Based on the trials conducted on the various MP PET resins, and compared to the baseline materials, the MP based PET resin displayed a higher rate of crystallization and degree of crystallinity when compared to traditionally recycled PET. The reason for this is still unknown and we suspect it may be attributed to the contamination and UV degradation of the MP PET incorporated into the MP blend in place of curbside recycled PET. In addition to the contamination or degradation theory, the MP PET was subjected to additional processing in order to be pelletized prior to transportation from the MP supplier collection point to the plastic resin supplier, palletization is a requirement due to the plastic waste transportation restrictions under the Basel convention.

5 Challenges

There were many challenges faced during this project that should be highlighted as they are relevant to many trying to implement recycled materials, including MP, into an existing product or supply chain.

5.1 Tooling

One challenge that became evident during the moulding trials is that the tooling needed to process this material did not match the ABS/HIPS tools that were designed for the product selected. PET is not commonly used in electronics but is the most abundant in the MP waste environment. We attempted to formulate a drop-in replacement using the existing moulding tools which were designed for different material properties. Because of the higher crystallization rate of PET the product design should include designing the tools to be compatible with the intended material for the best results. Many of the cosmetic and reliability issues, such as marks, higher concentration of mould release agent, mould flow issues, and brittleness may have been averted if the product design and tooling was tailored to the PET material properties. All four plastic resin suppliers were confident that they would be able to mould all required parts without issues if the tooling was customized for their material properties.

5.2 Material Consistency

The MP feedstock within the MP blend will vary based on where and when it is collected, how is it cleaned, and the level of material degradation depending on how long it was exposed to UV rays before collection and processing into the MP resin. Due to the variability of the MP feedstock the recycled MP PET resin will have inconsistent material properties as well which may result in a higher defect rate during a product mass production cycle.

The largest concern that comes with this MP feedstock is the variance of UV degradation, resulting from the MP feedstock sitting in the sun for long periods of time. This UV degradation breaks down the polymer chains within the PET and can lead to a weaker MP feedstock, and consequently a weaker MP material. The amount of degradation in each lot of MP feedstock is difficult to predict, and this is the reason that the Microsoft MP supplier stabilized their MP PET material with 50% curbside recycled PET in addition to the MP feedstock to achieve a consistent quality for the MP PET material.

5.3 The Basel Convention

The Basel Convention is an agreement involving 187 countries that restricts transboundary movement of specifically listed waste. In this case the MP PET feedstock, cleaned and “flaked” MP PET, was covered by the treaty and therefore could not be moved transboundary from the collection source to the plastic resin supplier until it was in pellet form. Because of the restriction on transboundary movement of plastic “waste” the collection and palletisation of MP feedstock must be done prior to shipping. This sets limits on where MP waste can be collected and processed if it is to be integrated into the plastic resin directly, ideally the collection and processing of the MP feedstock would be in the same country as the plastic resin supplier’s facilities. As a result of the restrictions implemented by the Basel Convention, the MP feedstock supply for this project was limited to sources that were already pelletized, or in the plastic resin supplier’s region, and thus could be transported to the plastic resin supplier’s facility for formulation purposes.

5.4 MP Material Sourcing

Because of the process involved in collecting, sorting, cleaning, pelletizing, and shipping the MP feedstock there is a cost associated with each of these processing steps. The aforementioned processing of the MP PET feedstock resulted in a cost 10-15 times that of curbside recycled PET materials. It is possible that with a more efficient process, and more localized collection partners, that the material could reach cost parity with curbside recycled materials at some point in the future

6 Summary

The results indicate that a viable MP resin is possible even though there were reliability concerns with the MP blends attributed to the tools being optimized for an amorphous thermoplastic as opposed to semi crystalline. All four of the resin suppliers that participated in this project were confident that with the correct tools they would be able to produce parts that would pass Microsoft reliability requirements.

Beyond the feasibility of the material properties there are additional concerns with a new material and supply chain regarding the continuity of the supply chain. The MP feedstock was very difficult to source and the MP feedstock volume was not sufficient for the mass production associated with a consumer electronic device. The tooling could be specialized for the MP blend but the continuity of the MP feedstock supply chain, and consistency of the material, are still a significant risk and any disruption in the supply chain would be detrimental to the production facilities and throughput. There is no denying the MP feedstock is available and sadly abundant, but the retrieval of the MP feedstock still must mature to support the mass production of a MP blend in a mass production scenario.

In summary, based on the technical findings of the trials, MP blend are a viable resin for electronic devices when accounted for in the design stage. Ideal opportunities for the MP blended resins, while the supply chain matures and develops, include non-cosmetic and high tolerance parts or products that do not require strict mechanical, cosmetic, or chemical tolerances. Additionally, small parts, or parts with low production numbers are the most viable due to the high cost of this material and developing supply chain in order to ensure the continuity of MP blend resin throughout the product production cycle.

Figure 3: A keyboard made with plastic resin containing approximately 10% MP

7 Literature

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Grading system for post-consumer recycled plastics from WEEE

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Abstract

Recent years, the European Commission has been fostering a transition to a circular economy for plastics. To increase the use of recycled plastics, manufacturers are requested to develop new supply chains and find new sources of secondary materials. In this research, a grading system is presented to facilitate and to stimulate the international trade of post-consumer recycled WEEE plastics between recycling companies focussing on the pre-processing and recycling companies focussing on the compounding, as well as between recycling companies and original equipment manufacturers, either directly or through an online trading platform. Two main phases involving 3 stakeholder groups where the grading system should be applied in the supply chain are identified: the phase between pre-processor and plastic recycler, where plastics are exchanged in form of mixed plastic flakes and the phase between plastic recycler and product manufacturer, where recycled plastics are present in form of granulates. Interviews with industry experts representing different phases of the plastic value chain were conducted to determine relevant grading criteria for mixed plastic flakes and plastic granulates. Based on their responses, the key criteria are identified and summarized in a three-pillar model in the following three categories: quality, reliability and availability. These three pillars are considered to support a harmonized and transparent communication in the value chain by providing a defined set of relevant criteria that can be used for grading by the downstream stakeholders.

1 Plastic recycling: Value chain and re-application

The European Strategy for Plastics in A Circular Economy has the objective to develop markets and to boost the demand for recycled plastics [1]. Today, this demand is estimated at only 6 wt% of the plastics market. According to the European Commission, one of the reasons for this low demand is the uncertainty whether recycled plastics will meet the needs of Original Equipment Manufacturers (OEMs) for a reliable, high-volume supply of materials with constant quality [1]. The requirements that a plastic needs to fulfil are mostly defined by OEMs, governments or by the European Union [2], [3]. To ease the search for suitable materials, quality needs are translated into material requirements and in this process thresholds are mostly based on virgin plastics [4]. No general definition of quality for recycled plastics exists and measurable quality requirements are strongly dependent on the final application [5], [6]. For this reason, recyclers have the objective to produce recycled plastics at highest possible quality to satisfy customers and to increase value, while considering the trade-off every recycler needs to make between the yield and the purity, which strongly influences the plastic quality. Making proper trade-offs is also challenging due to the long chain of different recycling processes and multiple actors in the value chain, which can be categorized in seven phases:

(1) Collection: Collection of End-of-Life products

(2) Pre-Processing: Main focus is decontamination

(3) Metal Sorting: Separation of metals for recycling

(4) Plastic Sorting: Separation of mixed plastics into single plastic streams

(5) Primary Compounding: First compounding step (e.g. melt filtration, additives)

(6) Secondary Compounding: Special compounding (e.g. glass fibers) or blending with virgin

(7) Product Manufacturing: Production of a plastic component

The definition and order of the phases in the supply chain is based on common European WEEE processing operations. Typically between 3 and 6 stakeholders are involved and some phases might be skipped or performed by the same company. For example, some cover the entire process from pre-processing up to primary compounding, whereas others are not involved in

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the pre-processing and metal sorting and only buy a mix of plastic flakes as an input material for their sorting and compounding processes. However, since large recyclers are often supplied with additional input material for their processes by pre-processors or metal recyclers and because the different phases are in some cases performed at different sites, the seven different phases are considered relevant for most recycling companies. Only, the secondary and more specialized compounding is not always part of the value chain and if applied this is mostly carried out by specialized companies. It is also possible that OEMs conduct secondary compounding to blend recycled plastic with virgin prior to the reapplication in new products. Most commonly trade and material exchange takes place between the phases 2-4 or 3-4 (Pre-processor/metal recycler – plastic recycler) in form of mixed plastic flakes and between 5-7, 5-6 or 6-7 (plastic recycler – OEM) in from of plastic granulates.

In parallel to this research the Plastics Recyclers Europe publish bales guidelines for plastic flakes from WEEE and ELV. The guidelines cover most of the criteria determined in this research for mixed plastic flakes, but also do not mention standards for testing and no certification schemes for the reliability of companies is indicated. This paper presents a grading system for mixed plastic flakes and recycled plastic granulates based on an industry survey which serves multiple purposes. First, the system aims to increase the trust of manufacturers in the abilities of recycled plastics to fulfil high-quality requirements and replace virgin plastics without compromises. Second, it aims to increase the trade of recycled plastics while improving communication and transparency among the stakeholders in the supply chain.

2 Materials & Methods

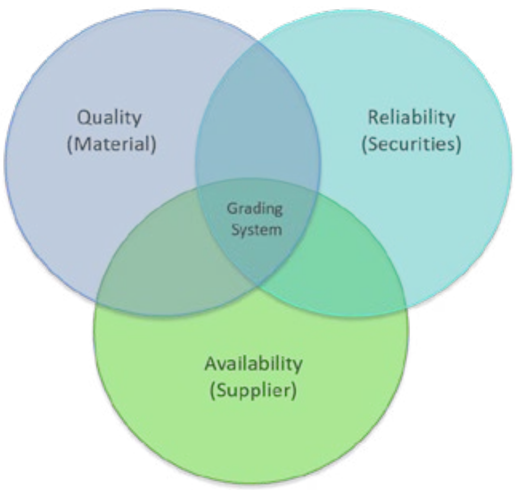

Figure 1: Grading system with the three pillars quality, reliability and availability

The research of this paper focuses on the mechanical recycling of WEEE plastics, which are mainly PS, ABS, PC/ABS and PP. An unstructured list of relevant criteria that should be included in a grading system for recycled plastics was developed within the Horizon 2020 PolyCE project with partners in brainstorming sessions. Afterwards, these criteria were clustered and integrated in a 3-pillar model with the following categories: quality, reliability and availability (Figure 1). Subsequently, surveys with industry experts were carried out in the format of one on one interviews to improve the definition and to prioritize the relevant criteria. For criteria for mixed plastic flakes 5 recyclers and for recycled plastic granulates 5 OEMs and 2 recyclers were interviewed.

The interview results were summarized and criteria that were considered too specific and only relevant for a specific application, too costly to perform the required tests were excluded. However, criteria that are not suitable to be included in the grading system, but could be of significantly added value are discussed in this paper. The remaining criteria are presented and interpreted in this paper and form the basis for a uniform grading system for recycled plastics.

3 Results and discussion

The results of the interviews with industry experts on most relevant criteria for a uniform grading system of traded recycled plastic granulates and flakes are summarized in Table 1.

3.1 Grading system for mixed plastic flakes

In the context of this research, mixed plastic flakes are mostly produced by pre-processors and in some cases a separated fraction in metal recycling. Trade of mixed plastic flakes is done with plastic recyclers that use them as input material in their recycling plants.

3.1.1 Quality

For recyclers, the most important quality criteria of mixed plastic flakes are related to the material composition (wt %): type of plastics, the presence of contaminants that could cause problems in the recycling process; and the presence of fillers in the plastics. Combined with physical characteristics, such as flake size and fines content, this information allows recyclers to predict the expected yield of their recycling process [7]. The colour composition was only considered relevant by recyclers that have colour sorting in place, which allows them to separate the white plastics with higher economic values. Another major criteria is the presence of bromine, which should be lower than 2000 ppm to be considered "bromine free" and is mostly related to flame retardants, some of which are subject to substance regulation such as RoHS and REACH. Most

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WEEE recyclers have systems in place to remove plastics containing brominated flame retardants which results in lower yields. Furthermore, mixed flakes containing brominated flame retardants can be considered hazardous waste, which is subject to difficulties in waste shipment (especially cross-border) and can require the recyclers to possess specific permits to treat it. In addition to the bromine content, also the communication of cadmium, lead, mercury and chromium (RoHS directive [8]) are encouraged.

Recyclers have also indicated that the source of the mixed plastic flakes could help them estimate material compositions, expected yield and potential quality threats. The source could be given at sector level (e.g. WEEE, automotive, household waste or packaging) and at collection category level (e.g. small household appliances, large household appliances, etc for WEEE) and if possible even at product level (fridges, freezers, etc.).

The processing history should indicate which of the following main processing steps have been applied: The processes that should be indicated are decontamination (EN 50625), size-reduction, magnetic-, Eddy-current-, sink-float-, colour-, electrostatic-, spectroscopic-sorting. This is complementary information with the material composition, but is considered helpful for recyclers to estimate the quality of the mixed plastic flakes.

Table 1: Overview of most relevant criteria for plastic granulates and flakes to be considered in a grading system for trading

Flake		**Granulate**	
Quality		**Quality**	
Material composition	**Standard/Legislation/Declarations**	**Properties**	**Standard/Legislation/Declarations**
Plastic types	wt% Estimation	Colour	ISO 11664
Metals	wt% Estimation	Flexual Modulus	ISO 178
Rubber	wt% Estimation	Tensile Strength	ISO 527
Glass, Ceramic	wt% Estimation	Strain at Break	ISO 527
Wood, paper	wt% Estimation	Charpy impact strength - notched	ISO 179
Foams	wt% Estimation	Density	ISO 1183
Other materials	wt% Estimation	Melt flow Index	ISO 1133
Presence of Talc/CaCO3 /Glass fibre fillers	wt% Estimation	**Compliance**	
Size		REACH	1907/2006/EC
Fines<3mm	Sieving	*if applicable*	
Size	Estimation (shredder screen dimensions)	*RoHS*	*2011/65/EU*
Compliance		*Toy Grade*	*EN 71*
Bromine content	EN 14582	*Food contact recycled plastics*	*1935/2004/EC*
Waste Stream		**Environmental**	
Source composition	WEEE/Automotive/..	Recycled content	UL 2809 or EN 15343
Collection categories (WEEE directive)	LHA/SHA,…	Origin	Post-consumer/Post-industrial/virgin
Processing History		**Other**	
Main processing steps	Decontamination/size reduction/magnetic-/Eddy current-/sink-float-/colour/electrostatic-/spectroscopic-sorting	Target Process	Injection moulding/Extrusion/..
Other			
Picture of mixed plastic flakes			
Reliability		**Reliability**	
Use of international standards	EN/ISO/UL/..	Use of international standards	EN/ISO/UL/..
Quality Management		**Quality Management**	
ISO 9000	Certificate	ISO 9000	Certificate
ISO 14001	Certificate	ISO 14001	Certificate
WEEELABEX	Certificate	EUCertPlast	Certificate
Availability		**Availability**	
Supplier name and address		Supplier name and address	
Region of availability		Region of availability	
Production scale		Production scale	
Sale	Spot/contract	Sale	Spot/contract
Form	Granulates/flakes	Form	Granulates/flakes

Finally, a picture of the mixed plastic flakes could be included. Beyond the colour and size of the mixed flakes, a picture was considered by the interviewed experts to also deliver information on possible contaminants, as well as on how the material is stored.

<u>Determination of quality criteria for mixed plastic flakes</u>

The determination of the material composition in the grading system is based on estimations by the supplier. The recyclers indicated in the interviews that testing would be beneficial, especially to determine the types of polymers and bromine present in the mixed flakes, but did not consider it a necessity. High costs of testing and the need for reliable sample taking procedures are seen as the main reasons why the material composition should be estimated rather than tested. Estimations can be done by visually inspecting the material, based knowledge of typical compositions based on the origin of the material or experience. In addition, the declaration of main processing steps that were applied to the material, this can give a good representation on the expected composition.

However, testing of the material composition can provide more detailed information, as well as a higher certainty in the composition data and is, for this reason, highly encouraged. To assure representative results the sampling procedures are crucial. Examples for representative sampling are given by Gy et al. [9]–[13]. For the specific case of sampling WEEE there are several working protocols and standards mentioned in the WEEELABEX documentations, such as EN 14899.

The only quality criteria that requires a measurement is the presence of bromine (and other RoHS restricted elements), which cannot be estimated. Handheld XRF scanners have been reported as suitable field-equipment for bromine determination and some bromine determination procedures are described in WEEELABEX documentation [14].

A cheap and practical technique to estimate the mixed flake composition is to test the weight of material that sinks or floats in selected density ranges. These results of estimated composition per density range could be communicated in addition to the total estimated material composition. However, no standard procedures are known to the authors.

Research showed that automated testing by manual composition analysis, FTIR, XRF and computer vision allows to analyse the types of polymers, presence of some fillers, presence of RoHS restricted elements, the amount of metals, glass, wood, and other materials [7]. While today such analysis could be performed by third-party testing institutions, they are still quite labour intensive and expensive and further research is required to enable a higher degree of automation of the testing to increase the economic viability of better and more systematic testing.

3.1.2 Reliability

In general, two levels of reliability can be defined, the reliability of the material or consistency on the indicated quality and the level of the recycling company's reliability or trustworthiness. The reliability criteria for mixed plastic flakes are similar to those for the plastic granulates, including both material and company reliability. Due to a higher heterogeneity at flake level, the variation in material properties is of even higher importance. To deliver information on the variation of composition data, systematic testing would need to be in place, which is currently not the case. In addition to the testing, the importance of proper sample taking procedures is of high importance to overcome the heterogeneity and provide reliable information on material properties to the recycling companies.

As for the reliability of granulates, also for the mixed plastic flake the use of international standards and proof of quality management systems in place are indicators to be included in a grading system to cover the company reliability of pre-processors. Declaring the possession of ISO 9000, ISO 14001 and WEEELABEX certificates are considered to be of value to increase the trustworthiness and to give an indication on the companies ways of working. In the future, it should be investigated if background checks (e.g. VAT number, law clearance certificates,..) could be suitable measures to be included in a reliability grading.

3.1.3 Availability

Most recyclers are looking for long-term suppliers of material and try to build up reliable sources for their processes. For the recyclers, the amount of material available is valuable information so they can exclude suppliers with insufficient volumes for their application needs. However, the production capacity (tonnes available per month/year) is considered sensitive information for recycling companies. Nevertheless, companies are highly encouraged to provide information on the availability of recycled material, now and in the future. In the meanwhile, different types of offers, such as single spot or contract offers can already give an indication on whether the material is only offered at the moment or if long-term purchases are possible. Furthermore, recyclers indicated the value of information on the supplier name and address, as well as the region where the material will be available.

Pre-processors producing mixed plastic flakes are encouraged to provide information on requirements for reporting of the suppliers, which can be needed based on national law or for audits. One example is the declaration of the percentage of plastics that can be recycled and the percentage that will be incinerated or documentation confirming the ability to treat mixed plastics with bromine. A major difference of mixed plastic flakes is that the region of availability is influenced by waste shipment regulations. Depending on national law, mixed plastics can be seen as waste, which influences shipment procedures and permits.

3.2 Grading system for plastic granulates

Recycled plastic granulates are produced by plastic recyclers and mostly subject to trade between the recyclers or distributers and OEMs.

3.2.1 Quality

Based on the interview findings, most OEMs do not differentiate between quality criteria of recycled plastics and virgin plastics. Many properties mentioned by OEMs (Table 1) can already be found on most datasheets provided by recyclers. However, previous research showed that these basic properties are not able to adequately answer application specific quality needs of OEMs and physical application testing is always needed to make a final decision in a material selection process [4]. In addition, the following properties were considered important, but only for specific types or applications: Shrinkage (ISO 294), tensile stress at break (ISO 527), tensile strain at yield (ISO 527), heat deflection temperature (ISO 75), filler content (and filler type) (ISO3541/D5630) and flammability rating (UL 94). Next to material properties, the declaration of one or more targeted processes of the plastic, such as injection moulding, extrusion, thermoforming,.. should be declared by the material producer. Further, communication of pictures showing application cases in which the material was used, was requested by the OEMs to give a better impression on the quality. While most OEMs supported the idea, recyclers indicated that they would rely on approval of OEMs, which is why the communication of such pictures can only be voluntary and not included in a grading system. Compliance to substance regulations like REACH and RoHS (in the context of WEEE plastics), was considered of major importance by OEMs. This can be interpreted as mistrust in the quality, as described by the EU [1], because also virgin plastics need to comply to these substance legislations.

Next to the recycled content and origin from post-consumer or post-industrial sources, the OEMs also expressed the need to be informed about the environmental advantage for their products of using granulates from recycled plastics. Quantifying such environmental benefits is not straightforward for a number of reasons. First, the benefits of secondary resources are generally shared between different product systems: the one generating and the one using the recycled material. However, the appropriate allocation remains a topic of discussion among most LCA-practitioners and clear rules are necessary to avoid double counting. Second, limited data are available related to the potential quality losses or the substitutability of recycled material for virgin material which would allow to compare their performance for a specific functionality. Third, in practice, the granulates will not be produces from 100% recycled material but the maximum allowed recycled content will depend on the quality of the recycled flakes used to produce the granulates.

"Circularity" which can be defined as the ability to conserve both the quantity and the quality of the material is another measure that could be used to describe the contribution of the recycled granulates to a more circular or less resource intensive economy. For example, the content of recycled material used could be calculated with the 'upstream' circularity measure from the UL 3600 standard [15]. However, it should also be emphasized that a completely circular product is one that is produced from recycled materials and that is designed to be recycled.

3.2.2 Reliability

When recycled plastics are purchased by OEMs, reliability is the most important topic they want to be informed about. This reliability information can reduce the mistrust and misbelieve of many OEMs that recycled plastics are inferior in quality compared to virgin plastics. The survey showed that international standards should be used for testing and declaring the criteria. In addition, statistical data to reflect the inherent variability of material properties would significantly improve the ability to manage the risks associated with using recycled plastic in a reliable way. However, this information is considered confidential by recyclers and is only communicated in exceptional cases to long-term customers. Nevertheless, quality testing by independent institutions is highly encouraged as it increased the trustworthiness of the declared criteria for many OEMs. However, as many recyclers possess the capabilities of testing material properties according to international standards and because third-party testing will entail additional costs, a criteria for third party testing is not included in the grading system.

On company level, OEMs that want to use recycled plastic in their products are confronted with entirely new and significantly smaller companies compared to the virgin producers. The communication of quality management systems in place is seen as a suitable measure to support the reliability on company level. In addition, certifications, such as ISO 9000, ISO 14001 and EUCertPlast, increase the trustworthiness in the manufacturing practices of recyclers. As this is considered important for many OEMs, a reference to the according certificates should be included if available.

3.2.3 Availability

The criteria for availability for recycled plastic granulates do not differ significantly compared to mixed plastic flakes. In contrary to flakes, the OEMs are both interested in spot and in contract sales, depending on the company and application.

3.3 Grading system

The aim of the surveys was to define criteria relevant for grading in a systematic and uniform context for WEEE plastics recycling. The grading system is intended to establish first points of contact for trade. The establishment of long-term contract relationships between stakeholders might require more detailed information and additional criteria.

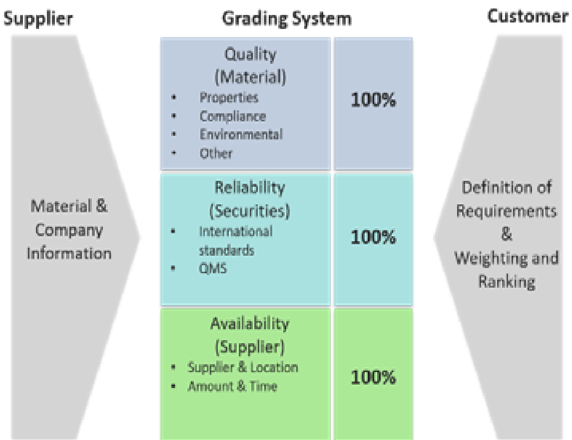

Figure 2. Grading system for the communication between supplier and customer.

The system defines a set of criteria for the communication between the supplier and the customer in the plastics recycling supply chain (Figure 2). A 3-pillar structure categorizes the defined criteria and results in a qualitative overview in form of a percentage of information that is actually provided. This forms the basis for actual grading by weighting and ranking of the criteria in function of the defined quality requirements of a downstream stakeholder. This approach is necessary as quality and availability requirements strongly depend on the specific company and application needs. At the same time, a structured and harmonized communication of the most relevant criteria to make a material pre-selection is necessary.

Different types of grading were considered, shown in an overview in Table 12. Grading by a star rating is considered an alternative for the percentage grading of the information provided. Both deliver a simplified information without any weighting or ranking required, which could induce bias. In addition, the amount of criteria that can be included are unlimited, which allows the grading system to be extended. The use of an ABC grading or the traffic light model require ranking into good or bad property values. The use of more complex grading, such as the honeycomb-star model or the circle diagram, which are often found on food packaging, are a good way to convey a limited amount of criteria. However, in the view of the authors the criteria for recycled plastics cannot be limited to an amount that would be suitable for this kind of grading.

Table 2. Overview of grading types.

System	Simplification	Criteria-Weighting	Amount of criteria
Star rating	high	no	unlimited
Percentage	high	no	unlimited
ABC grading	high	yes	unlimited
Traffic light model	high	yes	unlimited
Honeycomb-Star-model	medium	yes	limited
Circle diagrams	medium	yes	limited

4 Conclusions and future work

Surveys with OEMs and recyclers showed that the reliability of the material and supplier are a major concern to engage with new suppliers. The experts interviewed indicated that the use of international standards and quality management systems allows to improve the reliability of companies and future research should further investigate measures that can support the transparency and availability of information in the supply chains of plastic recycling. Therefore, a grading system is developed and presented in this research, which compiles a set of criteria and related standards that are considered relevant for trading with unknown suppliers. Due to various application and company specific requirements, the percentage grading of providing the defined criteria is chosen over other grading options for a uniform grading system for recycled plastics. The grading system can structure and harmonize the communication in the plastics recycling supply chain. Quantitative grading requires weighting or ranking of criteria and can only be done for a material or application specific context.

The interviews highlighted that the origin of the material plays a key role for the estimation of the expected composition and can be used as a quality indicator. However, long-term expertise in the field is needed. The limited availability of information on waste compositions remains a limitation for recycling and can only be overcome by increased transparency of the supply chains and systematic testing of waste streams.

This should be supported by standards and technologies for testing of mixed plastics. Future research should focus on the development of testing procedures that allow to systematically test mixed plastics by reducing the cost of testing.

5 Acknowledgement

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WEEE plastic characterization and recyclability assessment – A case study for household appliances

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Abstract

Plastics in waste electrical and electronic equipment (WEEEP) pose a multitude of challenges in material recycling. To improve the recycling of WEEEP, it is necessary to consider recycling barriers in the design phase of EEE (electrical and electronic equipment) and maximize their recyclability. Most of the existing recyclability assessment methods are either focusing on environmental, on economic or on technical aspects, but rarely in combination or with consideration of material quality loss and recycling barriers. This case study focuses on WEEEP characterization of vacuum cleaners and coffee machines to investigate influencing factors on the recyclability assessment of WEEE plastics. In addition, technological limitations for characterization (plastic identification and additive quantification) were assessed. The case studies conducted have shown the extent to which detailed information on product characteristics and technology specifications influences the result of recyclability assessment.

1 Relevance of (W)EEE plastic

Worldwide, waste electrical and electronic equipment (WEEE) represents a growing waste flow, with an expected annual growth rate of 2% to 4% [1][2] and is of increasing environmental concern. The European Commission states electronics as a key product that is in urgent need of improved circularity in its value chain. Therefore, current existing barriers for a high recyclability need to be identified and addressed [2].

The recycling targets for WEEE set by the European Commission (WEEE Directive) vary with the WEEE categories (Annex III, WEEE Directive): 55% for small IT and telecommunication (categorie 6), 70 % for screens and monitors (category 2), and 80 % for large and temperature exchange equipment (category 4 and 1) as well as lamps (category 3) [3]. These targets are mass based, without any material specification. While WEEE consists on average of 20% plastics [4], current recycling processes are focused on recovering metals and other valuable materials [5]. But the plastic fraction can also contribute to precious metal loss. Precious metals end up in plastics streams without being recovered. An improved plastic separation would therefore also have a positive effect on other material recycling processes [6].

There is still a significant share of plastics, which has an unexploited potential for recycling [7][8]. The plastic shares in (W)EEE indicated in literature are consistently high and can be up to 70% depending on the WEEE category [9]. In general, plastic recycling is considered as resource-saving and avoids primary production from fossil fuel [10]. Moreover, most of the plastics used in EEE are engineering thermoplastics, which are remeltable. Therefore, plastic fractions could represent a major recycling potential and increase the overall recycling rate of WEEE [11]. On the other hand, WEEE plastics (WEEEP) consist of a wide variety of plastic types [12], many of which are present only in small quantities and are incompatible for recycling among each other [10]. They can contain a variety of additives, which may pose a problem for further recycling [13]. Existing sorting techniques (e.g. near-infrared spectroscopy (NIR), float-sink) are not always capable of separating all plastic types in WEEE, especially when the plastic material is contaminated [14], contains certain additives and fillers, is coated or black [15]. Many issues associated with WEEEP recycling are currently challenging the recycling industry, but without an increased recycling of WEEEP, the recycling quotas set by the WEEE Directive will not be met [16]. To overcome this situation, it is therefore also necessary to consider recycling barriers in the design phase and thus a trade-off between product options with different abilities to be recycled. Hence, this study aims to develop approaches and to demonstrate limitations for an improved recyclability assessment of WEEEP.

2 Recyclability vs. Recycling of (W)EEE

The technical report IEC TR 62635:2012 defines recyclability as the “ability of [a] waste product to be recycled, based on actual practices”, where recycling is “any operation by which waste products are reprocessed into products, product parts, materials or substances whether for original or other purposes” [17]. Various other definitions of recyclability can be found in literature [18][19][20]. A major step in the direction of a systemized and harmonized recyclability assessment (RA) was done with DIN EN 45555:2020-04. The standard defines a general framework and essential steps for recyclability assessment on the example of energy-related products (ErP). Here, a mass-based calculation method for the recyclability of ErP is proposed:

$$R_{cyc} = \frac{\sum_{k=1}^{n}(m_k \cdot R_{cyc,k})}{m_{tot}} \cdot 100$$

R_{cyc}	Recyclability rate of the product
n	Number of components/materials
m_k	Mass of the k-th component
$R_{cyc,k}$	Recyclability factor of the k-th component/material
m_{tot}	Mass of the whole product

The recyclability assessment and respectively $R_{cyc,k}$ need to be conducted on product-specific reference EoL network to be chosen for each component or material DIN EN 45555:2020-04.

On the other hand, the achievement of the recycling targets of WEEE set out by the WEEE Directive are calculated by "dividing the weight of the WEEE that enters the recycling/preparing for re-use facility […] by the weight of all separately collected WEEE for each category, expressed as a percentage."

The recycling targets evaluate the used treatment route for different product groups on a waste level, while the recyclability rate estimates the eco-design of a product when it is reaching a reference EoL scenario in the future [22].

3 Influencing factors for the recyclability and recycling of WEEEP

To assess the recyclability of WEEEP, it is necessary to understand the WEEE processing chain and its plastic output streams. Usually, two different plastic fractions can be generated in WEEE processing: i) (partly presorted) plastic fractions from dismantling and ii) mixed shredder residues rich in plastics that are generated as a by-product during metal recovery [23]. Dismantled or selectively removed plastic parts have the benefit of having fewer contaminations than a shredded fraction, but a lower economic viability due to time and labor cost intensity [15]. For plastic parts or components from manual dismantling, the treatment process can consist of several steps: cleaning and removal of the inserts, (automated) identification of polymers/additives, and sorting into clean and regrind-compatible fractions for reprocessing [23]. For shredded material, mechanical treatment and sensor-based sorting, feedstock recycling or incineration are possible treatment routes [23]. Usually, mechanical treatment and sensor-based sorting of the shredded WEEE plastic fraction are associated with high investments [15], which is why this is often a less favorable choice. Here, also the demand for recycled plastics plays a role in economic feasibility.

Besides economic factors, environmental aspects influence WEEE plastic recycling. Although additives improve the properties of plastics, some substances can pose a risk to humans and the environment [24]. Heavy metals and other substances of concern in additives are for instance, cadmium, chromium (VI), lead, phthalates, and brominated flame retardants (BFR) [24]. Meanwhile, many of these substances have been phased out by industry, partly voluntarily, partly due to legislation (POP, RoHS, etc). However, especially brominated flame retardants (BFR) are still problematic since some were still allowed to be put on market in recent years. EN 45555:2020-04 specifies further influencing factors for the recyclability of products: the product design characteristics (e.g. structure, material composition, and indication) and the technology (and their combination) used to recycle the specific waste streams (Figure 1). On the product design and material level, further essential aspects for an increased recyclability of WEEEP exist, e.g. using a reduced amount of plastic types and plastic coatings as well as increased plastic markings [15].

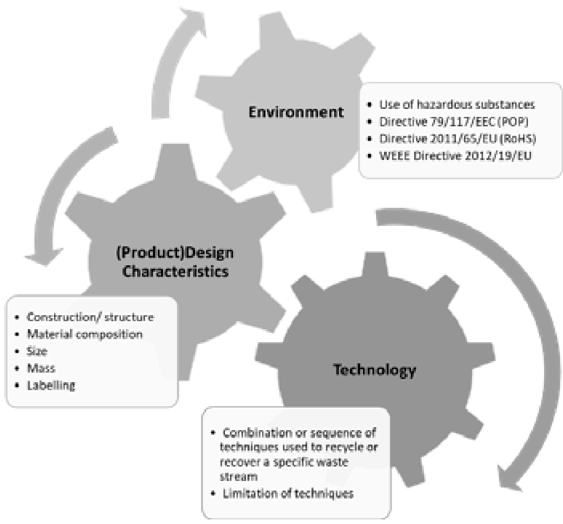


Figure 1: Influencing factors on the recyclability of products

3.1 Investigation of influencing factors for assessing the recyclability of WEEEP – A case study of household appliances

A case study was conducted to investigate relevant factors for assessing the recyclability as well as recycling barriers for WEEE plastics. Therefore, WEEE samples were collected in 2018 at a Berlin-based recycling company (Figure 2). In total, 32 different WEEE devices (14 coffee machines (CM), 18 vacuum cleaners (VC), in sum 140 kg WEEE) were dismantled for material characterization and test measurements (plastic identification and additive quantification). The devices had different brands and differed in their models and/ or production year (1987-2014), although the production year could not always be identified.

Figure 2: WEEE devices (coffee machines and vacuum cleaners) for dismantling, characterization, and documentation purposes

All components were documented, weighed and the material was specified (plastic, metal, mix, glass). Printed circuit boards (PCB) and cables were defined as material mix, since plastic and metal components are present. (Figure 3)

Figure 3: Dismantled vacuum cleaner (VC 16) and its components

3.2 Product (design) characterization of coffee machines and vacuum cleaners (first insights)

The dismantled WEEE devices showed considerable differences in their product (design) characteristics, which underlines the high variability of WEEE, even within one product group. In total, about 50% by mass of the dismantled WEEE was documented as plastics. More than half of the total separable plastic fraction consisted of housing plastics. Therefore, housing plastics represent a mass-relevant fraction for sorting and recycling. Regarding variability, both plastic shares in the devices and share of housing plastics in the plastic fraction differed from device to device. The mass share of plastics in the devices ranged from approx. 35% to approx. 70%. Results of FTIR (Fourier transform (mid) infrared spectroscopy) ATR (attenuated total reflection) measurements showed that the main plastic types found were ABS (approx. 60% in VC; approx. 28% in CM) and PP (approx. 30% in VC and 68% in CM), two of the most frequently recycled plastics from WEEE.

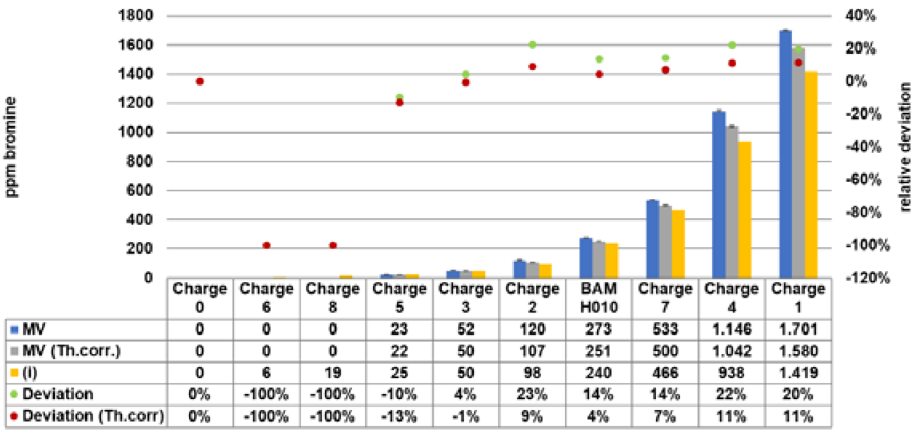
One possible sorting method for WEEE plastics is the manual sorting by labels. Therefore, all plastic components of the dismantled devices were examined for labels, for both information on plastic type and additives used. Considering only housing plastics, 81% by mass were labeled, of which 0.3% by mass had additional information on the additives. It could be seen that the proportion of lables varies from device to device. Three of the 32 devices had no label at all. The share of labeled plastics can vary from at least 30% by mass to almost 100% by mass. However, sorting by plastic type based on labelling can be achieved for most plastic parts in most devices.

Black plastics accounted for the largest share with 46% by mass in the total plastic fraction of the dismantled WEEE (42% by mass for housing plastics). With only 6% by mass of the total plastic fraction and 7% by mass of housing plastics, the visible coating represented a lower relevance for plastic identification methods. However, the share of plastics with a transparent coating could not be documented.

The latest version of the standard CENELEC TS 50625 for the treatment of waste electrical and electronic equipment specifies that a separation process must be ensured for plastics when the total bromine concentration exceeds 2,000 ppm [25]. Due to unknown concentration levels (not provided by label or producer information), XRF measurements of the plastic components were conducted. The results showed that 10 WEEE devices had plastic components exceeding the CENELEC limit value. The concentrations range from 2,000 ppm up to 220,500 ppm. Those components with exceeding the CENELEC limit value were usually inside the devices, which increases the effort of disassembly.

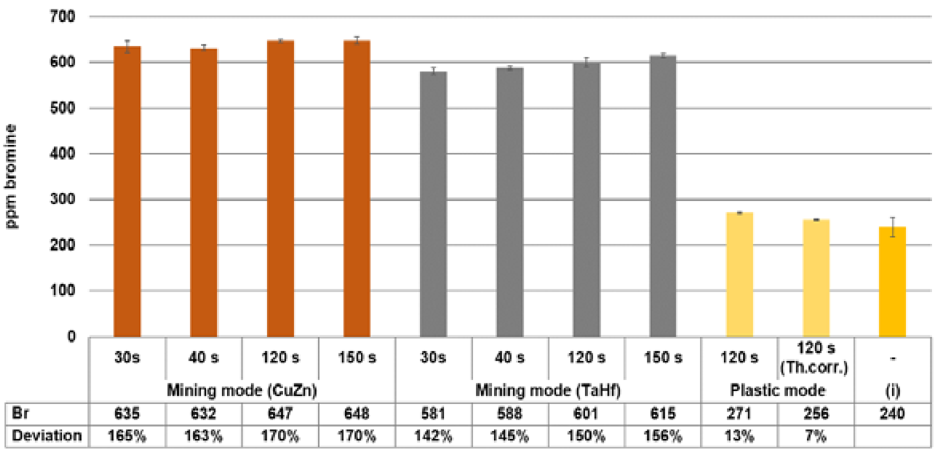
3.3 Technological limitations for characterization and sorting of WEEEP

The technologies used in plastic recycling involve a wide range of different techniques such as sorting, cleaning, processing, or reprocessing techniques [26]. Several studies indicate that existing plastic sorting and recycling technologies have significant (identification/recycling) limitations, influenced by WEEEP characteristics [26][15]. Moreover, the selection and order of those used technologies significantly influence the resulting output streams. To evaluate identification and sorting limitations in more detail, two sensor-based plastic characterization methods, FTIR and X-ray fluorescence (XRF) technique, were investigated in the case study. WEEE plastic samples were measured with different plastic identification methods (FTIR ATR, FTIR specular reflectance, Sliding Spark Spektroscopy with NIR (Near-infrared spectroscopy) to compare the measurement performance of FTIR characterization methods. The test measurements showed differences in performance and results. All instruments were unable to correctly identify plastic materials with coating. The presence of flame retardants in plastics did not hinder the detection of polymers, but glass fibers did. The identification of copolymers such as ABS/SAN, HIPS/PS, individual PA/PE types as well as blends (PC-ABS) was often not possible. In most cases only the main polymer could be identified. This can lead to a higher uncertainty of literature data with regard to correct compositional data of WEEEP, depending on the measurement method and database used.



	Charge 0	Charge 6	Charge 8	Charge 5	Charge 3	Charge 2	BAM H010	Charge 7	Charge 4	Charge 1
MV	0	0	0	23	52	120	273	533	1.146	1.701
MV (Th.corr.)	0	0	0	22	50	107	251	500	1.042	1.580
(i)	0	6	19	25	50	98	240	466	938	1.419
Deviation	0%	-100%	-100%	-10%	4%	23%	14%	14%	22%	20%
Deviation (Th.corr)	0%	-100%	-100%	-13%	-1%	9%	4%	7%	11%	11%

Figure 4: Measured mass fraction of bromine in ABS reference material, 10 ABS discs with 6 mm diameter each (Charge 0-8; BAM H010) with different concentration levels. (i) represents the concentration of the reference material. The absolute results (MV: mean value) and the relative deviations are indicated. All measurement results from thickness correction 'on' are indicated with '(Th.corr.)'



	Mining mode (CuZn)				Mining mode (TaHf)				Plastic mode		(i)
	30s	40 s	120 s	150 s	30s	40 s	120 s	150 s	120 s	120 s (Th.corr.)	-
Br	635	632	647	648	581	588	601	615	271	256	240
Deviation	165%	163%	170%	170%	142%	145%	150%	156%	13%	7%	

Figure 5: The bromine mean values from XRF measurements at different measurement time, including the standard deviation and the deviation from the actual Br concentration in the reference material. (i) represents the concentration of the reference material. Results from thickness correction 'on' are indicated with '(Th.corr.)'

XRF measurements were performed on different plastic reference materials (ABS and PE) containing tracer elements (e.g. Br, Sb) or RoHS relevant substances (Cd, Cr, Pb, Hg). Furthermore, WEEE samples containing different concentrations of bromine (Br) were measured. All measurements were conducted with different configurations (thickness correction, measurement time and mode). The measurement results showed a higher accuracy with an increasing thickness of the plastic materials specifically for RoHS-relevant tracer elements. With thickness correction 'on' in plastic mode, better results could be obtained, especially for bromine (see figure 4). In general, plastic materials show a low X-ray absorption. As a result, samples often have to be several millimeters thick to achieve sufficient thickness and more accurate quantitative measurement results [27]. The information depth determines the depth in which 90% of the information and thus the concentration of an element in a material is determinable. However, the information depth is not the same for all plastic materials and is for instance larger for PE than for PVC [28]. Nevertheless, measuring the thickest part of the plastic component is difficult to realize in the dismantling process. It may require additional sampling and preparation efforts to identify the thickness of the plastic. Hence, a direct measurement using XRF is not always feasible under real conditions. Ten ABS reference materials with bromine concentrations from 0 ppm to 1,419 ppm were measured in the case study (see figure 4). With increasing bromine content, the same relative deviation of the measurement results compared to the indicated concentration in the material could be observed. Therefore, it can be assumed that the method is suitable to measure bromine values around the CENELEC limit value and lower concentrations with the same accuracy. Varying measurement times (10 sec to 180 sec) showed no significant influence on the result for all RoHS relevant elements. This is particularly advantageous for manual dismantling, as a long measuring time would lead to higher labor costs. Regarding the accuracy of measurements with a short measuring time, the XRF method is suitable for manual sorting during dismantling. On the other hand, the change of the different XRF measurement modes to be selected showed significantly higher measurement deviations for all RoHS relevant substances. In 'mining mode', deviations of up to 170% of the certified bromine concentration were observed (see figure 5). In contrast, in 'plastic mode' the deviation accounted for 7% to 13% for bromine (see figure 75. In many publications, the XRF technique is mentioned as a potential device for screening and sorting out BFR in WEEEP. Moreover, handheld XRF devices have been used in many studies to quantify tracer elements in WEEEP [29][30][31][32]. Nevertheless, most publications do not explain how they proceeded with the measurements, e.g. which settings (module, thickness correction, time) were used during the measurements. This potentially renders measurement results from literature incomparable and prevents an accurate estimation of the actual bromine mass fraction in WEEE plastics.

4 Assessing the recyclability and recycling of WEEE(P) – Preliminary findings

4.1 Existing assessment methods and data availability

Most existing assessment methods, including recyclability, are either focusing on environmental, economic or technical aspects, but rarely in combination [33]. Technical approaches oftentimes seem to be weight-based while material quality loss and recycling barriers are not considered [33].

One remaining challenge is the existing limited data availability on product-specific characteristics and waste treatment routes as well as their efficiencies. These are needed to reliably assess the recyclability. End-of-Life (EoL) related information are oftentimes not easily accessible or partly unknown (e.g. due to export of WEEE). The reference network for recyclability assessment or estimating recycling quotes are also affected by the respective geographical and temporal scope, which in many cases is difficult to identify [22]. Moreover, historic WEEE which contain hazardous substances, now prohibited, still reach the dedicated waste management processes. Those are significantly influencing the recycling and recyclability of other products. The condition of WEEE in which they reach the EoL phase has also an influence on the treatment route and output streams. The degree of contamination (e.g. from intensive use, historic WEEE) but also the aging of plastics (e.g. from heat and light exposure) can hinder recycling but is difficult to quantify/consider in calculations. The waste framework directive states that member states shall take measures to promote high-quality recycling. Yet, no specification of "high-quality" exist. However, recyclability assessment should consider wether low-quality or high-quality recycling of the materials can be achieved.

From a methodological standpoint, DIN EN 45555:2020-04 is a step forward in the field of recyclability assessment in general, but also for product groups other than energy-related products. However, no reference networks are prescribed. Therefore, the recyclability rate still depends significantly on the chosen system boundaries and considered treatment steps and their order, causing significant uncertainties. According to DIN EN 45555:2020-04, losses during collection, storage, transport, preparation for re-use as well as cleaning do not need to be considered in the indicated calculation method. But especially the collection of WEEE as the first step in waste management effects decisively the recyclability of products. A database for EoL treatment performances and networks (considering geographical aspects) would allow a more standardized and harmonized assessment already in the design phase of EEE. Product designers need easy methods and tools to assess and improve the recyclability of WEEE(P) [33].

4.2 The case study of household appliances (first insights)

Very few publications describe how they characterized WEEEP or how characterization methods were applied. This lack of information leads to a limited comparability of measurement results. Therefore, literature data on WEEE plastic composition and bromine content in plastics can not be regarded comparable and reliable. The case study showed on a small scale the heterogeneity of WEEEP and influencing factors on the measurement results. In the future, more transparency should be provided in publications for improved comparability and better assessment of potential sorting efficiencies or WEEE plastic characterization. Nevertheless, it should be noticed that the results are to be evaluated critically. Since only coffee machines and vacuum cleaners were investigated, no statement can be made for WEEE in general. For a better assessment, more equipment types (e.g. ICT) need to be examined in the future.

5 Conclusion and Outlook

The assessment of the recyclability of products in the design phase must take into account both current and future environmental requirements as well as EoL technologies and networks. Consequently, high recyclability rates should be reflected in recycling targets. Despite increasing standardization of RA methods, EoL networks still contain flexibility in the description and consequently, high uncertainties in the evaluation result and the (temporal, local) validity. Moreover, whether only low-quality or high-quality recycling can be guaranteed, remains not considered in current assessment methods. The conducted case studies on WEEEP in household appliances have clearly shown the extent to which detailed information on product characteristics and technology specifications influences the result of recyclability (identifiability, measurement accuracy, etc.). The harmonized collection of comprehensive data and free access to this information will define the reliability of the RA results in the future and should be a key priority towards a circular economy (for WEEEP).

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Removing hazardous substances to increase the recycling rates of WEEE, ELV and CDW plastics

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Abstract

Plastics are nowadays used in a large variety of applications because of their widely properties. To ensure certain properties and specific characteristics plastics are mixed with additives such as flame retardants, stabilizers and plasticisers. Over the years, some of these additives have been classified as "hazardous" resulting in a challenge for the recycling sector. According to recent statistics [1], plastic recycling rates are still too low, especially for the electric and electronic equipment (EEE), automotive and construction sectors, in comparison to the targets set by European Union in the EU Directives for 2020. This research addresses the challenge to increase the recycling rate of plastics from the above-mentioned sectors focusing on the removal of hazardous substances by developing and optimizing recycling processes and developing sustainable alternatives for the upgrade of recyclates and by-products of the recycling process.

1 Introduction

Plastic is a widely diffused and important material, employed in many different uses. According to the latest statistics [1], the European plastic demand is more than 50 Mt (2018) of which 6.2% (~3.2 Mt) in Electrical and Electronics Equipment (EEE) sector; almost 20% (~10 Mt) in Construction sector; and 9.9% (~5Mt) in the Automotive sector. Nevertheless, the plastic recycling targets are estimated to be almost 45% for Waste of Electrical and Electronic Equipment (WEEE), 30% for End-of-Life Vehicles (ELV) and 36% for Construction & Demolition Waste (C&DW) according to the report published by Deloitte [2]. These rates are too modest taking into consideration relevant EU Directives and the Plastics Strategy [3] adopted by the European Commission for WEEE (Directive 2012/19/EU), ELV (Directive 2000/53/EC) and C&DW streams (WFD 2008/98).

An important challenge for the recycling plastic value chain is the content of legacy hazardous substances: waste streams mentioned are hindered by the presence of these substances (e.g. 30% of the WEEE plastics contain flame-retardants) [4]. Fractions containing these substances are generally incinerated or landfilled, with potentially harmful consequences for human health and the environment due to a lack of techno-economically reliable, environmentally sustainable and cost-effective recycling processes.

The identification of hazardous substances in plastic streams and the development of cost-effective plastic recycling solutions are a challenge to create viable markets for recycled plastics.

2 Hazardous substances

After decades of additives use, attention has now turned to the potential environmental impact of additives in plastic waste, which has in turn led to the intro-

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duction of more restrictive legislation up to and including complete bans on the production, marketing and utilisation of some of the most hazardous substances.

Possibly hazardous compounds in waste plastics streams have been discussed for decades including brominated flame retardants (HBCD (Hexabromocyclododecane), PBDE (Polybrominated diphenyl ethers) and less hazardous alternatives), as well as phthalic acid-based plasticizers [5].

More specifically, in this research brominated and chlorinated flame retardants are addressed mainly.

- **WEEE** - PBDE, TBBPA (Polybrominated diphenyl ethers), BTBPE (1,2-Bis(2,4,6-tribromophenoxy)ethane), Chlordane, mainly applied to ABS (Acrylonitrile butadiene styrene) and HIPS (high-impact polystyrene)
- **ELV** - DecaBDE (Decabromodiphenyl ether), applied to PP (Polypropylene) and ABS
- **C&DW** - TBBPA-DBPE (Tetrabromobisphenol A bis(2,3-dibromopropyl ether)), applied to PP pipes, HBCD applied to EPS (Extracellular polymeric substances)

While it is necessary to remove these hazardous substances for pulling the plastic waste back into circularity, it is also of utmost importance that these materials are safely disposed, ensuring no harm to the environment. Over the years, the threshold limits for these substances in recycled plastics have tightened.

3 The current recycling technologies, limitations and challenges

The recycling technologies can be split into two main categories: physical and chemical recycling. Physical recycling comprises all technologies that does not affect the molecular weight of the polymer. On the contrary, chemical recycling is a breakdown process from the polymer to the monomer units. The well-known mechanical recycling is included in the physical processes and consists of a sorting stage followed by a compounding activity. When several sorting technologies are combined (sink/float separation, electrostatic separation, suction process, rubber separation, etc.), a purity above 98% in one polymer can be achieved leading to the production of high-quality recycled compounds. Another technology included in the physical category is the solvent based dissolution. This process can recover and clean restricted plastics, thanks to the filtration of the prohibited substances from the polymeric matrix. The combination of these technics allows the recycling of most plastic materials included in the waste stream with the following prioritization based on material feedstock:

- mechanical recycling: plastics containing substances of concern below the restriction limits;
- solvent based dissolution: plastics containing substances of concern above the restriction limits and reinforced plastics (glass fibres, composites);
- chemical recycling: Plastics not recyclable in the two above sections.

In order to promote the recycling activities to the right level and match the targets set by the European Commission, some regulatory gaps should be filled:

- European end-of-waste criteria for plastics: end-of-waste (EoW) status is a legal status where waste legislation stops to apply and product legislation starts to apply. It is a status that needs to be applied for and officially documented. The Waste Framework Directive sets the frame for this status, but unfortunately, it is not defined in a specific manner. In order to get recycled plastics generally accepted by the public as a raw material, a well-defined European wide EoW criteria is needed;
- standardized method to ensure representative sampling and analysis of mixed plastic wastes: sampling is key in order to obtain representative results. In the field of recycling, the material is heterogeneous. To increase the accuracy of the results, a proper sampling process has to be performed including items of all sizes expected in the output stream and it shall be representative of the entire population. The laboratories, recyclers and producers should be aligned;
- common database of potential substances per polymer: a centralized tool should be established to combine the different substances and their regulations. This tool would help the recycler to monitor and ensure the safety of its output fraction.

Standardized method for screening REACH (Registration, Evaluation, Authorisation and restriction of Chemicals), RoHS (Restriction of Hazardous Substances Directive), POP (Persistent Organic Pollutants) substances: according to the exhaustive number of substances restricted, some guidance regarding the testing and quantifying of those elements should be expected. Unfortunately, no methods of screening substances are yet officially released. Being transparent regarding the recycled material composition will communicate the right message regarding the safety of the recycled plastics and therefore lead to an increase of the recycling rates.

4 The challenge of NONTOX

The NONTOX project is targeting at materials, which have long been ignored, and ill-treated due to the lack of techno-economical recycling technologies and also due to the absence of a dedicated infrastructure where these materials could find new life. Therefore, NONTOX project takes a holistic approach in bid to increase the recycling rates of such plastics. Essentially, improving the whole value chain right from the start, where these waste streams are collected after the end of their life, until the very step where the recycled plastics are safely introduced back into the economy. Even though this is quite challenging, confronting the challenge by improving the whole value chain appears to be the only way to ensure that the values of these materials are retained. Sadly, in the past the recycling infrastructures pertaining to these streams have mostly focused on metal recycling citing unestablished markets for such plastic waste.

4.1 The overall approach

NONTOX aims to address the challenge of increasing, with a value chain approach, the recycling rate of plastics from three selected streams: WEEE, C&DW and ELV. The project aims to (i) optimise and demonstrate the efficacy of different technologies to extract hazardous substances, such as BFRs (Brominated Flame Retardants) and POPs and produce high quality recycled plastics; (ii) develop and improve techniques for efficient characterisation and pre-treatment of hazardous plastic waste as well as (iii) increase the efficiency of downstream recycling technologies by developing and demonstrating guidelines for each step of the plastic value chain. Moreover, the efficiency, sustainability and competitiveness of the entire system will be increased by the valorisation of process residues and non-target plastic waste, using thermochemical conversion techniques to produce additional valuable products, such as liquid fuels, chemicals and solvents and simultaneous recovering of the hazardous substances in a safe manner for their disposal and/or commercialization. Finally, a thorough life-cycle assessment of the economic, social and environmental impacts will be exploited to boost the market uptake of plastic recycling technologies and of their recycled products.

4.2 Scenario

The NONTOX scenario starts from the same dismantling and sorting stages currently applied to WEEE, ELV and C&DW plastics, but adopts several innovative processes (CreaSolv®, Extruclean, Pyrolysis and Modix) developed for removing toxic compounds from plastics of interest and enhancing their recycling rates.

4.2.1 Material selection and flows definition

Three different input streams are considered in the NONTOX project: WEEE, ELV and C&DW. More specifically, flame retardants are the most common hazardous legacy compounds in WEEE [5]. In ELV plastics (excluding textiles) BFR play a minor role, however PCBs and plasticizers have been identified in ELV plastics [6]. With respect to C&D waste, plasticizers like phthalates and the brominated flame retardants are known possibly hazardous additives [5].

Fortunately, these potentially hazardous materials have only a minor share in total volumes of the respective waste streams; however, in plastics streams recovered from WEEE, ELV and C&DW they may be enriched. This is especially true for density separated plastic fraction with densities higher than 1.1 kg/L. These fractions from WEEE are especially chosen for the CreaSolv® approaches, as well with BFR containing PP pipes from C&DW. In addition, plastics streams with lower content of flame retardants (e.g. density fractions below 1.1 kg/L) are addressed by the Extruclean process. Side steams of both processes as well as waste plastic streams not targeted by these fractions are treated with thermochemical conversion (TCC) processes in NONTOX.

4.3 Material and product design

Increasing the recycling rates of plastics, improving the economy of the recycling process as well as the quality of the recyclates are also achievable by proper material and product design. NONTOX from the perspective of design for recycling works in the development of materials and products designed to fit the nowadays commercially available and economically feasible separation by density with focus on monomaterial products and self-reinforced composites with focus on streams of polyolefins and styrenics. Following the separation by density, polyolefins (PE (polyethylene) and PP) are recovered at densities 0.91 to 1.0 g/cm3 and styrenics (ABS, PS (Polystyrene), HIPS) in the range 1.0 to 1.1 (Table 1). Polyolefins and styrenics are the most abundant polymer groups in the recycling streams therefore is worth to design properly the next life of the materials from the current application. In these ranges of densities, the recyclates show commonly levels below 2000 ppm Br. Considering the applicable EU regulations, these fractions are, in most of the cases, not considered hazardous and do not require decontamination prior to application. When the polyolefin-based compounds exceed density 1.0 g/cm^3, e.g.

by the addition of fillers or flame retardants, they become detrimental for the fraction of styrenics.

Table 1. Density separation: Practical density ranges in NONTOX for separation in WEEE, ELV and C&DW

Density range (g/cm3)	***Major polymers in the stream***
<1.0	PP, PE
1.0-1.1	ABS (low Br), PS &HIPS (low Br)
1.1-1.25	ABS (high Br), PS &HIPS (high Br), PC, PC/ABS, soft PVC, PMMA
>1.25	Hard PVC

5 Technologies

5.1 CreaSolv®

For treatment of waste plastics containing hazardous legacy additives like PBDE solvent based approaches have been discussed [7] [8] like the CreaSolv® Process (Fig.1, CreaSolv® is a registered trademark of Creacycle, GmbH, Grevenbroich). This technology dissolves a defined target polymer selectively from a mixture and cleans the polymer solution in depth using mechanical end extractive approaches. Non-target polymers may either be targeted in a second dissolution step or be separated as side stream. Hazardous additives, however, are separated and remain as a hazardous side-stream, whereas the applied solvents are recycled within the process. Both side-streams however, are considered to be treated by thermochemical conversion processes to produce both monomers and fuels. Monomers can be used to produce fresh virgin polymer for application in a second life.

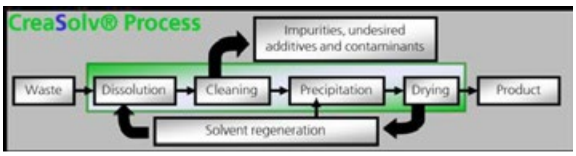

Figure 1: Scheme of the CreaSolv® Process

Earlier CreaSolv® studies reported the recovery of HIPS and ABS from shredded WEEE plastics containing BFR. In addition, PC/ABS recovery from WEEEE has been studied in the European CloseWEEE project [9].

5.2 Extruclean

Extruclean is a mechanical recycling technology based on extrusion with simultaneous extractions by supercritical carbon dioxide (sc-CO_2). Hazardous substances are volatilised and extracted during degassing phase with a vacuum pump from the polymer melted during extrusion. The removed substances will be adsorbed in activated carbon-based filters. These filters will be recycled thermochemically to recover bromine or otherwise safe disposal is ensured by a hazardous waste management company.

Besides being a clean technology, since it reduces the use of chemical substances, water and energy, as well as the generation of wastewaters, this new system will allow to improve the quality of the recycled material. The new recycled material will have other potential applications as a result of its decontamination.

5.3 Thermochemical conversion

Thermochemical conversion, named also pyrolysis, is a well-developed process for converting plastics into liquid products. By means of both thermal and catalytic configurations, a high throughput of oil (hydrocarbons) can be obtained for the production of fuels and petrochemicals. Pyrolysis offers treatment for difficult plastic waste that are otherwise sent to incineration or landfilled because they cannot be viably handled with conventional mechanical recycling [10]. Therefore, in NONTOX project, pyrolysis is a promising route to the thermochemical valorisation of polymers contained in rejects and residues from the Extruclean and CreaSolv® recycling processes, as well as in those rejects considered directly as non-target polymers (fines, dust and sludge) by recyclers in their sorting process for WEEE plastics (about 10 wt%), which commonly present high contents of toxic halogenated flame retardants and are currently derived to incineration. Therefore, the thermochemical decomposition of those hazardous feedstocks requires a strategy that necessarily involves dehalogenation processes that must be carried out in a series of steps. Firstly, the initial thermal cracking (500 – 600ºC) and halogen trapping using low cost materials (iron oxide, red mud, different clays, etc.) that would significantly reduce the halogens content of the liquid hydrocarbon fraction. Secondly, a catalytic hydro-dehalogenation step for removing the last traces of halogen in the final hydrocarbon products, which would be ready for their utilisation as valuable feedstock to produce fuels and/or chemical [4]. So far, the thermal pyrolysis of different non-target WEEE samples (fines, sludge, dust and residues from the CreaSolv® process), containing very broad range of polymers (ABS, PE, HDPE, PP, HIPS, EVA, PMMA, PS, PVC, PC, PA, PET) and a broad interval of Br and Cl content, has been satisfactorily tested at a lab-scale reactor. Next steps will involve the safely halogens elimination from the oils employing inexpensive materials to be compared with the thermal pyrolysis oils.

6 Results

6.1 How the entire process will be evaluated

Environmental and socio-economic performances of the NONTOX management scheme will be evaluated in a life-cycle perspective by adopting a life cycle thinking (LCT) approach, which recommend to assess overall impacts related to a product (goods and services) taking into account all activities/phases from "cradle to grave".

The Environmental Life Cycle Assessment (E-LCA) is an objective and standardised tool [11] developed from the LCT concept and able to quantify environmental impacts in a reliable way. In last decades, LCA has been increasingly utilised by industries to support and drive the reduction of the overall environmental burdens related their activities, by companies to improve the competitiveness of their products, and by government bodies to improve communication in the environmental matter. LCA is used as a support tool for decision-making processes to improve product design, during the choice of materials, the selection of technologies, specific design criteria, and the definition of the way for technology investments and/or innovation systems [12].

Analogously, the Social Life Cycle Assessment (S-LCA) is focused on the social impacts deriving from a product during its whole life cycle in order to improve the well-being of the involved stakeholders [13] The S-LCA is not yet fully standardized as the E-LCA, but it is under a continuous development and implementation.

E-LCA and S-LCA for NONTOX project will share the first phase of "Goal and scope definition", during which several mandatory elements (such as comparative scenarios, functional unit and system boundaries) are established. In particular, with reference to WEEE plastics management scheme both E-LCA and S-LCA *comparative scenarios* will be:

- the NONTOX management scenario, identified as the possible future management systems including the innovative processes proposed in the framework of the project (CreaSolv®, Extruclean, Modix, Pyrolysis, and Plastic upgrading).
- the current waste plastic management scenarios, i.e. those currently adopted in Europe to manage waste plastics coming from WEEE, including the conventional processes of mechanical recycling and thermal treatment.

The functional unit will be the management of annual amount of WEEE plastics with an average polymeric composition. The *system boundaries* will be those generally indicated as a "gate-to-gate", where: the input gate is that of mixed plastic obtained by WEEE separate collection, dismantling and preliminary sorting and the final gate is that of decontaminated recycled plastics and oil (in NONTOX scenario) or energy (in current scenario).

7 Conclusions

NONTOX project will provide new solutions for the whole plastics recycling value chain which will ultimately allow to increase the quantity, quality and safety of secondary plastic fractions. As such, NONTOX output will be highly relevant for future market exploitation primarily in the plastic waste management but also for consumer products industries (e.g. EEE, automotive, etc.). A preliminary exploitation/business plan has been drawn up to ensure a rapid and smooth delivery of innovation to the market. Nonetheless, a more detailed exploitation strategy will be included to be delivered during the project and will be continuously updated during the project life. The consortium's goal is to realise all the exploitation pathways for the project results as follow: a) Commercial exploitation: a key exploitation route will be the industrial use of the project knowledge and technology developments, for the creation of new products, new processes and advisory services to deliver high competitiveness and growth impacts; b) Further research providing the knowledge and skills for future spin-out research and development projects will have a high impact for raising the European knowledge base on circular plastic economy.

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WEEE plastics flows and the corresponding behavior of brominated flame retardants – A Japanese case before and after China's ban on waste imports

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Abstract

This study estimates the flows of plastics in Japan originating from waste electrical and electronic equipment (WEEE) and the flows of brominated flame retardants (BFRs) contained in those plastics. Results show that WEEE plastics are mainly recovered as mixed plastics or shredder residues. In 2017, the most recent year for which detailed data are available, a large proportion of recovered mixed plastics were being exported. However, owing to China's import ban on post-industrial plastic waste, the amount of exported mixed plastics was expected to significantly decrease after 2018. While this is sure to increase domestic processing of mixed WEEE plastics, it appears that a substantial quantity of the recycled pellets from WEEE plastics was still being exported in 2019. The results of this study show that a large proportion of BFR-containing plastics in the bulk mixed plastics that are processed are removed through wet specific-gravity separation and X-ray sorting and then incinerated, indicating that a large fraction of the BFRs contained in the original mixed WEEE plastic is being removed from the recycling chain.

1 Introduction

There is an increasing need to promote the cyclical use of plastics, including the recycling of plastics from waste electrical and electronic equipment (WEEE). Although the recycling of WEEE plastics has been promoted in Japan and Europe, cascading recycling is still common, highlighting the need for more advanced approaches such as the use of recycled WEEE plastics for the production of new electrical and electronic equipment.

During WEEE processing, a large percentage of WEEE plastic is recovered as mixed plastics, much of which has been exported to other countries, mainly China. However, because of China's ban on the import of post-industrial plastic waste after 2018, these materials can no longer be exported to China. As a consequence, the destination of Japan's mixed WEEE plastics has shifted to other Southeast Asian countries, although strengthened import regulations in these countries made it increasingly difficult for Japanese exporters to find accommodating destinations. In addition, the export of WEEE as mixed metal scrap (often called "zappin"), which has been considerable, has also become more difficult due to the more stringent regulations imposed in 2018 by the Japanese government on the export of mixed metal scrap. These changes mean that an increasing amount of WEEE will be domestically processed and that an increasing amount of WEEE plastics will be domestically recycled. Based on these circumstances, promoting the domestic recycling of WEEE plastics, including the application of more advanced approaches, has become critical.

Adding to the challenge is the fact that certain WEEE plastics, such as television casings, contain flame retardants. Some brominated flame retardants (BFRs) are listed in the Stockholm Convention on Persistent Organic Pollutants (POPs), and plastics containing these BFRs at or above specified concentration levels should be eliminated from recycling. Because the presence of these regulated BFRs imposes limits on WEEE plastics recycling, a thorough understanding of the flow of BFR-containing plastics through the recycling process is essential.

This study estimates the flows of plastics originating from WEEE and the contained BFRs through the recycling and disposal process in Japan. Based on our results, the effect of China's ban on the import of plastic waste on the flows of WEEE plastics and the contained BFRs is discussed.

2 Materials and methods

2.1 Target systems

In Japan, the collection and recycling of WEEE is controlled by two recycling laws: the Home Appliance Recycling Law and the Act on Promotion of Recycling of Small Waste Electrical and Electronic Equipment (sWEEE). The Home Appliance Recycling Law applies to four specific categories of post-consumer home appliances, namely air conditioners, refrigerators and freezers, washing machines and clothes dryers, and televisions (including CRT, liquid crystal, and plasma televisions). Under this law, home appliances in these four categories are collected and recycled by manufacturers or importers. The second law, the Act on Promotion of Recycling of sWEEE, applies to all other categories of post-consumer electrical and electronic equipment. The collection and recycling of such items is not an obligation under this act. Most municipalities currently collect post-consumer sWEEE from consumers in various ways and turn over the items collected to designated recyclers; however, a large proportion of sWEEE is still discarded and treated as municipal solid waste (non-combustible waste or bulky waste).

In this study, we estimated the flows of plastics in the target product categories of the two recycling laws. Specifically, we considered air conditioners, refrigerators and freezers, washing machines, and sWEEE. Televisions were not included, as, in most cases, television plastics are collected separately from other product categories and then properly treated (mainly incinerated) or recycled in cases where it is clear that they contain no regulated BFRs.

The geographical boundary of the study was set to Japan. The flows were estimated for 2017, the latest year for which detailed data on WEEE flows were available at the time of our estimation. The results thus show the estimated flows before the implementation of China's ban on the importation of post-industrial plastics waste. Our discussion of flows after China's import ban is based on our estimates from 2017 and interviews with stakeholders regarding the ongoing situation of WEEE plastics in Japan.

2.2 Estimation of the flow of WEEE plastic through the recycling and disposal process

The flow of WEEE plastics was estimated using the procedure described below.

The total amount of WEEE plastics domestically generated in Japan was estimated by multiplying the mass of domestically generated WEEE in Japan by the proportion of plastics in the WEEE. The mass of the domestically generated WEEE was obtained from estimates by the Ministry of the Environment, Japan (MoEJ) [1,2]. The proportion of plastics in the WEEE was calculated from the officially reported amounts of WEEE processed and of plastics recovered and disposed of by WEEE recyclers [2,3] (Table 1).

	WEEE domestically generated	Proportion of plastics in WEEE	WEEE plastics generated
	10^3 t/year	-	10^3 t/year
AC	265	24%	63.8
R/F	238	46%	109.0
WM/CD	169	41%	69.8
sWEEE	450	34%	154.5

AC: air conditioners, R/F: refrigerators and freezers, WM/CD: washing machines and clothes dryers.

Table 1 Estimated domestic generation of WEEE plastics in Japan in 2017.

The estimated amount of WEEE plastics assigned to the various recycling and disposal destinations was set according to the ratio of WEEE destined for each destination. The destinations included designated WEEE recyclers, municipal solid waste (MSW) treatment facilities, industrial or hazardous waste treatment facilities, scrap collectors, and exporters of secondhand goods. The ratio of WEEE sent to each destination was obtained from estimates by MoEJ [1,2] (Table 2).

	Destination			
	Designated WEEE recyclers	MSW treatment	Industrial/ hazardous waste treatment	Scrap collectors/reuse (overseas)
AC	43%	–	0.7%	56%
R/F	79%	–	0.8%	21%
WM/CD	82%	–	0.6%	17%
sWEEE	16%	28%	37%	20%

AC: air conditioners, R/F: refrigerators and freezers, WM/CD: washing machines and clothes dryers.

Table 2 Ratio of WEEE destined for each destination in 2017.

The amount of plastic produced by WEEE recyclers and waste treatment facilities was estimated by multiplying the amount of plastic processed by the distribution ratio for each recovered fraction. The distribution ratios were set based on officially reported data on WEEE recycling by WEEE recyclers [2,3], previously reported experimental material balance data [3,4,5], and information obtained from interviews with recyclers (Table 3).

The amount of recovered mixed plastics to be recycled was assigned to domestic mechanical recycling processes and export (as mixed plastics). The percentage for each destination was set based on information obtained from interviews with recyclers. For mixed plastics recovered from the four specific categories of home appliances, the percentage for each destination in 2017 was set to 20% for domestic plastic recycling and 80% for export. A large part of the mixed plastics was still being exported in 2017, as previously explained. For the mixed plastics recovered from sWEEE, it was assumed that all were processed in domestic plastic recycling since designated sWEEE recyclers are obliged to turn over the recovered materials, including the recovered mixed plastics, to domestic recyclers.

	Distribution ratio			
	Single-material plastics to be recycled	Mixed plastics to be recycled	Mixed plastics or shredder residue to be incinerated*	Shredder residue to be landfilled
Designated recyclers				
AC	10%	60%	30%	-
R/F	40%	20%	40%	-
WM/CD	2%	78%	20%	-
sWEEE	-	10%	62%	27%
Industrial/hazardous waste treatment facilities				
AC, R/F, WM/CD	(Same as designated recyclers)			
sWEEE	-	-	70%	30%
MSW treatment facilities				
sWEEE	-	-	20%	80%

AC: air conditioners, R/F: refrigerators and freezers, WM/CD: washing machines and clothes dryers.

* including energy recovery.

Table 3 Distribution ratio of WEEE plastics for each recovered fraction by WEEE recyclers and waste treatment facilities in Japan.

The amount of plastic produced in the sorting processes of mixed plastics by domestic WEEE plastic recyclers was estimated by multiplying the amount of plastic processed by the distribution ratio for each recovered fraction. Domestic WEEE plastic recyclers separate mixed plastics into polypropylene (PP), polystyrene (PS), acrylonitrile butadiene styrene (ABS), high-specific-gravity fractions, and other plastics. The distribution ratio of the processed mixed plastics assigned to each recovered plastic fraction was set based on previously reported experimental material composition data for WEEE [6] and information obtained from interviews with WEEE plastic recyclers (Table 4). In addition, at a few of the plastics recycling facilities in Japan, the sorted plastics subsequently undergo X-ray sorting to separate out high-bromine-containing plastics. Based on the information obtained from interviews with WEEE plastic recyclers, as well responses to a questionnaire survey of WEEE recyclers, it was assumed that 60% and 10% of the sorted plastic fractions (PP, PS, and ABS) from the three categories of home appliances and sWEEE, respectively, were subsequently processed using X-ray sorting.

Origin of mixed plastics	Distribution ratio				
	PP	PS	ABS	High-specific-gravity fraction	Other plastics
AC, R/F, WM/CD	50%	15%	15%	20%	-
sWEEE	13%	25%	50%	6%	6%

AC: air conditioners, R/F: refrigerators and freezers, WM/CD: washing machines and clothes dryers

Table 4 Distribution ratio of mixed WEEE plastics for each recovered plastic fraction by domestic plastics recyclers in Japan.

2.3 Estimation of the flow of BFRs through the recycling and disposal process

The flow of BFRs was estimated in a manner similar to that for the flow of WEEE plastics. The distribution ratio for each destination was set to the same value as the distribution ratio for WEEE plastics except for the processes in which the BFR-containing plastics would show different distribution behavior from that of the total mixed plastics. For example, during the sorting of mixed plastics, a substantial portion of the high-BFR-containing plastics can be separated into a high-specific-gravity fraction because they have a higher specific gravity than plastics that contain a low level of (or no) BFRs. As noted earlier, some plastic recyclers in Japan use X-ray sorting to further separate out high-BFR-containing plastics in order to increase the purity of the sorted plastics. We estimated the distribution ratios of BFRs for such processes based on previously reported experimental and analytical data [4,7] and interviews with WEEE plastics recyclers. Since the behavior of high-BFR-containing plastics during these sorting processes is determined by their elemental bromine content rather than by the individual compounds of BFRs, the flows of BFRs were estimated using the distribution ratios of the amount of elemental bromine.

3 Results and discussion

3.1 Destination of WEEE plastics

Figure 1 shows the estimated flows of WEEE plastics generated in Japan in 2017. Of the total end-of-life (EoL) products in the three specific home appliance categories included in the study (air conditioners, refrigerators and freezers, washing machines and

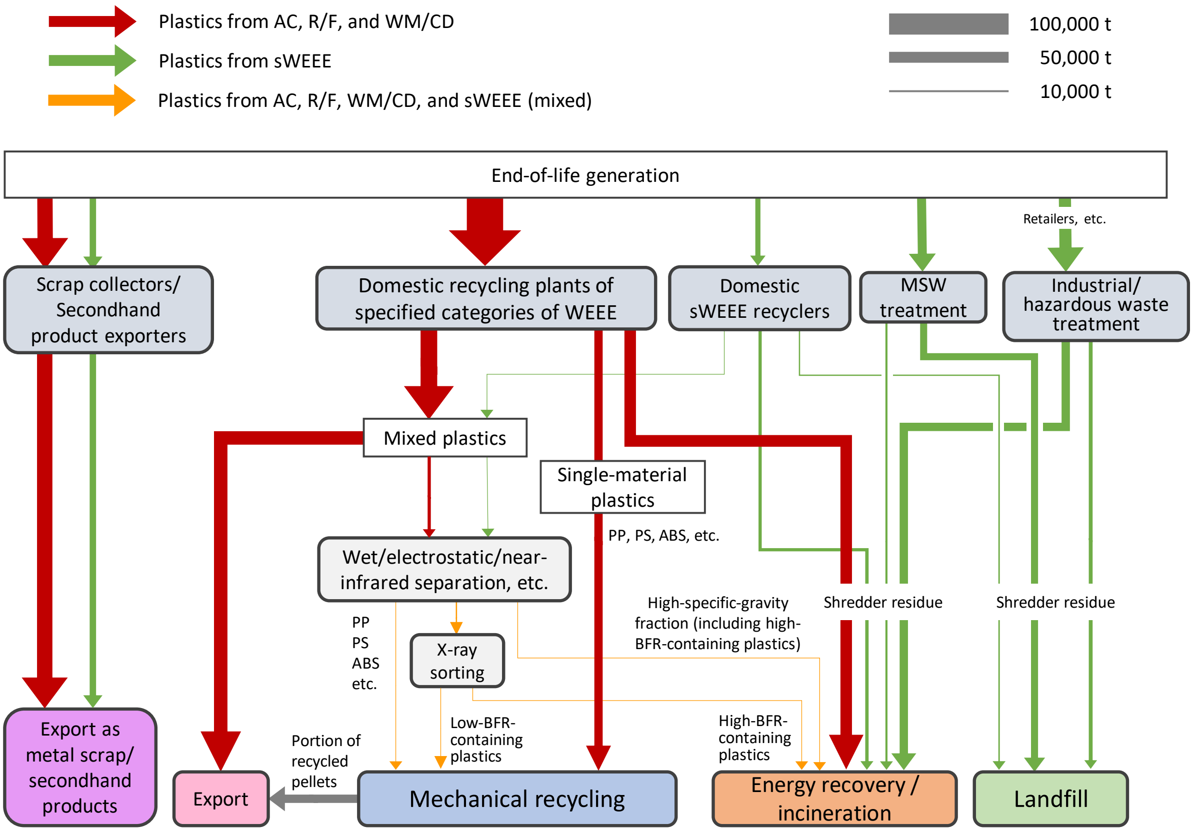

Figure 1 Estimated flows of plastics from three specific categories of home appliances (AC: air conditioners, R/F: refrigerators and freezers, WM/CD: washing machines and cloth dryers) and sWEEE generated in Japan (2017)

clothes dryers), approximately 70% were processed at domestic recycling plants operated or managed by manufacturers under the Home Appliance Recycling Law. The amount of plastics contained in these EoL products was estimated to be 173 thousand tons, most of which was recovered as mixed plastics (approximately 50%) or as shredder residue (approximately 30%) by the designated WEEE recyclers.

As for sWEEE, according to the MoEJ, an estimated 450 thousand tons of EoL products were generated in Japan, which we estimated to contain around 154 thousand tons of plastic. Although most municipalities collect post-consumer sWEEE, many people still discard their end-of-life sWEEE as municipal solid waste. During the period under study, even designated recyclers were sending much of the plastics recovered from sWEEE to incinerators or landfill sites, as their focus was mainly on the recovery of metals from sWEEE and thus, in many cases, they were unable to process plastics. Only some of the designated sWEEE recyclers recovered plastics (mainly as mixed plastics), which were then shipped to plastic recyclers for mechanical recycling. We estimated this to account for only 10% of the plastics processed by designated sWEEE recyclers (1%–2% of total plastic from EoL sWEEE) in 2017. According to our interviews and questionnaire survey of sWEEE recyclers, this situation had not changed substantially in 2019.

In 2017, most of the recovered mixed WEEE plastics in Japan were exported, mainly to China, and only a small portion was recycled by domestic plastics recyclers. However, owing to the implementation of the China import ban on post-industrial plastic waste and other import restrictions in Southeast Asian countries, the export of mixed plastics is likely to show a significant decrease. In response to this, several large facilities for processing mixed WEEE plastics have been constructed in Japan during the past 1–2 years, and the amount of mixed WEEE plastics domestically processed has almost certainly increased. According to our interviews with domestic plastic recyclers, however, a large portion of the recycled pellets from WEEE plastics is still being exported to China and other Asian countries. Some of those interviewed noted that recycled pellets were being shipped to Chinese electronics companies, suggesting that a certain amount of recycled WEEE plastics may be being used for new electrical and electronic products. Other stakeholders, however, told us that the majority of the recycled pellets are being used for building materials, and that only a small portion is being used for new electrical and electronics products in Japan.

According to the MoEJ estimates, approximately 30% of the EoL products in the three home appliance categories targeted in this study and 20% of the EoL sWEEE were exported as mixed metal scrap in 2017. This is equivalent to 71 and 31 thousand tons of plastics, respectively. These numbers were expected to decrease in 2019 owing to the strengthened government regulations on the export of mixed metal scrap from Japan, which took effect in 2018. This change will almost certainly result in increasing the amount of WEEE and WEEE plastics processed by domestic recyclers and municipalities as MSW.

3.2 Flows of WEEE plastics during the sorting processes of mixed plastics

Domestic WEEE plastic recyclers commonly use a combination of wet specific-gravity sorting and electrostatic sorting or near-infrared sorting to separate mixed WEEE plastics into PP, PS, and ABS, although details of the processes differ depending on the facility. The sorted PP, PS, and ABS are then converted into pellets that are either consumed domestically or exported for use overseas. The proportion of the various types of plastics sorted varies across the three categories of home appliances and sWEEE, but, the estimated total amount of the sorted PP, PS, and ABS accounted for 15 thousand tons in 2017.

An estimated 3.3 thousand tons of high-specific-gravity plastics were generated from the wet specific-gravity sorting process. This fraction includes high-BFR-containing plastics. In addition, an estimated 1.6 thousand tons of high-BFR-containing plastics were separated from the sorted plastics by X-ray sorting at some of the WEEE plastic recycling facilities.

3.3 BFR flow through the recycling and disposal process of WEEE and plastics

Interviews with domestic WEEE plastic recyclers revealed that a substantial amount of the high-BFR-containing plastics are separated from the bulk mixed WEEE plastics by wet specific-gravity separation. This is because these plastics have a higher specific gravity than plastics that contain lower levels of BFRs. Based on experimentally acquired data on the behavior of BFRs during the sorting process, we estimated that 50% of the high-BFR-containing plastics were separated from the total plastics by wet specific-gravity separation. As previously described, this fraction is mainly incinerated (including energy recovery). Incineration (hazardous waste incineration) is listed among the destructive and irreversible transformation methods for POPs (including the regulated BFRs) in the technical guidelines of the Basel Convention [8]. We then considered that approximately half of the BFRs contained in the mixed WEEE plastics are eliminated from the recycling chain and properly destroyed as a result of this separation.

Following wet specific-gravity separation, a portion of the remaining mixed plastics is processed through X-ray sorting by some of the WEEE plastic recyclers in order to further separate out high-BFR-containing plastics. Our estimates show that 5% of the BFRs contained in the processed plastics were distributed to the low-BFR-containing plastic fraction (~95% of BFRs were eliminated) by X-ray sorting, whereas approximately 80% of the plastics were recovered as the low-BFR-containing plastic fraction used for mechanical recycling.

3.4 After China's import ban on plastic waste

As previously discussed, we assumed that the amount of WEEE and mixed WEEE plastics domestically processed in Japan would increase after 2018 owing to the enforcement of the China import ban on post-industrial plastic waste and the Japanese government's tightened regulation of exports of WEEE as mixed metal scrap from Japan. Further assuming that all the WEEE and WEEE plastics in Japan are treated by domestic recyclers and municipalities and that the same parameters (distribution ratios for the various destinations and the recovered material fractions) can be applied, the destinations of WEEE plastics generated in Japan and the BFRs contained therein were estimated for the most recent year (2019).

We estimated that the proportion of domestic mechanical recycling of WEEE plastics would increase from 13% of the EoL generation in 2017 to over 30%. In terms of BFR flows, it was estimated that approximately 50% of the BFR content in the EoL product total was exported in the form of mixed metal scrap or mixed WEEE plastics in 2017. Because the recycling situation involving exported WEEE plastics was unclear, we were concerned that a portion of the BFRs was mixed into the recycled plastic products. However, we estimated that a majority (approximately 80%) was incinerated in 2019, suggesting that China's import ban and the more stringent Japanese regulations on mixed metal scrap export has resulted in promoting appropriate management of the BFRs contained in WEEE plastics.

4 Conclusions

In this study, we estimated the flows of WEEE plastics (including sWEEE plastics) and BFR-containing plastics through Japan's recycling and disposal process. We found that the majority of WEEE plastics were recovered as mixed plastics or shredder residues by domestic WEEE recyclers. In 2017, a large part of the recovered mixed plastics was being exported to other countries. However, it was expected that this amount would decrease markedly in 2019 owing to the Chinese import ban on plastic waste and Japan's increased regulation of mixed metal scrap exports.

We found that a substantial percentage of the high-BFR-containing plastics in the bulk mixed plastics were being removed by wet specific-gravity separation and X-ray sorting, and subsequently incinerated, indicating that a large fraction of the BFRs in the original mixed WEEE plastic was being eliminated from the plastic recycling chain. The proportion of BFRs to be incinerated was expected to increase after China's import ban on plastic waste, which suggests that China's ban and the new Japanese regulations on mixed metal scrap export have promoted proper management (destruction by incineration) of the BFRs contained in WEEE plastics.

Usefully, the distribution ratios of plastics and BFRs described in this study can be applied to similar processes, as they are basically determined by existing sorting technologies. Thus, it would be possible to apply these parameters to estimate the flows of WEEE plastics and the associated BFRs in countries where similar processes are used.

5 Acknowledgment

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Development of Life-Cycle Inventories on recycled plastics from WEEE to promote the integration of recycled plastics into EEE

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Abstract

In 2017, **ecosystem** published a Life Cycle Inventories (LCI) database on waste electrical and electronic equipment (WEEE) management. This database contributes to solve several challenges faced by producers to adopt a circular approach, notably by providing them with robust data to model the end-of-life of their products.
In 2019, **ecosystem** launched complementarily a project for the development of LCI of recycled plastics from WEEE. This project aims at improving the consideration of the environmental benefits associated with the integration in products of plastics coming from WEEE recycling. This study addresses some current gaps in the environmental datasets available on recycled plastics, especially from WEEE sector. This work is also part of a more global approach to assess the global benefits associated with recycled plastics from WEEE. Since this project is still under development., this paper will expose the main challenges encountered for the modelling of such LCI.

1 Introduction

Representing about 4000 Electrical and Electronic Equipment (EEE) producers, **ecosystem** is a non-profit organisation accredited by the French Public Authorities to collect, depollute and recycle household WEEE, professional equipment (professional WEEE), lamps and small fire extinguishers. In 2019, **ecosystem** achieved the collection of more than 643 000 tons of WEEE.

ecosystem assists its producer members through the various stages of "end of life" oriented ecodesign approach in order to design sustainable products and reduce their environmental impact. Among other, **ecosystem** supports recycled materials integration in EEE and especially the use of recycled polymers. Through its special position between producers and recyclers/regenerators, **ecosystem** plays a facilitating role in the emergence of projects for the integration of recycled materials.

In order to support recycled plastics integration projects and to meet a demand from various producer members, **ecosystem** launched 2019 the development of LCI of recycled plastics from WEEE. This project aims at filling a data gap regarding the data available to assess the global environmental impacts associated with the use of recycled plastics from WEEE, especially for closed-loop recycled plastics (WEEE to EEE).

The main challenge of this work is to model, out of the combination of a multi-step and a multi-actor chain, the different stages a recycled plastic goes through, from the electr(on)ic waste to its regeneration.

This project is still in progress. This paper aims at providing an overview of the challenges encountered to model such LCI in a robust way, representative of the complexity of the WEEE recycling chain.

2 From WEEE to recycled plastics, a multi-stakeholders and multi-steps chain

2.1 The chain organised by ecosystem in France

ecosystem is one of the two Producers Compliance schemes accredited in France for the collection and treatment of WEEE. In 2019, **ecosystem** achieved the collection of more than 643 000 tons of WEEE, which represents about 75% of the WEEE collected in France.

To ensure a proper management of WEEE, **ecosystem** contracts with logistic operators to collect waste and recycling operators who carry out the decontamination and treatment of the WEEE collected. These operators perform the first steps of the WEEE treatment, necessary to separate the main materials that the WEEE contains into specific fractions. Other stakeholders then take over, to continue the processing of the different fractions until their final regeneration or recovery or elimination.

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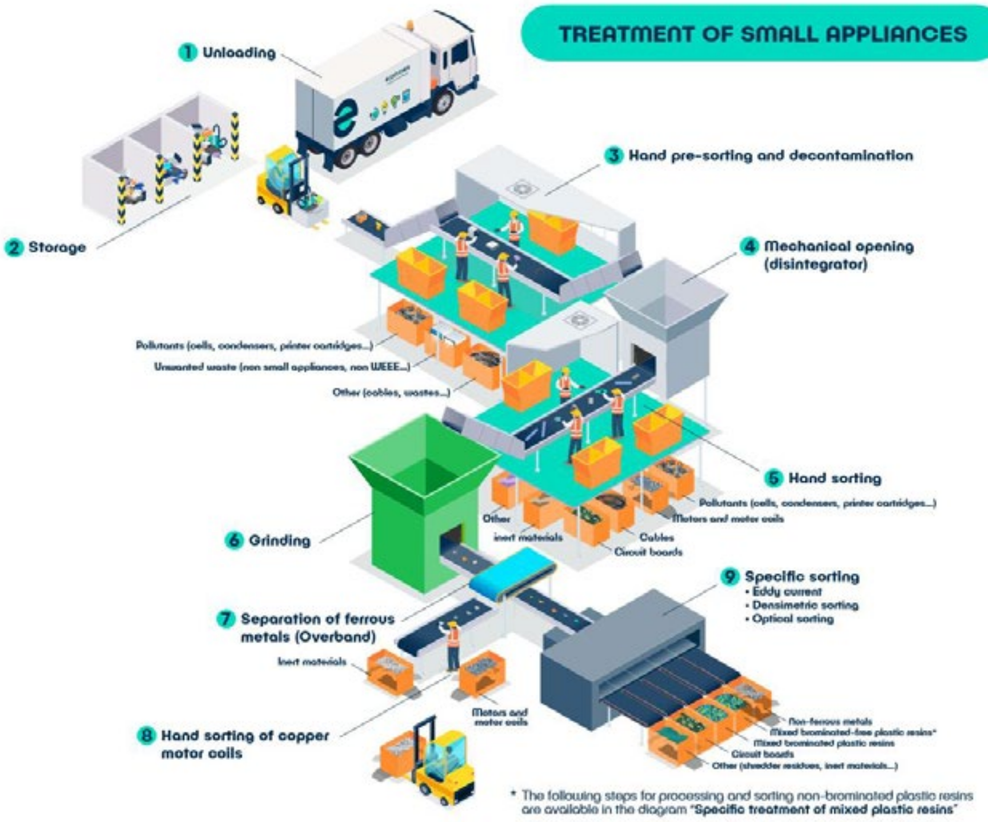

Figure 1: Operational steps for the treatment of small appliances (SHA)

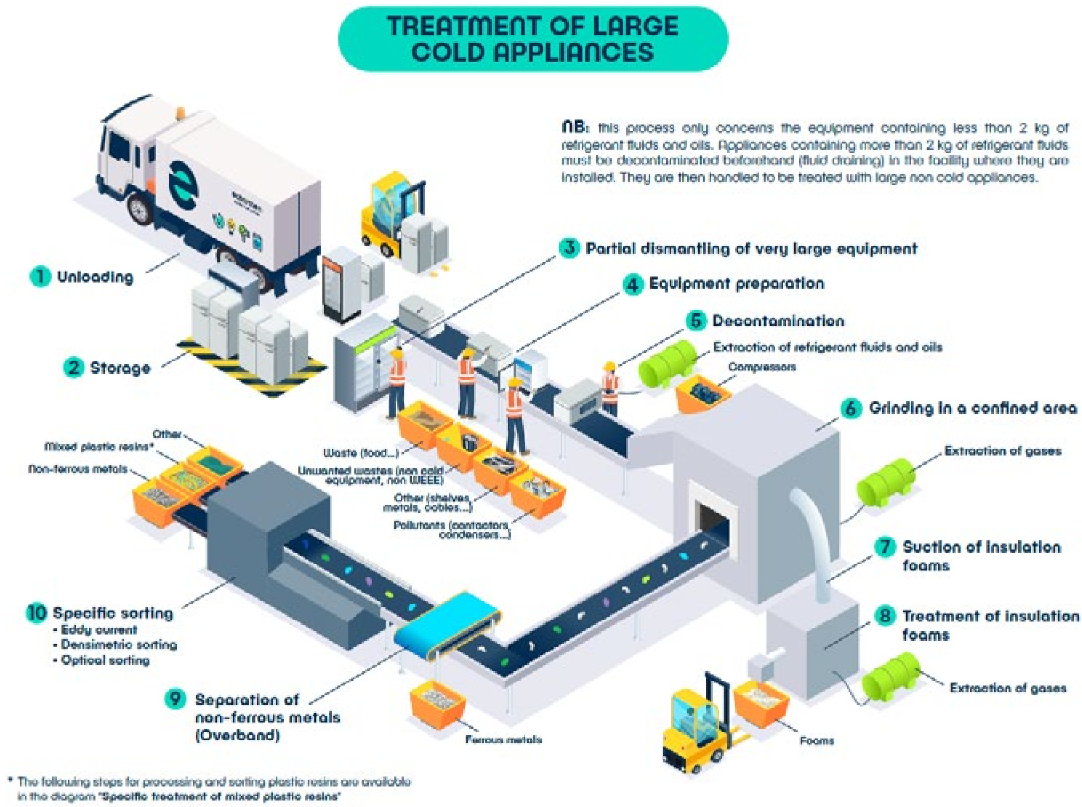

Figure 2: Operational steps for the treatment of large cold appliances (LHA cold)

2.2 A chain structured in WEEE streams

WEEE are collected and treated in specific streams. The organisation in streams is necessary to perform an efficient depollution of some specific categories of equipment, gathered in a same stream.

For example, the recycling of household WEEE is organised in five WEEE streams:

- Large cooling household appliances (LHA cold) such as refrigerators, air conditioning equipment… whose gases have to be extracted and neutralised.
- Large household appliances non cold (LHA non cold) such as washing machines, clothes dryers, electric stoves…).
- Small household appliances (SHA) which include a wide range of small equipment such as vacuum cleaners, microwaves, mobile phones, electric kettles…:
- Flat screens and CRT screens (Screens) parts or components of which require a special decontamination.
- Lamps.

In each stream, equipment follows successive processing steps to decontaminate, open and grind the WEEE, detect and sort the different materials by material families (e.g. ferrous metals, non-ferrous metals, mixed plastics fraction…). In the specific cases of SHA and Screens, an additional step has to be performed on the plastic fraction to isolate the resins containing brominated flame retardants.

These steps vary from a WEEE stream to another one. Figure 1 details an example of the treatment steps of SHA and Figure 2 an example of the treatment of LHA cold. In the case of SHA, several steps for depollution can be observed. In LHA cold, other steps allowing the extraction of refrigerant fluids and oils are added. The grinding is also be performed in a confined area to capture the gases present in the insulating foams Each treatment step is characterised by several materials outputs. The scheme for other treatment processes are available on **ecosystem** website [1].

2.3 Some plastics in WEEE

Depending on the WEEE stream, the plastic share among the other materials may vary. The program that **ecosystem** carries out on the analysis of material composition of the streams, shows that there is for example almost two times more plastics in LHA cold and in SHA streams than in LHA non cold.

The nature of the polymers and their share in the total plastic content may also vary. PS and ABS are the main plastic polymers found in LHA cold, while in SHA, ABS, ABS/PC and PP represents more than 80% of the resins found.

Beyond these criteria, other parameters are to be considered. The nature and share of plastics containing fillers is not constant from one stream to the next, as well as the share of plastics containing brominated flames retardants. This influences a lot the quantities of plastics which can be recycled in the end and thus the quantities of output material along the treatment chain.

Colours are significatively different from a stream to another. The LHA stream is generally characterised by lighter colours while SHA stream gives a mix of colours (see Figure 3).

Figure 3: Mixed plastic fraction from SHA treatment.

If plastic fractions composition is different by streams, it is also true at the level of the first operators who propose several kinds of plastic fractions (more or less pure in terms of plastic content purity) to the downstream stakeholders, depending on the processes steps they perform on their sites. .

2.4 Recycled plastics from WEEE

After the treatment of WEEE and the obtention of a mixed brominated-free plastic fraction, the polymers in the fraction still have to be separated.

As for the equipment treatment, the treatment of mixed plastic resins until their final regeneration (extrusion and granulation) requires several steps, including a new sorting to separate residual metals and unwanted wastes, grinding, washing, resins sorting which can imply several successive sorting techniques (see Figure 4). As for the equipment, each of these steps leads to the separation of materials, then oriented towards recycling, recovery or elimination.

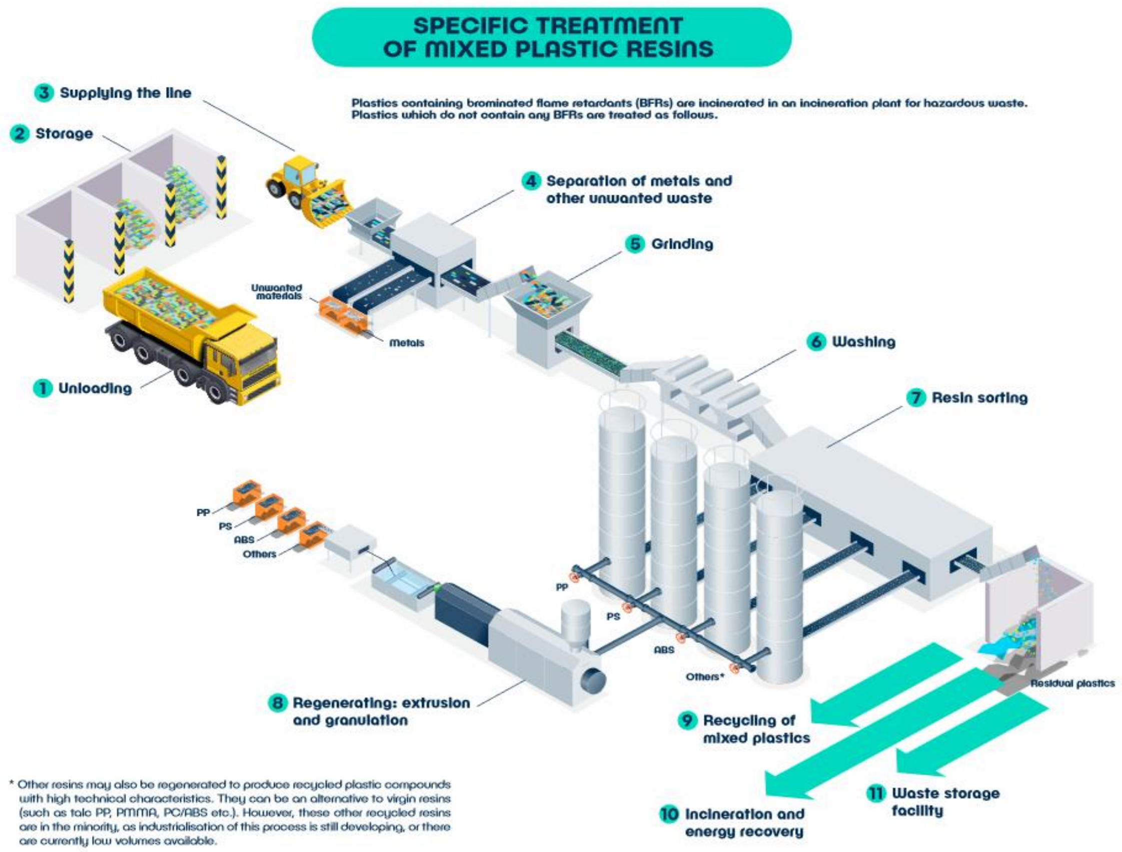

Figure 4: Specific treatment of mixed plastic resins after this fraction has been isolated from the others

On the almost 20 families of plastic polymers potentially present in shredded mixed plastics from WEEE, to date, about 5 will be recycled in the end, because:

- Appropriate recycling operational technologies are available (e.g. thermoplastic vs. thermoset resins).
- They have specific technical features (including their density) enabling their identification, and thereby their efficient sorting.
- They are present in large quantities making their recycling efficient from a technical and economic point of view

These resins are PP, ABS, PS and to a lesser extent, ABS/PC and PC.

2.5 Plastic regeneration and varying levels of integration

The future use of the recycled resins influences the number of treatment steps and their complexity. Indeed, depending on the use, the process could stop when reaching plastics under a flake form; continuing until the granulate form requires to add an extrusion and granulation step. An additional sorting by colours may also be necessary for specific applications requiring light-coloured recycled plastics. This will be done especially on plastic fractions coming from LHA cold (containing mainly light plastics) for economic reasons. The level of purity required may also evolve depending on the use and the technical specifications expected by products manufacturers.

Moreover, starting from WEEE, plastics recycling requires a succession of multiple processes with various stakeholders that can cover different steps of the chain. This succession of processes is specific to the stakeholders involved. For example, some will perform the brominated sorting and a first separation by resin families, others will not perform the brominated sorting but will cover all the steps to resins sorting, some may perform an additional sorting of the unwanted materials in the plastic fraction and then the sorting of the resins, etc.

The nature (complexity – multiple resins, purity – presence of residual metals…) of the plastic fraction from WEEE entering the "regenerators" can thus be very variable. In addition to this variability, it must be taken into account that most "regenerators" receive resins from different sectors (packaging, end-of-life vehicules…), in quantities that can be much higher than plastics from WEEE sector.

These elements highlight the global complexity of the WEEE treatment chain (and its interaction with other sectors) which is composed of many stakeholders with their own expertise and specialities.

3 Main steps towards the construction of recycled plastics from WEEE LCI

Based this overview of the WEEE recycling chain, the development of the LCI of recycled plastics from WEEE has been organised in 5 main stages.

3.1 Perimeter definition

This LCI development aims at screening the environmental impacts associated with recycled resins from WEEE. From a manufacturer perspective, this work should help measuring the environmental benefit of such plastic recyclates in comparison with a virgin resin he could have used instead. Consequently, the different steps covered in these LCI include the upstream stages which lead to the plastic mix entering the “regeneration” step.

These LCI thus intend to cover all the steps from the WEEE collection and treatment steps to a recycled plastic resin.

3.2 Consideration of upstream stages and data collection

Through the work **ecosystem** first published in 2017, all data needed to cover the upstream stages have already been consolidated. This previous work, also based on a Life Cycle Assessment (LCA) approach, allowed the collection, aggregation and consolidation of data from the field. In particular, these data model all stages of transportation, depollution, first sorting and further sorting as structured in France.

Details on this previous work are freely available [2].

3.3 Consideration of “regeneration” steps and data collection

To precisely model the regeneration steps with all its complexity, data must be gathered from the field. This implies first to identify the key stakeholder performing these “regeneration” steps and then to perform the data collection.

For the need of its activities, **ecosystem** contracts with the first operators of the value chain insuring the depollution and the first steps of material sorting. This makes it possible to check that the decontamination is carried out in compliance with the most challenging standards Then, the important number of operators alongside the value chain, makes it more difficult to have a precise overview of all the stakeholders and their representativity (which may vary from a year to another) on all the plastic resins recycled from WEEE coming from France.

Some other **ecosystem** studies (e.g. to accompany EEE manufacturers in integrating recycled plastics) made the identification of the key European stakeholders regenerating plastics from WEEE collected in France easier. The panel of “regenerators” who accepted to join this study, despite the investment of time that it represents, makes it possible to guarantee the confidentiality of the data which could be published in the end, through aggregation. This is often a prerequisite for the running of such projects. Future updates could lead to integrate even more stakeholders to improve representativeness.

Indeed, the modelling of this stage involves data collection on several process-related parameters and especially on consumptions and emissions to build the LCI. The data collection has been performed through a questionnaire to first gather data and then allow easily to complete them or discuss the way to get data which are not easily accessible. For example, energy consumptions such as emissions are most often monitored at the site level. This raises methodological questions when the site produces several recycled plastic resins (questions to allocate the consumptions between the different resins) or when the site produces different versions for the same plastic with specific format and/or properties (e.g. questions on how to separate the main steps of the process to allocate the right consumptions/ emissions to the resin under flake version vs under granulate version). Going down to this level of details is very time-consuming but greatly benefits the robustness of the study.

3.4 Methodological arbitrations

All the previous points presented in this paper highlight the methodological challenges the development of LCI recycled plastics from WEEE raise. Such study thus needs to consider a real time for methodological arbitrations.

Methodological issues are pointed out in the following section.

3.5 Modelling under an LCA software

All the data collected feeds the model built under an LCA software. When all the work is completed, a final work to edit the LCI will be necessary.

4 Methodological issues

The structure and complexity of the WEEE recycling chain raise several methodological issues. Work is still in progress to solve these issues. Choices will be submitted to a critical review process, which will rule on the validity of the choices made.

4.1 Perimeter definition as regards the use of the LCI

ecosystem assists its producer members in integrating recycled materials from WEEE into new products. The development of these LCI will help to answer a question that is often asked on the benefits for the environment to integrate in the product a recycled resin instead of a virgin resin. **ecosystem** launched the development of these LCI to meet these questionings.

In order to allow the comparison between recycled and virgin resins, perimeters must be comparable. This means the LCI of the recycled resins must cover all the steps from plastic collection through the WEEE collected to the regeneration of the recycled resin (in equivalence to the different steps from raw material extractions to the virgin resin production). For the recycled resins, the first steps (transportation, WEEE material sorting…) imply consumptions and emissions which won't be negligible as regards the consumption and emissions of the whole chain.

With a view to using these data for the entire life cycle modelling of a product, LCA practitioners should pay special attention to the allocation rules between the upstream and downstream of the life cycle to avoid double counting.

4.2 Allocation issues along the chain

Allocation issues arise at each step of the chain. The following sections list some examples where allocations are necessary.

4.2.1 WEEE collection

As previously detailed, each WEEE stream contains a wide range of materials. These materials may be:

- plastic resins targeted for recycling and which will be recycled
- plastic resins targeted for recycling, but which will not be recycled (e.g. pieces made of PP but oriented to the "wrong" fraction due to sorting errors caused by a gluing to another material)
- plastic resins not targeted for recycling (e.g. thermoset resins)
- Other materials.

For the development of LCI on recycled plastics, there is a need to determine which part of the collection should be allocated to the recycled plastics.

4.2.2 First treatment steps

As for collection, the plastics which will be recycled at the end go through different steps which are necessary for the depollution. For example, in the LHA cold stream, the whole products go through different steps to extract the refrigerant and insultation gases contained in the equipment (first extraction of fluids and grinding in a confined area with a system to capture the emitted gases). Then the gases are treated specifically to be eliminated. Should part of these consumptions and emissions be allocated to the plastic fraction to recycle?

In the same way, if the plastic fraction contained in the LHA cold stream goes through different steps allowing to sort the metals before sorting the plastic, should part of these steps be allocated to recycled plastics or to metal scraps?

4.2.3 Other steps

In the specific case of the SHA and Screens streams, plastic containing brominated flame retardants are separated to be eliminated in hazardous waste incineration plants. Should this sorting and elimination be allocated to the plastic targeted for recycling?

4.2.4 Regeneration steps

As detailed previously, the last steps toward the regeneration of plastic may also rise questions regarding allocations. Additional materials may be also sorted at this stage to reach a high level of purity for the plastic.

Some plastic may be eliminated because of a too high density or because the resins are not recyclable. Residual metals can be sorted too. In that case, should the impacts but also the benefits of sorting these additional materials and eliminating them (e.g. plastic with fillers) or regenerating them (e.g. residual metals) be taken into account?

The allocation choices have a significant influence on the LCI of recycled plastics from WEEE and the environmental impacts associated. That is why all these choices will be documented in the methodological report.

First answers

An assessment is always goal dependent. The current study aims at developing LCI of recycled plastics coming from WEEE management. The study does not intend to build LCI of the WEEE end-of-life or LCI of the end-of-life of the PP found in the WEEE streams. In this case, all the final destinations reached by the PP (recycling, recovery, elimination) should be integrated in the LCI. This study is also not about developing LCI of the whole activities of plastics "regenerators", which would have meant to have a close look at all the different fractions leaving their process.

Our point of view is that the technical choices for allocations must follow the key following principle: the waste management choices made for other materials than the recycled plastics should not influence the LCI and the environmental impacts of the recycled plastics. This means for example that impacts linked to gases treatment should not be allocated to the plastic resins of the LHA cold, as well as the benefits of residual metals recycling in the last steps.

4.3 Granularity issues

The recycled resins can be produced, for each resin, under different formats (e.g. flakes vs granulates), or with different properties (colours, levels of purity…). These format or properties imply that complementary steps may be added to the process, to reach specific characteristics. The environmental impacts of these additional steps might be significant compared to other steps. These formats and properties also influence the use which will be made of the resin.

In terms of LCI development, two options for the modelling are possible:

- To establish an average modelling for all the format and properties
- To establish detailed LCI for each plastic format, to reflect the reality of the processes implemented, which are not the same from one format to another.

In the first case, producing an average modelling can allow to use more global data established at a site level. It masks differences between the various formats by averaging them, and thus the potential environmental impacts variations for reaching some specific characteristics. It erases at the same time a part of the "regenerators" expertise to reach specific characteristics for their recycled material. This option could also lead to more variable LCI at each update (e.g. if at the update time the "regenerators" produce more granulates than flakes in average than during the first modelling).

The second option allows a better mapping of the various formats of plastic recyclates and their use. It is more oriented towards users of recycled materials It is however more difficult in terms of data collection (see section 3.3).

Whatever the final choice, it will imply to be very clear in the data description allowing the practitioners to compare properly the recycled plastic with virgin plastic, taking into account that the virgin plastics databases can also encounter limitations to represent the large spectrum of existing virgin plastics.

5 LCI use and perspectives

This study is part of a global approach to support recycled plastics integration projects and to promote the use of recycled plastics. It thus should help supporting works to use recycling plastics in substitution to virgin plastics. This naturally leads to the question of the recycled plastic quantity needed to replace the virgin resin. Feedbacks on this question are varied, and answers widely depend on the properties of the recycled resin considered, on specific properties given to the recycled resin through additional treatment steps, on the technical properties required for the part manufactured… For the LCA practitioner, using these LCI could thus lead to such questions.

Answering this additional question is also one of the main challenges of such studies. A comparison of plausible scenarios would shed some light on this part.

To conclude, this study is part of a more global project. The assessment of environmental benefits of such circular polymers will be put into perspective with social and economic issues in order to provide a complete set of arguments usable in the companies to different profiles (product developers, marketing department and decision makers) to promote the use of recycled plastics.

6 Literature

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B.3

RECYCLING SYSTEMS: COMPLIANCE SCHEMES AND WEEE DEVELOPMENTS

Strategies in EPR Compliance Operations from Producer's Perspective

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Abstract

Producers have a challenging time managing environmental impacts because legislation and implementation systems are completely unsynchronized – both within the EU and globally. WEEE legislation is particularly varied. Legislation appeared first in European countries and there is now a proliferation of legislation in regions and countries which include the European Union, the US, Canada, Japan, Mexico, Brazil and China. Yet, there is a lack of harmonization both within countries and between them.

The complex implementation of the WEEE Directive in different regions and the differing or absence of e-waste infrastructure in other regions also make it costly and resource intensive for producers to manage WEEE at a company level.

HP has been involved in all stages of WEEE Directive from the first conception in 1998 to WEEE II implementation. We operate in 28 EU countries and manage 87 contracts with Producer Responsibility Organizations (PROs). We deliver 766 compliance reports annually.

This paper describes various components of HP´s strategy in compliance operations to demonstrate how much effort and dedication a producer needs to put in order to fulfil its obligation beginning from addressing environmental management in their organizational structure, managing multiple compliance solutions through outsourcing of compliance operations, collaborative partnership to lobbying activities and value chain creation.

HP´s strategy in compliance operations

Setting out a clear environmental strategy is crucial, but for strategy to become practice, implementation is key. HP has found that different challenges affect different areas of the business. Thus, the most effective way to ensure responsible environmental management across the business is for it to be integrated. At HP, integration has been promoted by creating environmentally focused job roles and internal goals throughout the business units. However, although the implementation of the environmental strategies is in the hands of all business units, compliance assurance processes are managed centrally across the company. This is necessary to ensure the requirements of hundreds national environmental regulations are met. At HP, more than 200 people globally work solely on sustainability and product compliance. Complying with legal obligations is a matter of collaboration between different environmental teams. Product Stewardship and Technical Regulation Specialists take care of environmental labels and user information to be included in the product. Environmental Country Managers work with policy makers and authorities in helping create more effective legislation and clarify ambiguities. They track and interpret legislation and communicate their findings to Program Managers. Program Managers are in turn in charge of take back compliance operations necessary to comply with the legal requirements. They work with Reporting Managers, IT Specialists, Engineers, Product Managers and also auditors to demonstrate to local government authorities that HP takes responsibility not only for the environmental impacts of their products downstream by recycling and proper product disposal, but also for their upstream activities inherent in the material selection and in the product design.

WEEE Directive implementation in Member States

The WEEE Directive has been implemented in each Member State, through the transposition of the Directive into national law. Figure 1 depicts the high level requirements from producer' perspective, laid out in the WEEE Directive implementation at the Member State Level. The obligations can be split into two areas:

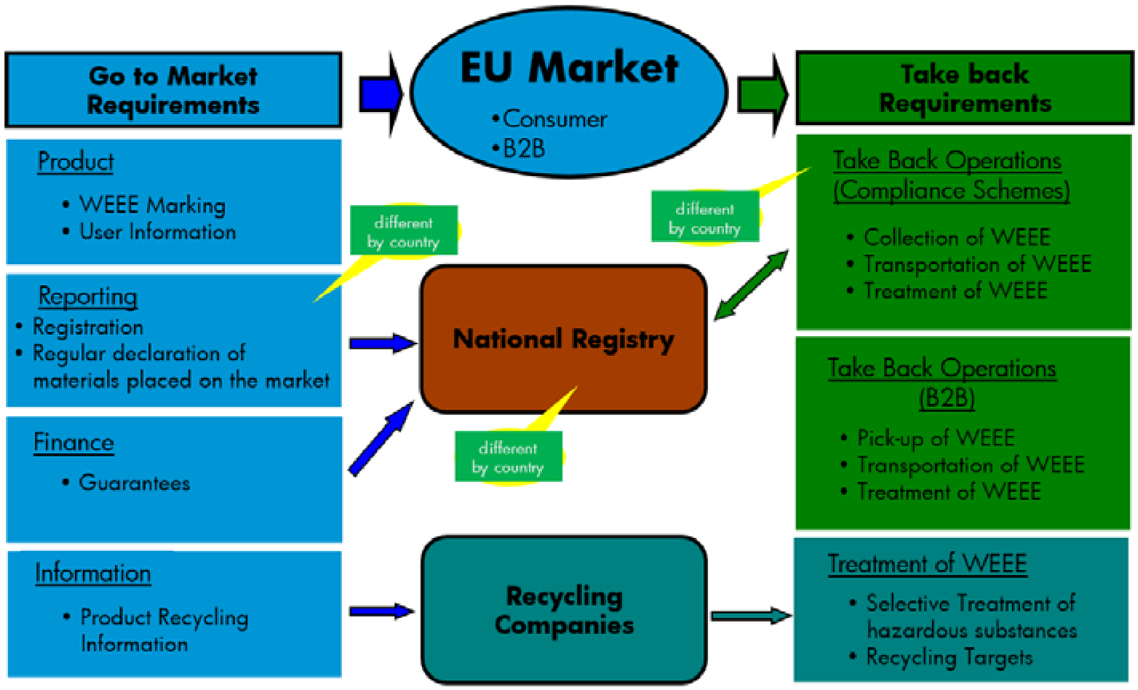


Figure 1. Producer`s obligation

1. Go to market requirements such as registration, reporting, financial guarantee's and product marking.
2. Take back requirements such as operation of collection and recycling obligations and treatment processes and recovery rates.

The requirements for compliance differ considerably country by country.

In order to place products on the market, HP must register in the National WEEE Registry in each EU Member State, label their products, and make information available to users about proper product disposal. Often the requirement of where this information must be located or how it must be transmitted varies from country to country with considerable ambiguity. Based on real product quantities placed on the national market and product weight information, HP must make periodic declarations to the national authorities of how much it sells in each Member State. The format of these declarations varies from country to country and from one PRO to another. HP also makes available to recyclers dismantling guides and recommendations for easy dismantling, depollution and recovery of WEEE as required by the Directive. When it comes to end of life treatment obligations, HP takes responsibility for its products after use. HP organizes take back and recycling of WEEE with the support of PROs for household customers, while to serve its commercial customers HP set up Planet Partner Program with recyclers and Asset Recovery organizations to offer its commercial customers free B2B services. The evidence of material quantities collected and treated is reported to National Registry to show that HP´s producer obligation has been met.

Experience with multiple compliance solutions

HP´s main strategy for complying with WEEE Directive has been through the emergence of Producer Responsibility Organisations (PROs), established to carry out part of the obligations of Producers, namely, the collection and treatment of WEEE from private households. Depending on the Member State there are different rules of PROs. In some Member States the PROs must be a consortium not for profit (e.g. Italy), in other Member States they can be for profit (e.g. UK). Across the 28 EU Member States, 6 PROs operate under monopoly regimes for WEEE compliance (i.e. obligated producers have one option only) and 22 Member States have competitive markets for producer compliance. Two notable outliers are the UK and Germany. At the time of writing, the UK has 36 approved producer PROs by the EA and Germany officially has no PROs, but multiple options for producers looking to outsource their obligations via recyclers or consultancies. Germany implemented the Individual Producer Responsibility which means that regulation does not permit collective compliance and makes Producers responsible for their own waste products.

Compliance to the WEEE obligations at Member State level requires individual country contracts with recyclers and compliance organisations to be established. In other words compliance is a country by country affair. This adds complexity to daily compliance operations in HP. Each local sales entity needs to be a member of, most often, three different PROs to fulfil producer´s obligation of WEEE, batteries and waste packaging. Having centralized the compliance management in HP, the Take Back Operations team is in charge of communication with multiple PROs and recyclers. This requires full time staff dedicated to managing the complexities which are inherent with a multi-vendor, multi-country compliance program such as frequent changes in reporting requirements, price fluctuation, audits and data analysis.

In addition to reporting obligation, HP must finance the recycling of WEEE in each Member State and also the administration of this obligation varies considerably. PROs established numerous methods of calculating financial obligation based on product volumes declared, e.g. per collected treated volumes or per put-on-the-market volumes from previous month or quarter of the current year or previous one, two or even three years. In some countries financial obligation depends also on the market share and number of members in the compliance scheme. Compliance material fees can also fluctuate depending on raw material prices. In addition to the volume-dependent compliance cost, there are annual fees and communication campaigns charges. After submitting end of year declarations of volume placed on market to PROs, a producer often receives a balance report that result in adjustment between the invoices paid during the year and total obligation. The administration complexity of producer´s compliance cost requires a robust process of invoice coordination and financial forecasting.

IT infrastructure for compliance management

A major part of complying with WEEE requires the correct reporting or product sales in scope of the Directive. Reporting formats, reporting periodicity and even scope of reporting vary country to country. For example if HP sells a product from country A to a distributor in country B, this sale might be excluded from HP's Producer obligation in country B, due to the definition of Producer in country B. On the other hand, if HP in country A, sells to an end user in country B (by distance communication) this is most likely an HP producer obligation in country B. For another country "C" sales made to a distributor in that country from country A may, contrary to the EU definition of "Producer" be an HP obligation. Knowing all the nuances in producer definition and scope of the Directive in each Member State is important to ensure an accurate and compliant reporting is made.

In order to manage the complexities in reporting, HP has developed specific IT tools that are essential for compliance management. Timely delivery of the reports to local authorities and PROs which differs across Member States would be impossible to prepare manually taking the extensive product portfolio that include thousands of products having a unique specification and the varying reporting requirements of each Member State. HP has to present the information to the local authorities and PROs often monthly or quarterly, making the beginning of the following month or quarter a period of high workload for the reporting team. A Compliance Calendar has been defined and implemented to keep track of reporting frequency and delivery timelines.

In the back end, HP has developed the Business Objects web-based tool for data retrieval and report generation that generates reports with details on sales and products and allows HP the adjustment of the parameters e.g. sales channels or sales entities to report according to legal requirements (Figure 2).

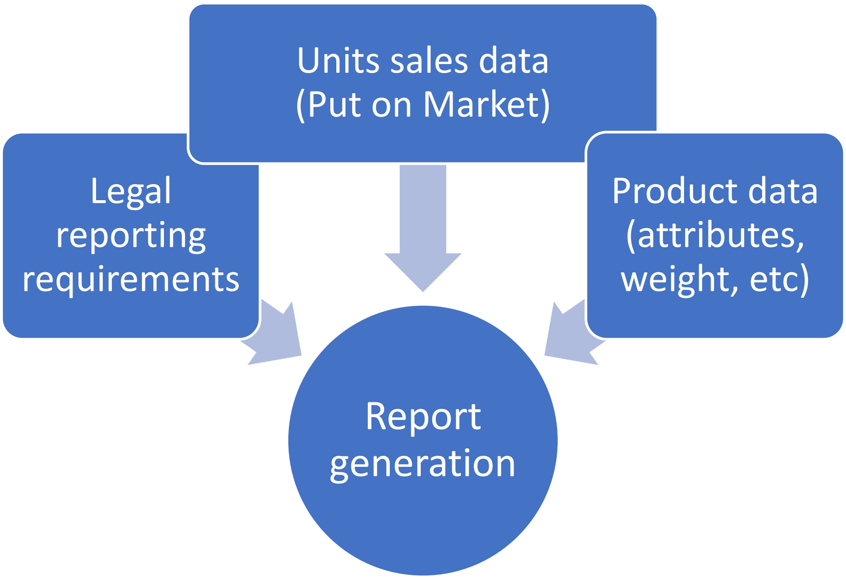
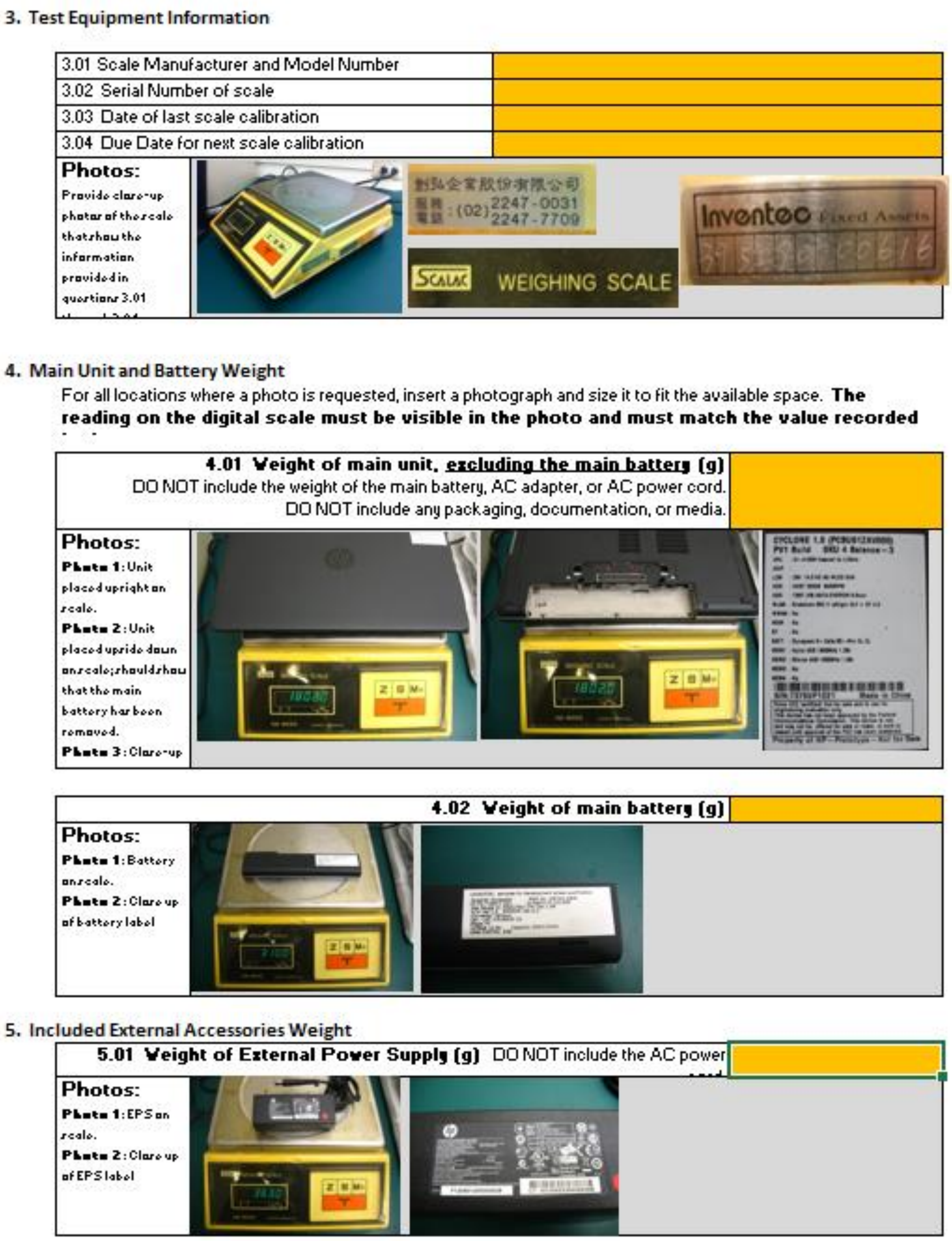


Figure 2. Input information to report generation

While the sales data come from the common system used also by other HP departments, the product information database has been developed specially for the purpose of take back compliance reporting. This database contains information on product components, its materials and weight relevant for WEEE, associated packaging and battery chemistry relevant for Packaging and Battery Directive reporting. The level of details is aligned with all the compliance requirements in all countries. Product information is sourced from engineers and is recorded in special files created for every new product (Figure 3). These files contain information about product weight, material contents, and recyclability and contain photo evidence of the weight of the product and each sub-components (such as mouse, product battery, cables and cartridges).



3. Test Equipment Information

3.01 Scale Manufacturer and Model Number	
3.02 Serial Number of scale	
3.03 Date of last scale calibration	
3.04 Due Date for next scale calibration	

Photos: Provide close-up photos of the scale that show the information provided in questions 3.01

4. Main Unit and Battery Weight

For all locations where a photo is requested, insert a photograph and size it to fit the available space. **The reading on the digital scale must be visible in the photo and must match the value recorded**

4.01 Weight of main unit, excluding the main battery (g)
DO NOT include the weight of the main battery, AC adapter, or AC power cord.
DO NOT include any packaging, documentation, or media.

Photos: **Photo 1:** Unit placed upright on scale. **Photo 2:** Unit placed upside down on scale; should show that the main battery has been removed. **Photo 3:** Close-up

4.02 Weight of main battery (g)

Photos: **Photo 1:** Battery on scale. **Photo 2:** Close up of battery label

5. Included External Accessories Weight

5.01 Weight of External Power Supply (g) DO NOT include the AC power

Photos: **Photo 1:** EPS on scale. **Photo 2:** Close up of EPS label

Figure 3. Photo proves of product weight

HP established data validation process for every report to be checked in terms of completeness and consistency before delivering to national authorities. The new reports are compared against the previous ones (on the total level as well as category by category) to understand the trend of volumes reported over time and to check alignment between reported volumes of WEEE, packaging and batteries.

Once data quality is validated, report submission takes place. Submission method differs depending on the PRO or National Registries and requires manual work every month. Some schemes require data submission using their specific codes, others want it according to HTS codes and other require it according to the WEEE category codes 1-10. Some report submissions are manual and must be signed by a Director representing the HP national entity, others can be made online. Some online tools used by schemes do not allow automatic data upload and require manual submission, category by category. This means that despite developing IT infrastructure in HP for compliance management, this process is still cumbersome due to limitations of the vendors and environmental authorities to which reports need to be delivered.

Maturity of Producer Responsibility Organisations

Since the publication and transposition of the WEEE Directive in 2012, comprehensive WEEE collection networks have been built and rolled out across the 28 EU Member States. The number of WEEE specific treatment plants increased, logistic companies and collection points started to create activity dedicated to WEEE, PROs were created, WEEE registers and coordination centres emerged and supporting businesses such as consultancies and legal advisers specialised in WEEE matters were established.

Some of PROs now combine their resources and expertise to provide new compliance solutions to producers which include the fulfilment of both bureaucratic administrative obligations and the management of operational obligations. Joint forces of PROs resulted in coalitions, e.g. WEEEForum which has been created to offer EU Wide compliance solutions that help simplify compliance for producers. Similar initiatives have also been taken by companies such as WEEELogic, Reverse Logistics Group and Landbell Group which change their focus from compliance operations at the country level to pan European compliance solutions. These companies have developed compliance software and begun offering total compliance management solutions that are designed to take over several elements of compliance activities from producers especially beyond the country border.

Outsourcing of compliance management

In order to reduce the complexity of operations, HP has decided to outsource some part of compliance operations to organisations of a unique pan-European set-up and broad experience in service optimisation through its extended network. These organisations create control towers which established their own recycling standards and reporting tools. They consist of local teams managing the daily local activities and a European team coordinating cross country services to optimise the internal organisation and to help multinational companies like HP fulfil their obligations in different countries. These organisations operate as a bridge between the producer and the local authorities, in the same way as national PROs, with the additional advantage that the compliance support services are provided by a central dedicated team of compliance experts to multiple countries. In countries, especially where these organisations do not operate directly or in which monopolistic organisations/schemes are the norm, they have built relationships with local PROs.

Outsourcing some compliance operations as described above can drive improvement of internal control, increase efficiency and optimize costs while reducing work burden for HP in non-core activities. The organisations which specialise in reducing the complexity of extended producer responsibility legislation, have compliance solutions in the heart of their business. Their sharp business focus and economy of scale of their operations have encouraged HP to create partnerships with them for strategic leverage. Such leverage helps both parties to increase their core competences and benefit from collaboration. Thanks to support of received in compliance operations, HP can dedicate more time to enhance a circular, low-carbon economy – continuing to transition our company and our customers from linear “take, make, discard” toward a more circular “make, use, return” approach. Examples of current projects under development are sourcing of recycling plastic and new value chains creation.

"Fast Tracks": a requirement for a Circular Economy of Electronic Wastes within the EU.

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Abstract

In the European Union, the principle for the free movement of goods involves the removal of all trade barriers between the member states. As principle, goods that have once been lawfully placed in the internal market of the European Union can move freely in the market. Unfortunately, this wonderful principle does not count for recyclable wastes. The EU has decided to implement the Waste Shipment Regulation that is based upon the principles of the Basel Convention. After the classification of the waste into a range of waste codes, an ever-increasing amount of wastes types need notifications. This is a complex administrative procedure to obtain prior consent for international shipments of these wastes, which involves much time and money, especially from the producers of secondary raw materials. For recycling companies, producing secondary or Post-Consumer Recycled materials, this is a competitive disadvantage in comparison to the producers of primary raw materials which can move freely within the European Union. This paper describes a concept that is currently discussed widely, which would facilitate recyclable wastes to move between compliant recycling companies within the EU much more easily. The Circular Economy plan for the EU simply shouts for simplifications in these waste shipment rules.

1 History

The first North Sea Resources Roundabout (NSRR) Fast-Track pilot notification, for a shipment of recyclable WEEE material between a recycling company in the Netherlands and a WEEE recycler in Austria, was approved on March 20 2019, setting the total time needed for approval by Dutch and Austrian competent authorities to 21 working days. This constitutes a very significant improvement compared to regular notification procedures, which can take as long as several years. Making shipments between compliant recyclers in the EU faster and easier can help to significantly boost the circular economy in Europe.

This document outlines the objectives and context of this first NSRR Fast-Track Notification case, as well as the practical work done in this NSRR working group.

2 Implementation of pre-consents in the EU: regulatory practise

Article 14 of the European Waste Shipment Regulation (WSR) stipulates that there may be so called pre-consented facilities for waste recovery, i.e. compliant recyclers.

The EU website states that there should be a much shorter response time for notification requests by pre-consented facilities:

"Pre-consented facilities for waste recovery. Following the OECD Decision on transboundary movements of waste for recovery operations, Article 14 of Regulation No 1013/2006 provides that the competent authorities of destination which have jurisdiction over specific recovery facilities may decide to issue pre-consents to such facilities. This means that the authority of destination will not raise objections concerning shipments of certain types of waste to the facility, and as a consequence the time limit for objections by the authorities of dispatch and transit is shortened to 7 working days."

Thus, the concept of pre-consented facilities potentially is a valuable instrument that can help facilitate the recovery and uptake of (secondary) resources in the circular economy by allowing for faster and easier procedures for known compliant recyclers.

In the summer of 2016 the European Electronics Recyclers Association EERA did a study on the use of the concept of pre-consented facilities and sent out questionnaires to 64 Competent Authorities (CA's) working on the implementation of the WSR, inviting them to participate. The summary of the survey:

Only 50 % of competent authorities that responded, replied that they issue pre-consents (Art. 14 WSR).

The study also showed, that where the concept of pre-consents is applied, they are not applied in a standard way. The requirements appeared to differ a lot, but it

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was impossible to obtain a clear picture of the requirements.

However, the general conclusion was obtained that the treatment process seems to be the most important criterion for issuing pre-consents.

Consequently, quite some countries or regions do not recognize the concepts offered by Article 14 of the Waste Shipment Regulation. Experience shows that often there is no difference in the handling of these notification requests, compared to those requests for deliveries to non-pre-consented facilities. A response time of one week has not been reached in any of the countries/regions.

The conclusion of this study was that the concept of pre-consents not recognized in major parts of Europe and that many of the identified issues are related to a lack of business rules, standard procedures and lacking electronic data communication. The Waste Shipment Regulation allows for pre-consents, but the implementation of rules and procedures for pre-consents and notifications to pre-consented facilities are lacking.

Clearly, Article 14 of the European Waste Shipment Regulation remains underused. Increasing its use, based on harmonised rules and procedures, could be a valuable step towards eliminating unnecessary barriers to the circular economy in Europe.

3 International Green Deal North Sea Resources Roundabout

Every year in the EU, nearly 16 tonnes of materials are used per person, while each EU citizen generates, on average, more than 6 tonnes of waste annually, of which some 60 % is landfilled or incinerated. The circular economy is a response to the aspiration for sustainable growth in the context of the growing pressure of production and consumption on the world's resources and environment. The use of waste material as a secondary resource is one of the first actions that businesses could consider to improve both their economic and environmental performance. Value chains are often cross border in nature and so require trans-border shipment of secondary resources. However businesses perceive barriers in trans-border shipment of waste and secondary resources. Many (perceived) barriers are related to the uncertainty regarding the waste or resource status and the subsequent waste shipment requirements. Procedures to get clarity on waste or resource status are complex and time consuming or aimed at an EU-wide or national solution only. This can result in different interpretations between countries and so create confusion and a lack of legal certainty. Addressing these barriers and identifying shared solutions has the potential to accelerate the transition towards sustainable growth: this is what the North Sea Resources Roundabout (NSRR) aims to achieve.

The NSRR was initiated by The Netherlands in the period in which the Netherlands held the EU presidency, UK, France and Flanders with the aim to stimulate the circular economy in the North Sea region by facilitating trade and transportation of secondary resources. The five-year deal was signed in March 2016 and is envisioned to accommodate a maximum of ten secondary resource streams or cases. For each case, a working group tries to come up with practical and scalable solutions to the barriers encountered. Most solutions are likely to involve the harmonisation of existing national procedures and enforcement of EU legislation (often WSR) and will not require the adoption of new rules or regulations.

'Fast-Track Notifications' is the fifth case for the International Green Deal NSRR. Following the request by HKS and MGG, both EERA members, and after a quick scan of the proposal, Dutch, Austrian and French public and private sector experts started a NSRR working group aiming to facilitate shipments between compliant EU WEEE recyclers through harmonisation of their criteria and procedures. Among other things, the competent authorities in the working group set common criteria for pre-consented facilities, pledged to respect each other's pre-consents and discussed procedures. Flemish and UK colleagues, as well as the European Commission, are observing the work of the working group. Two European Recycling Associations, EERA and EuRIC, are actively involved by participating in these discussions.

Making shipments to compliant recyclers in Europe easier and faster will allow these secondary raw materials to flow much in the same way as primary raw materials do, thus boosting the production of secondary raw materials necessary for the European circular economy. Also, Fast-Track Notifications are expected to free up time and resources from the authorities, which can then be used to fight illegal exports of waste. The concept of Fast-Track, once effectively implemented, can be used for shipments of any type of recyclable waste to any pre-consented facility.

4 The process of the NSRR Fast Track Working Group.

During the opening session of the working group the participants were actively involved in the discussions and a number of keywords were agreed that require further detailed discussions in the next phases of the project:

• TRUST/MISTRUST

• CULTURAL DIFFERENCES

• FINANCIAL GUARANTEES AND COSTS

• REVOKING PRE-CONSENTS

• IT IS NOT ABOUT JUST PAPER

• END-OF-WASTE

Subsequently the working group agreed that the work process would follow the following steps:

1. Review the requirements for a pre-consent.

2. Agreeing a set of mutually agreed minimum requirements for a pre-consent status.

3. Review the requirements for a complete Notification Request to a pre-consented facility.

4. Agree a set of requirements for a complete Notification Request.

5. Trying out a first Fast-Track Notification procedure.

6. Evaluate the outcome of the first Fast-Track Notification.

7. Identify the key elements hampering the targeted one-week treatment time.

8. Discussing and finding solutions for these hampering elements – key words: electronic data interchange, financial guarantees, organizational aspects of the CA's etc.

The boundaries of the Fast-Track Notification (FTN) project were discussed and it was agreed to limit the FTN project to raw materials for recycling i.e. raw materials for the production of secondary raw materials.

It was clear that the issue of Electronic Data Interchange would be an important enabler for this concept but as this currently is a topic under discussion within the WSR Correspondence community, it was agreed to not make it part of this discussion, at least not in this stage. We would try to be involved in following up progress in this important work.

Reviewing and agreeing a set of mutually agreed requirements for pre-consents.

A quality discussion about each of the analyzed systems in place in the 5 participating competent authorities resulted in this baseline for granting the status pre-consented treatment facility.

It was agreed that ideally this would be treated by a centralized competent authority and France as implemented this concept in practice already.

5 Reviewing and agreeing a set of mutually agreed steps for a complete Fast-Track Notification request.

The discussion of the requirements of a notification request for deliveries of waste to a pre-consented recovery facility took a long time, as these requirements are open-ended today and as there is no harmonization in the kind of questions that can be asked. The meeting agreed that there is a need to harmonize the requirements for a "complete notification request" in the case of deliveries to pre-consented facilities. After all these facilities are thoroughly checked to be classified "pre-consented recovery facility".

The working group went through the in total 50 datapoints that are described as required questions for any notification and went through a quality debate as to the necessity and the content of each of these 50 datapoints much in the same way as any business process is being defined. It was concluded that quite some of these datapoints are redundant or needless. Take for instance the requirement to inform the exact routing of the shipments. If it involved regular and multiple shipments of recyclable wastes, it does not serve any environmental purpose to describe the exact routing, as any deviation of this routing, for instance as a consequence of congestion, would imply that the transport could be viewed as an illegal transport. After intensive debates is was concluded that the definition of cross-border points would suffice.

6 The learnings from the first Fast Track pilot project.

The learnings and discussion points that came out of this pilot project covered quite a wide range of topics and these topics will need further work.

Quick wins to improve the speed of the processing of the Fast-Track Notification:

- a standard English contract would have been used (except when all relevant countries involved in the notification have one common language)
- all information as agreed would have been supplied from the very start
- no original signatures would have been required
- Electronic Data Interchange (EDI)
  - a key factor for any improvement
  - this is work-in-progress for the WSR team
- Financial Guarantee
- Administrative Costs

The three most urgent complex issues are without any doubt the issues of EDI, the Financial Guarantees, and the administrative costs related to notifications.

Particularly with regards to the financial guarantee a disproportionately large amount of time and effort needs to be invested in agreeing the level of the Financial Guarantee especially when comparing this with the frequency of cases where any back guarantee was needed. At the same time this is one of the key time consuming issues in the notification process.

Electronic Data Interchange.

Electronic Data Interchange is a key requirement towards a more efficient Waste Shipment Regulation for future. The Commission (DG ENV) is actively developing EDI protocols for the Waste Shipment Regulation.

It is of key importance that the Commission works through the hurdles set by some of the competent authorities, particularly those who are in favor of the status-quo of original documents exchange in combination with original signatures.

Without the electronic exchange of data, as it is the case in the normal trade of primary products and articles within the EU, the Waste Shipment practices in the European Union will stay slow. At the same time it is unthinkable for the recycling industry that a combination of archaic manual administrative systems will continue to be used in combination with electronic data interchanges, as this would multiply the administrative work related to the cross-border transport of secondary materials.

Financial Guarantees

The issue of the "financial guarantees" is the most time consuming and costly element of Notification processes.

The assessment of Article 6 showed that the article goes into a lot of detail and it describes that all costs are to be allocated per individual notification.

These costs imply the elements:

- return,
- storage (90 days) and
- treatment
- and it may even require a financial guarantee for the downstream treatment.

The money involved and immobilized in the financial guarantee needs to be accessible for the period of notification plus the time needed for all material to be treated as intended. There is no risk sharing – each financial guarantee is allocated to an individual notification case.

Simplified, it can be compared to the risk cover for the burning down of a house, whereby the full value of the house is placed in an allocated bank account for the case that the house burns down.

The frequency of incidences in which the financial guarantee was required is approximately 1 on 10 000 cases or 0,01%. In quite some countries an actual requirement for the financial guarantees only happens in once per 2-5 years.

There are documented cases in which the value did not cover the full cost of the storage, return and treatment, in other words the amount of work to establish the value of the "cover" might not be correct.

The only competent authority within the working group that was able to assess the total value of immobilized financial capital was the competent authority of the Netherlands. The total amount of money immobilized by financial guarantees in the Netherlands alone is approximately 130 Million €. It was therefore concluded that the amount of money immobilized by financial guarantees in the EU must be well over 1 bn €.

The amount of money immobilized by financial guarantees and the amount of time needed to "negotiate" these financial guarantees are both disproportional and inefficient.

Going back to the comparison of the house with the fire risks, the problem probably has to be tackled in exactly the same way as what is done to cover any fire risks. The model of insurance shares the risks amongst many parties.

Particularly in the case of pre-consented waste treatment facilities it must be assumed that there is an interest for the companies to work compliantly. The risks of not being able to treat any material of a notification therefore is hugely limited and in most of the cases linked to risks like fire of any other element that can be quantified by insurance mathematical models. Hence to pool these risks in the form of an insurance based upon an insurance mathematical logic appears to be at least one possible way forward. Other models include models in which a “pool” is established – possibly on an EU level, in which funds are collected to cover such risks. Which of the parties would need to pay into this “fund” is still open for discussion.

The pre-consented facilities receiving the goods by nature have an interest to receive recyclable goods covered by the re-consent. Furthermore they “concentrate” flows, hence there might be a logic to reverse the obligations, but more work on these questions is still needed.

Administrative costs.

Administrative costs for notifications differ largely between the competent authorities in the EU.

In some countries there are hardly or no administrative costs that need to be covered by the notifying parties and in other countries or competent authorities there can be substantial costs involved, that can be well in excess of 10 000 €.

The “pricing table” of the United Kingdom can get as high as 24 0000 British Pounds. At least in parts of Germany the administrative costs are charged in the form of a variable fees, dependent on the volumes involved. In cases like these, the administrative costs become in fact a “tax” on notifications.

The Court of Düsseldorf Germany had to deal with exactly this question of the legality of such administrative fees in September 2019. The conclusion of this court decision is worth mentioning. The court decided that the quantitative assessment of an administrative fee constitutes a charge that has the equivalent effect as import or export duties and is therefore unlawful, having regard to the free movement of goods as a fundamental principle of Community law. According to the Court of First Instance, the effect is equivalent to that of customs duties.

The charging method for the administrative notification procedures between European countries thus shows fundamental differences.

Above all such quantity-dependent fees in their concrete form do not meet the requirements set by the European Court of Justice for such fees. The amount of a fee determined based on the weight of the product may thus no longer be used. The cases itself is described here: https://openjur.de/u/2176065.html

The fundamental problem is that compliant recyclers with pre-consents applying for notifications are disadvantaged over recyclers taking the risk of not applying for a notification.

7 Conclusion.

The concept of notifications to pre-consented treatment facilities urgently needs to be changed if Europe is serious about the promotion of the Circular Economy model. The current Waste Shipment Regulation review and recast offers the possibility to do so.

For recycling companies, producing secondary or Post-Consumer Recycled materials, notification procedures place them in a key competitive disadvantage in comparison to the producers of primary raw materials which can move freely within the European Union.

The Circular Economy plan for the EU simply shouts for simplifications in these waste shipment rules.

Environmental assessment of the recycling chain organised by ecosystem in France and perspectives regarding ecodesign of EEE

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Abstract

In 2019, **ecosystem** first exploited its Life Cycle Inventories (LCI) database to perform the environmental analysis of the recycling chain that it organises in France. This LCI database, which is freely accessible, gathers all the data needed to model the environmental impacts of the end-of-life of electrical and electronic equipment (EEE).
ecosystem reworked this data to integrate them into a model to build the environmental assessment of the recycling chain. This assessment helped identifying the main environmental hotspots all along the recycling chain. Most impacts indicators, such as Climate change, Mineral resources depletion and Fossil resources depletions were mapped for a multi-criteria overview. Both the impacts of the recycling steps and the benefits regarding virgin material substitution or depollution were considered in the analysis.
This work can also be turned into eco-design perspectives for EEE regarding their end-of-life.

1 Introduction

ecosystem is a non-profit organisation accredited by the French Public Authorities to collect, depollute and recycle household waste electrical and electronic equipment (WEEE), professional equipment (professional WEEE), lamps and small fire extinguishers.

Many stakeholders are involved in the activities managed by **ecosystem** including manufacturers, importers, distributors, local authorities, solidarity networks, treatment and logistics suppliers, professionals in charge of electrical equipment maintenance, waste managers, equipment users... **ecosystem** gathers more than 4000 producers of electrical and electronic equipment (manufacturers, importers, distributors).

In 2019, **ecosystem** achieved the collection of more than 643 000 tonnes of WEEE (around 75% of the WEEE collected in France). **ecosystem**'s performance is measured and challenged by objectives fixed in the specifications defined by the French Public Authorities and derived from the WEEE directive. These objectives are for example collection and recycling targets.

In addition to these legal requirements, **ecosystem** carried out an environmental analysis of the entire chain it organises, in order to identify levers to improve its environmental footprint, regardless of the legal objectives it is also pursuing. The main results of this analysis are presented in the paper as well as some levers of actions identified either to reduce the intrinsic impacts of the recycling chain, or to increase the environmental benefits.

These learnings will be of real help to keep stimulating the recycling chain and guaranteeing a high-quality recycling even more environmentally efficient.

2 Methodology overview

The environmental analysis of the recycling chain managed by **ecosystem** is based on a Life Cycle Assessment (LCA) and multi-criteria approach.

2.1 LCI to model the end-of-life of EEE

The environmental analysis is based on LCI first developed to be used by EEE producers in their products LCA. This was raised by increasing interests of manufacturers regarding resource efficiency and environmental impacts reduction. However, data concerning the WEEE recycling in LCA databases were lacking. There was thus a need for reliable and representative data from field experience.

2015 **ecosystem** launched a project to develop an LCI database to model the end-of-life of EEE collected in France. This project had been co-funded by ADEME, the French Environmental Agency and carried out by Bleu Safran, a consulting firm specialised in end-of-life modelling in LCA.

For the data collection phase, two main sorts of information were used:

- A tracking of each material entering the recycling chain through the WEEE: data were gathered from ecosystem logistic monitoring, input and output material flow analysis (based on data obtained with specific programmes,

such as characterization and sampling programmes), traceability of downstream operations and specific questionnaires filled by the treatment operators working with ecosystem.
- An evaluation of the consumptions and emissions of each process: data were gathered also from specific questionnaires filled by treatment operators **ecosystem** works with, or else from literature and adaptation of existing LCI.

All the data collected were used to model the successive steps of WEEE recycling with a high representativity [1]. These various steps are represented on Figure 1.

The LCI have been developed at the scale of a couple material/WEEE category (e.g.: LCI of the end-of-life of 1kg of steel in large household appliances, LCI of the end-of-life of 1kg of glass in lamps, etc.). Indeed, WEEE are treated in WEEE streams to allow an efficient depollution of a large panel of equipment. For each stream, the different steps for the recycling are not exactly identical (e.g. for large cooling household appliances, there are specific actions to remove the refrigerant gases or blowing agents whereas for flat screen a step to remove tubes with mercury is necessary). All the operations from waste collection to final destinations of the processed fractions (recycling, energy recovery, landfilling) are covered. Thereby, the database allows to take the complete recycling chain into account.

Two variants of each LCI have been produced:
- An LCI including the benefits of recycling and energy recovery (system expansion approach).
- An LCI not including them (cut-off approach).

Then a critical review was performed by recognized and independent experts (Philippe Osset, Ueli Kasser) to insure a huge robustness of the data. The overall quality for each WEEE flow modelled was fixed from "Good" to "Very good" [2].

This LCI database gathers now 954 LCI in total, covering the end-of-life of either household or professional EEE. The database and associated documents are freely accessible [3].

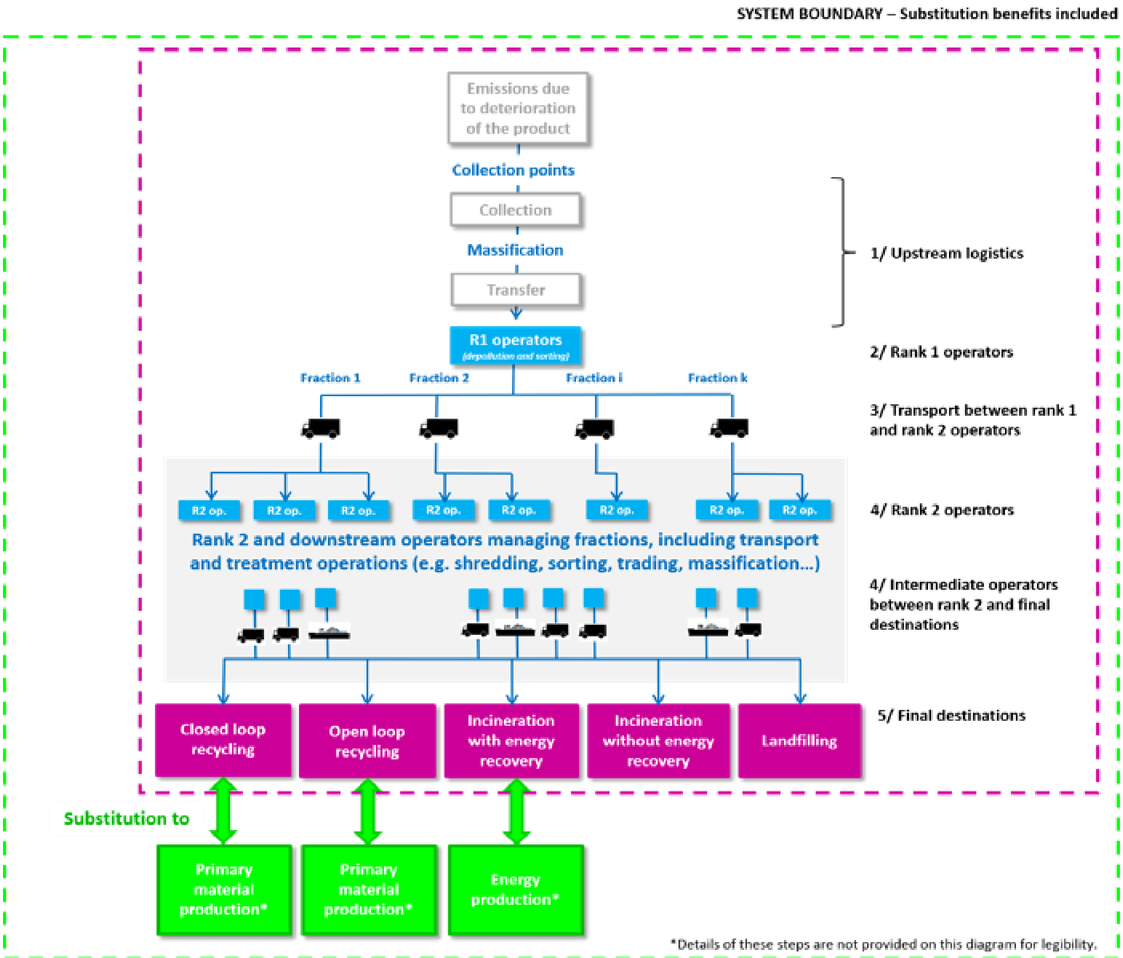

Figure 1: Different steps considered for each LCI (green = additional steps included in the LCI with benefits)

2.2 From LCI to the environmental analysis of the recycling chain organised by ecosystem

Each LCI is built at the scale of a couple material/WEEE category. This means that when weighted by the total quantity of each material collected by **ecosystem** through the WEEE streams**,** and then aggregated, LCI represent the total emissions and consumption flows linked to the end-of-life of WEEE in the recycling chain organised by **ecosystem.**

In 2019 **ecosystem** first exploited its recently published database to perform this analysis. The total quantity of each material collected through the WEEE streams was assessed thanks to a programme **ecosystem** have been performing for several years. This programme aims at dismantling WEEE sampled in the WEEE streams to analyse their material composition.

The inventory of emissions and consumptions of the chain was then turned into impacts using impact models. The choice of the impact models was made based on ILCD recommendations and was intended to be as much as possible in line with the latest discussions under the Product environmental Footprint (PEF) work. Table 1 details the impact models considered for the impact categories which will be detailed afterward.

Impact category	Impact model
Climate change	IPCC 2013
Fossil resource depletion	Center of Environmental Science (CML), Leiden university, Fossil Fuels Method, baseline, version 4.2, 2013.
Mineral resource depletion	Center of Environmental Science (CML), Leiden university, Ultimate Reserves Method, baseline, version 4.2, 2013.

Table 1: Impact models considered for the environmental analysis of the recycling chain organised by ecosystem

ecosystem manages the recycling of household and professional WEEE. Regarding household WEEE, the collection and treatment is organised in five WEEE streams:

- Large cooling household appliances (refrigerators, air conditioning equipment…): LHA cold
- Large household appliances non cold (washing machines, clothes dryers, electric stoves…): LHA non cold
- Small household electric equipment (vacuum cleaners, microwaves, mobile phones, electric kettles…): SHA
- Flat screens and Cathode Ray Tubes screens: Screens.
- Lamps

The LCI developed cover all these household WEEE streams.

Regarding professional WEEE, LCI were developed at a WEEE family level instead of a WEEE stream level. This is due to the more varied typologies of equipment in the professional WEEE, associated with lower quantities collected. Therefore, the LCI of professional WEEE developed does not precisely cover the perimeter of all professional WEEE collected.

Consequently, it was decided to first focus the analysis on the household WEEE streams, which represent 598 000 tonnes over the 643 000 tonnes of equipment collected in 2019 (meaning more than 90 % of the equipment collected by **ecosystem** in 2019).

3 Key results and main hotspots identified

A large panel of impact categories were screened for the analysis. Three main categories appeared as significant, relevant and robust enough to enable a robust exploitation of the results. Results for these categories are detailed in this paper. Other categories were identified as being of secondary importance for the chain (e.g. Ozone depletion, Acidification, Photochemical ozone formation), or not significant (e.g. Eutrophication…). Toxicity and Ecotoxicity were not analysed with this methodology due to its lack of robustness for these indicators. These topics are approached with another method that is not presented here.

3.1 Two indicators for Climate change

The results obtained for Climate change have led to the construction of two separate indicators. These indicators provide additional information for the analysis and highlight either the issues related to the recycling of materials or the issues related to the depollution of equipment containing refrigerant or insulation gases.

3.1.1 Non-emitted CO_2 indicator

The LCI with the benefits of recycling and energy recovery included were used to build this indicator. The impacts of the recycling chain (impacts of the WEEE transportation, of treatment factories…) are compared to the avoided emissions linked to material and energy recovery. Indeed, thanks to recycling, virgin material and energy can be substituted by recycled material or secondary energy. The production of the virgin material

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or primary energy is thus avoided. Refrigerant and insulation gases potential emissions are not considered in this indicator.

For the whole household WEEE collected in 2019 by ecosystem, the comparison of impacts and benefits shows a global saving of more than 490 000 tonnes of CO_2 (see Figure 2).

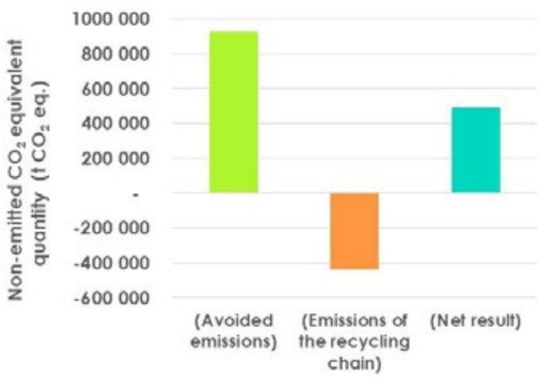

Figure 2: CO_2 equivalent emissions avoided through material recycling and energy recovery

The net result is linked:

- 49% to LHA non cold
- 29% to SHA
- 20% to LHA cold.

This hierarchy stems from two parameters:

- The tonnages collected for each stream (e.g. 286 000 tonnes of LHA non cold collected in 2019 vs 103 316 tonnes of LHA cold)
- The material composition of each stream which leads to different net results for 1 tonne of each stream treated (see Figure 3)

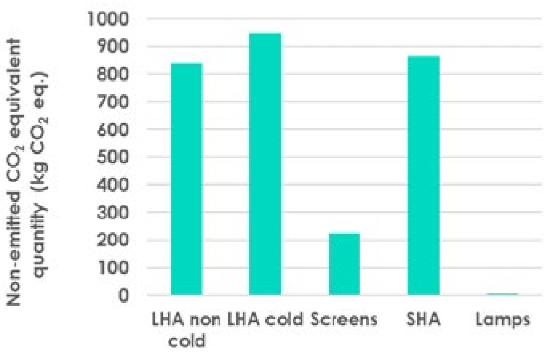

Figure 3: CO_2 savings for 1 tonne of each household WEEE stream treated (net results)

More particularly, a large part of the CO_2 avoided emissions comes from metals regeneration. Plastics can also play a positive role when the stream contains plastic resins which are widely targeted for recycling. It is not the case when the plastics cannot be recycled (thermoset plastic resins, presence of fillers or brominated flame retardants in the plastic…). In that case, there are not only very low avoided emissions, but higher emissions for the treatment, due to the elimination process of the concerned plastics.

3.1.2 Eliminated CO_2 indicator

Some equipment such as refrigerators, freezers, air-conditioners, hot water tanks…contains cooling gases used for refrigeration properties and / or blowing agents used for insulation properties. The appliances collected today are not representative of the equipment put on the market today, but of equipment put on the market several years ago. This is especially true for large household equipment. For instance, equipment containing gases with high Global Warming Potential (GWP) are still represented within the appliances collected, even if such gases have been banned years ago.

Figure 4 shows the GWP of all the gases in the WEEE streams collected and the emissions occurring along the recycling chain (from the collection of WEEE to the final destinations of their constituent materials). The net result represents all the CO_2 eliminated thanks to the depollution steps. Without the depollution of the gases in the equipment collected by **ecosystem**, more than 2 500 000 tonnes of CO_2 would have been released to the atmosphere in 2019.

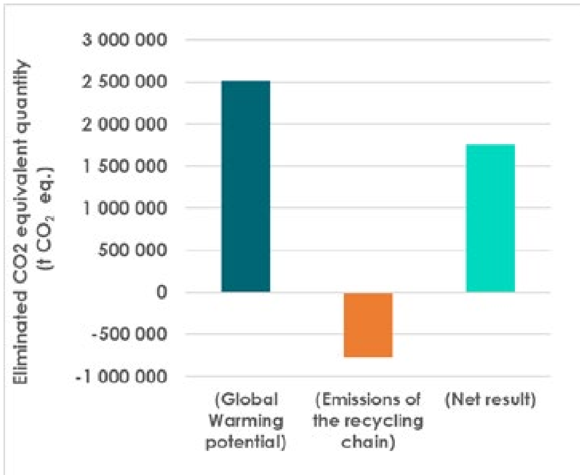

Figure 4: CO_2 eliminated thanks to the depollution of cooling gases and blowing agents contained in WEEE collected by ecosystem in 2019.

The net results for the depollution are huge. However, it should not overshadow that the emissions reach almost 770 000 tonnes of CO_2, which is higher than the savings obtained with material recycling and energy recovery. These impacts are largely determined by gas losses occurring before the equipment arrive on the depollution site. This can be caused by damages before the equipment reaches the collection point, scavenging degrading the equipment, or deterioration of the equipment during transportation. The relative share of each cause is not known at this time.

3.2 Focus on fossil resources depletion

Fossil resources depletion indicator highlights the pressure exerted on the fossil resources by the activities. Fossil resources are oil, coal and gas.

The profile of the results is quite similar to the one obtained for the Non-emitted CO_2 indicator (see Figure 5). In 2019, both material recycling and energy recovery allowed savings of more than 5 900 000 GJ. This is the equivalent of the energy consumed by 360 000 French people for their heating needs during a year [4].

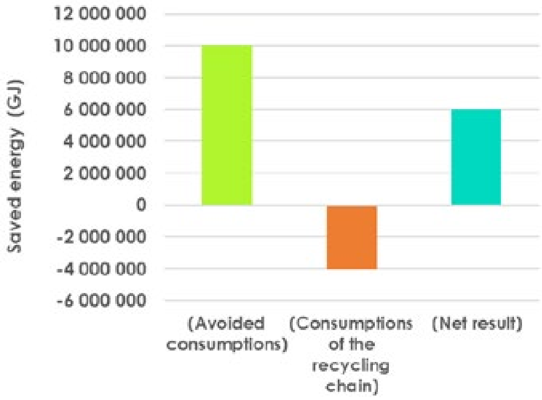

Figure 5: Energy (fossil consumptions) saved through material recycling and energy recovery

The net result is linked:

- 42 % to LHA non cold
- 34 % to SHA
- 19% to LHA cold

The difference however lies in the impacts and benefits linked to the plastics treatment and recycling. In this indicator, plastics resins which are targeted for recycling provide a good benefit, since they avoid the energy consumption necessary to produce virgin resins, but also the primary material (oil) necessary for virgin resins production. The SHA stream occupies a larger share since it contains a significant quantity of plastics.

3.3 Focus on mineral resources depletion

Mineral resources depletion indicator highlights the pressure exerted on the mineral resources by the activities. Mineral resources are metals, precious metals, rare earth elements…

For this indicator, the profile of the results is drastically different (see Figure 6). Indeed, there is almost no need of new mineral resources to regenerate one entering the recycling chain. In 2019, more than 64 tonnes Sb equivalent were saved by the recycling of household WEEE collected by **ecosystem**. This is equivalent to the mineral resources needed to produce more than 9 800 000 IT equipment [5].

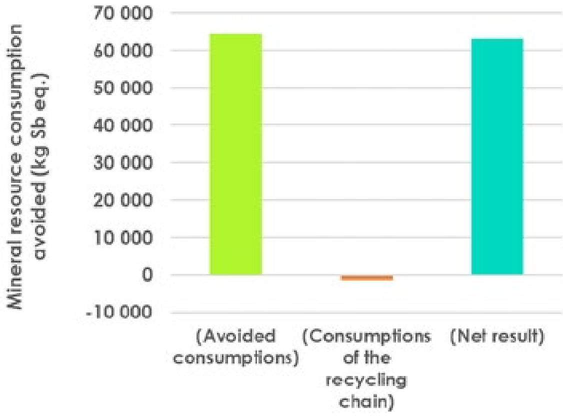

Figure 6: Mineral resources saved through material recycling

Moreover, the distribution between the WEEE streams shows the importance of the SHA flow for this indicator. SHA provide 65% of the global net result. Screens provide 10% of the global net result despise the tonnage of screens collected which is far lower than the tonnage of the other streams.

This profile is mainly determined by the presence of printed circuit boards (PCB) and their richness in critical metals. In the SHA stream, PCB are found in significant quantities. They contain gold, silver and platinoids which are recycled. Figure 7 shows the net results obtained for 1 tonne of each household WEEE stream.

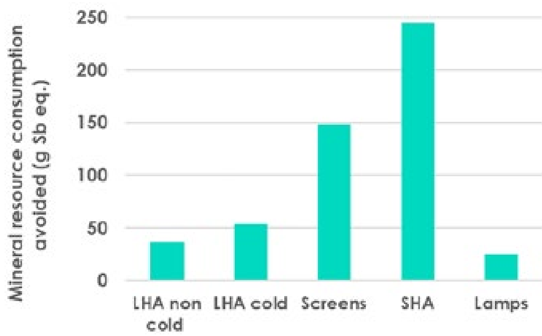

Figure 7: Mineral resources saved for 1 tonne of each household WEEE stream treated (net results)

For the SHA stream for example, the PCB generate almost 70% of the benefits of the flow. This highlights the crucial need for recycling the critical materials even if their recycling is almost insignificant in the total recycling rate of the WEEE stream.

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4 Discussion and perspectives

This analysis points to hotspots along the recycling chain and for different indicators. This overview is of real help to identify operational action levers either to reduce as much as possible the environmental impacts or to increase the environmental benefits obtained. It is also a good tool to highlight ecodesing actions for EEE producers.

4.1 Some operational levers on the field

Both reduction of environmental impacts and increase of environmental benefits improves the net result.

Regarding the impact reduction, the depollution of gases is an interesting example. Even if today legislation as evolved and now prohibit the use of gases with a huge GWP, such gases are still found in WEEE with refrigerant or insulation properties. The analysis showed the importance of fighting against the gas losses which can occur along the chain until the equipment are depolluted.

This involves several actions in parallel:

- The environmental analysis requires reliable data to perform robust calculations. In that case, gases mix found in the equipment keep evolving each year, since the legislations has led to technological developments and variations in gas compositions. Performing robust calculations each year thus requires an efficient monitoring of operational indicators on the field. Today, projections made have shown that the net result for this indicator will slowly start to decrease. Even if collected tonnages keep growing, evolutions of the mix of gases bring less harmful gases for the environment.
- The analysis showed that gas losses before the equipment arrive on the depollution site generate heavy impacts. These losses can have different causes: scavenging of the compressors (that are mainly made of copper) which results in an opening of the refrigerant circuit, degradation during transportation from the collection point to the depollution site,… Reducing these losses thus involves different actions, to better identify the share of each of these causes in the losses, to fight against scavenging, to identify potential ways to protect the equipment during transportation,… These are either actions on the field to reduce the impacts or actions to better understand which lever should be activated first.

Another example of actions levers to increase the benefits was highlighted through the Mineral resource depletion indicator. This indicator shows the importance of the recycling of PCB in terms of mineral resources preservation. PCB contains critical metals, albeit in small quantities but the benefit of recycling them is high. This confirms the importance of exploring recycling options for critical metals which are not recycled yet. The real benefits will then need to be assessed precisely to ensure a new recycling process brings more benefits than impacts on the panel of environmental indicators.

These are levers of action on the field, but some ecodesign recommendations can also be identified.

4.2 From recycling chain impact analysis to equipment ecodesign

This study highlights three main areas of eco-design.

4.2.1 Material selection during the product design

The choice of the materials is crucial to increase the recyclability of a product. As seen through this study, a material which is not recyclable will provide no environmental benefit, only environmental impacts for its treatment. For example, in the WEEE sector, some plastic resins are easier to recycle because:

- Appropriate recycling operational technologies are available to produce new resins (e.g. thermoplastic vs. thermoset resins).
- They have specific technical features (including their density) enabling their identification, and thereby their efficient sorting.
- They are present in large quantities making their recycling efficient from a technical and economic point of view.

This environmental assessment thus confirms the importance during the design phase to consider such easy-recyclable resins such as PP, ABS, PS and to a lesser extent, ABS/PC and PC.

Such conclusions can also be reached for plastics containing fillers or additives which alters the density of resins, and thus disturbs the systems sorting plastics by resin family in preparation for their regeneration. Less regeneration will mean less environmental benefits.

4.2.2 Selection of joining types in the product

One important point leading to less quantity of material recycled is the dispersion of the material in the “wrong” fractions.

Indeed, treatment processes cannot separate different materials that are combined irreversibly (e.g. gluing,

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over-moulding, bi-injection, co-extrusion.). Yet, most of combined materials are not compatible for recycling.

This has two consequences:

- Material losses: material can be oriented in the "wrong" fraction (e. g. a fragment of plastic within the post-sorting metallic fraction) where it will not be recycled. The environmental benefit decreases.
- Over-sorting: to avoid a "pollution" of a treated material fraction by other materials, an over-sorting might be necessary. This increases the environmental impacts of the treatment.

4.2.3 Issues surrounding depollution or specific treatment of some components or substances

The example of PCB speaks for itself. Circuit boards are components requiring a specific treatment as described in the WEEE Directive (Directive 2012/19/EU). They must be removed from the early treatment stages in order to be directed to specific treatment sectors. This specific treatment allows a recycling of the critical metals it contains. Some assembly methods make their removal more difficult, thus reducing the environmental benefits.

5 Conclusion

Performing an environmental assessment of the recycling chain is a prerequisite to identify environmental hotspots and prioritize actions on the field.

This analysis can be fine-tuned to adjust the environmental indicators as closely as possible to reality and to cover the entire perimeter of all the equipment ecosystem takes charge of.

Some levers of action to reduce the environmental footprint of the recycling chain have however already been identified, either to optimise the recycling on the field or to ecodesign the products.

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B.4

RECYCLING SYSTEMS: REGIONAL EXAMPLES

Development of Product Circulation Model to Evaluate Scenarios of Sustainable Consumption and Production for Southeast Asia

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Abstract

Sustainable consumption and production (SCP) is a key concept to transform the conventional linkage between consumers and producers toward a sustainable one. To clarify visions and pathways to achieve SCP, the authors have proposed the method for designing scenarios using expert workshops. The focus is on Southeast Asia because the energy and resource consumption there are rapidly increasing because of remarkable economic growth. To support scenario workshops involving experts, this paper proposes a simplified model called product circulation model to quantify SCP scenarios in terms of environmental impact, through which effective measures to achieve the visions can be identified. The model is developed based on a literature review, while input parameters used in the model are determined based on our past SCP scenario workshops. In a case study, we quantified SCP scenarios for Vietnam and then estimated the environmental impact reductions compared to the business-as-usual scenario.

1 Introduction

The United Nations has adopted the Sustainable Development Goals (SDGs). In SDGs, much attention has been paid to Goal 12 "Ensure sustainable consumption and production (SCP) patterns" [1], which directs to higher energy and resource efficiency in our lives while improving quality of life (QoL) [2]. Focusing on the concept of SCP, we have been involved in the five-year research project (2016-2020) called "Policy Design and Evaluation to Ensure Sustainable Consumption and Production Patterns in Asian Region (PECoP-Asia)" [3]. The focus is on Southeast Asia where the resource and energy consumption are rapidly growing. The objective of this project is to clarify the desirable linkage between consumers and producers toward sustainability.

To this end, we have proposed procedure to describe SCP scenarios using expert workshops with backcasting and local characteristics [4][5]. Details about design of SCP scenarios are explained in Section 2. An SCP scenario here refers to internally consistent story consisting of an SCP vision and the pathway to connect the vision with the present [4]. Through creating SCP scenarios, some measures for SCP, such as the diffusion of sharing services (e.g., carsharing) and the usage of digital technologies for dematerialization were suggested [5]. However, less research has been done to undertake the quantitative assessment of described SCP scenarios. This makes it hard to decide what measures we should take to achieve SCP.

In previous research, the authors developed a prototype model to conduct the quantitative assessment of SCP scenarios from an environmental perspective [6]. However, there are two problems to support the quantification process as follows – (i) the validation of the quantification results was not enough because only scenario designers were engaged in the process and (ii) the parameters used in the model did not sufficiently cover a range of SCP measures suggested in the previous expert workshops.

To solve these problems and clarify effective measures to achieve SCP, this paper aims to develop a simplified model called product circulation model to support participatory design of SCP scenarios. The idea is to develop the model to quantify scenarios through interactive discussions among workshop participants. This enables to collect participants' views and opinions as rationales for quantification. For enabling to assess the environmental impact, we develop the model by describing a whole product life cycle as the combination of life cycle processes, such as manufacturing, usage or recycling. We define the equation describing the input-output relation in each process based on a literature review. We extract input parameters from past workshop outcomes.

The rest of this paper is structured as follows. Section 2 describes the overview of designing SCP scenarios for Southeast Asia. Section 3 proposes the procedure of quantification and a model to quantify SCP scenarios combined with the procedure. Section 4 shows a case

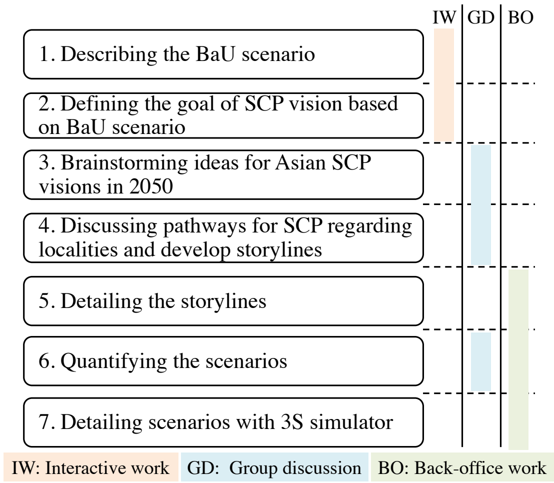

Fig.1. Procedure for designing SCP scenarios (updated from [4])

study for Vietnam. Section 5 discusses the effectiveness and challenges based on the case study results. Section 6 concludes the paper.

2 Design of SCP Scenarios for Southeast Asia

In PECoP-Asia, SCP visions and pathways are drawn using a participatory backcasting approach because the transition to SCP entails radical changes in many aspects, such as business model and product design. Also, localities are considered in expert workshops because situations such as people's lifestyles largely differ from one country to another [5]. In our method, expert workshops and back-office work by scenario designers are combined to maximize the efficiency of designing scenarios. Figure 1 shows the 7-step procedure for designing SCP scenarios that the authors have proposed [4]. Details of each step are as follows.

- Step 1: The scenario designers describe the business-as-usual (BaU) scenario based on collected information to understand what is likely to happen when no additional measures are taken from the present.
- Step 2: The scenario designers set the goal of SCP visions based on BaU scenario created in Step 1 to share the goal clearly.
- Step 3: The workshop participants generate ideas to describe SCP visions in workshops using backcasting.
- Step 4: Considering local characteristics, the participants develop SCP scenarios in narrative format (i.e., story lines).
- Step 5: The scenario designers detail the contents of scenarios in narrative format for quantification by workshop participants.
- Step 6: The participants quantify scenarios developed in Steps 3-5 in expert workshops by referring to the quantified BaU scenario.
- Step 7: The scenario designers develop SCP scenarios using 3S (Sustainable Society Scenario) simulator to create structured scenarios. 3S Simulator is a system to support scenario design. 3S Simulator helps the scenario designers compose new scenarios by enabling to formalize, computerize, and analyse scenarios, compare different scenarios, combine them, and, as a result, construct archives of scenarios in a reusable manner. [7].

Table 1 shows an example of SCP scenarios for Vietnam, which were developed in previous workshops [5]. These scenarios suggested a variety of measures for SCP such as car-sharing service.

The focus in this paper is on Steps 5 and 6 in Fig. 1 because these steps remain not addressed, but play an essential role to analyze effective measures for SCP in the scenario design process.

Table 1. Example of SCP scenarios (not exhaustive) [5]

Title	Storyline
A: BICS Society (BICS: Business-Individual-Customer-Sharing)	• Because sharing services are already popular, B2B leasing and B2C sharing are widely used. • Some people become prosumers to satisfy individual needs.
B: Beauty is only skin deep	• Products are designed by coupling generalized part and customized part. • Because Vietnamese people like new products, customization services are provided using augmented reality (AR) and virtual reality (VR).
C: Infrastructure innovation 2.0	• Sharing and replacement is accelerated by visualizing information for consumers. • An authorization scheme is introduced to improve repair skills in local industry.

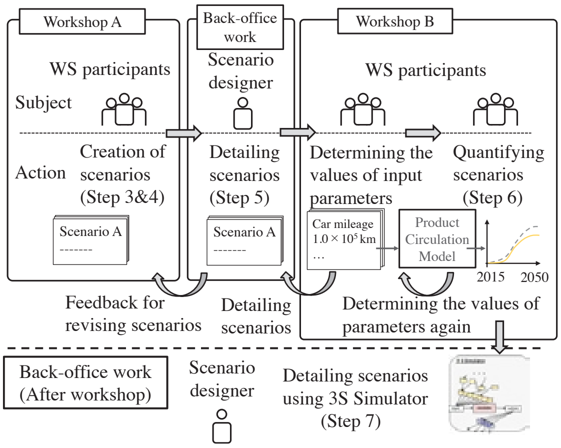

Fig. 2 Procedure of scenario quantification using workshops

3 Development of Quantitative Assessment Tool to Support Scenario Workshops for SCP

3.1 Approach

To solve the problems (i) and (ii) mentioned in Section 1, this paper aims to provide a quantitative assessment model called product circulation model to support design of SCP scenarios through workshops.

For addressing the problem (i), we assume the workshop-based quantification process of SCP scenarios as depicted in Fig. 2, which corresponds to steps 3-7 in Fig. 1. That is, scenarios are quantified based on interactive discussions in workshops with expertise provided by experts. In this process, workshop participants quantify scenarios using product circulation model. The procedure described in Fig. 2 consists of four parts, i.e., workshop A (corresponding to Steps 3-4 in Fig. 1), back-office work (Step 5), workshop B (Step 6), and back-office work after workshops (Step 7). In workshop A, narrative scenarios are developed by the workshop participants. In back-office work, the scenario designers detail the outcomes of workshop A. Also, the scenario designers quantify the BaU scenario using product circulation model. In workshop B, the participants determine the values of input parameters of product circulation model based on the narratives of SCP scenarios developed in workshop A. The participants set and change input parameters values in an iterative manner in a way that is consistent with scenario narratives. In this step, the scenario designers provide the quantified results of the BaU scenario in order to help the participants quantify SCP scenarios. In back-office work after workshop, the scenario designers detail SCP scenarios with 3S simulator.

To solve the problem (ii), we develop product circulation model based on a literature review and the results of past workshops. The model evaluates the environmental impact of the whole life cycles of durable products. Here, scenarios are evaluated in terms of CO_2 emissions and Total Material Requirement (TMR) [8] as the indicators of energy consumption and resource consumption, respectively. With the attempt to represent a full range of possible SCP measures, we define a set of input parameters used in the model based on the previous scenario workshops [5].

3.2 Product Circulation Model

3.2.1 Architecture

Figure 3 shows the architecture of product circulation model. To model the whole life cycle of products and the relationship between the life cycle and consumers' behaviors, we develop product circulation model by combining life cycle flow model and market model. These models are developed mainly based on literature review and the previous research [6]. Life cycle flow model represents a process chain as the combination of five process types, i.e., manufacturing, usage, landfill, remanufacturing, and recycling. Market model expresses the relationship between the life cycle and consumers' behaviors to simulate (a) future demand of a product, (b) customers' choice proposed in SCP scenarios (e.g. purchasing products or using sharing service), and (c) customers usage of the product . We relate the results of market model to the manufacturing and usage processes in life cycle flow model.

Table. 2 Examples of extracted parameters

No.	Input parameter	SCP measure	Associated life cycle process
1	EV rate in the market	Diffusion of EVs	Manufacturing
2	Electric mileage	Diffusion of EVs	Usage
3	Rate of shared car in market	Car-sharing	Market
4	Utility rate of shared car	Car-sharing	Usage
5	Utility rate of shared car	Car-sharing	Market

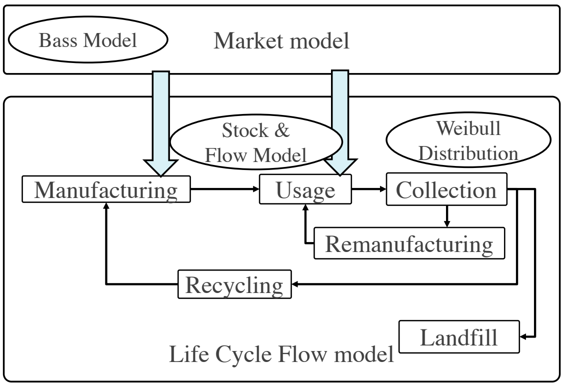

Fig. 3 Overview of product circulation model

3.2.2 Extraction of Input Parameters

To evaluate the environmental impact when various measures for SCP are taken, we extract the input parameters of product circulation model by analyzing the results of past scenario workshops. Based on our analysis of the three scenarios for Vietnam [5], we identified the total of 190 measures for SCP. Table 2 shows examples of parameter extraction in which SCP measures and corresponding input parameters in each life cycle process are shown. Totally, we defined 22 parameters as for a product for quantification. We note that we extract parameters which are very simple to reduce calculation time because calculation is done in workshop.

3.2.3 Market Model

Market model determines (a) future demand of a product, (b) customers' choice proposed in SCP scenarios and (c) customers usage of the product.

To express (a) the whole demand relating a product, we use Bass Model [10], which is often used to estimate the diffusion of products because products that we assess have not been popular yet such as cars or electric appliances.

The model represents (b) customers' choice and the choice influences on the volume of products in a life cycle process defined in life cycle flow model. We assume two types of customers' choice: (i) different kinds of product usage (e.g., using sharing services instead of product purchase), (ii) different types of a product (e.g., new or remanufactured products and normal or environmentally friendly products). Here, each of customers' selection is described in form of rate (i.e., how many customers in whole customers choose a choice). Although the choices can be detailed more for realistic analysis, they are defined in terms of three points as I mentioned before because this model needs less calculation time.

We express (c) the customers' usage of products by defining parameters which customers easily change such as annual mileage of car or utility rate of shared products, which express how many owned products are replaced by a shared product in terms of mileage. The customers' usage of products affects environmental impact in usage process of life cycle flow model.

3.2.4 Life Cycle Flow Model

This model defines the input-output relation of each process, which enables to calculate the environmental impact in the process. The environmental impact in process p at year t ($E_p(t)$) is obtained by the following equation:

$$E_p(t) = I_p(t) \times p_{product}(t) \quad (1)$$

where $I_p(t)$ and $p_{product}(t)$ express the environmental impact per unit and amounts of products in process p, respectively. The number of products in a life cycle process is calculated by the following equations.

- Usage

Flow & Stock model [9] express the transfer of products in a usage process as follows:

$$S(t) = S(t-1) + F_{in}(t) - F_{out}(t) \quad (2)$$

where S(t) is the volume of products used in year t and $F_{in}(t)$ is the volume of products produced at year t. It is the sum of new products and secondhand products.

$$F_{in}(t) = manufactuirng_{product}(t) + remanufactuirng_{product}(t) \quad (3)$$

$F_{out}(t)$ is the number of products which are out of use and collected at year t.

$$F_{out}(t) = collection_{product}(t) \quad (4)$$

- Manufacturing

The number of products manufactured at year t ($manufacturing_{product}(t)$) is calculated based on the demand estimated in market model. Not only new purchase but also replacement of products is considered considering with collection process.

- Collection

The number of products collected from the market ($collection_{product}(t)$) in year t is based on Weibull distribution model [11], which is often used to express the consumer durables of breaking probability in a year.

- Recycling & Remanufacturing

The amount of products recycled or remanufactured at year t ($recycle_{product}(t)$) and ($remanufactring_{product}(t)$) are expressed with rate of recycling or remanufacturing, which express the rate of products recycled or remanufactured in collected products. We mention that rate of remanufacturing or recycling are estimated in market model.

$$remanufactring_{product}(t) = collection_{product}(t) \times rate\ of\ remanufacturing \quad (5)$$

4 Case Study

In order to demonstrate how the developed model works, we organized an expert workshop online. Here, we quantified one of the SCP scenarios in Vietnam (see Table 3), that is, Scenario B: Beauty is only skin deep. This scenario describes SCP futures for Vietnam to 2050. Three members of our project were involved in the workshop. The goal of SCP was set as halving CO_2 emissions and TMR compared to the BaU scenario in 2050. For simplification, we quantified the scenario focusing on cars as a target product from the viewpoint of CO_2 emissions. The participants assumed input parameter values in 2050. Based on the procedure in Fig. 2, we conducted the workshop as follows.

1. The scenario designer detailed the scenario developed in previous workshop [5]. This process corresponds to Back-office work in Fig.2.
2. The workshop participants discussed the values of input parameters of product circulation model in workshop B in Fig.2, while comparing the values of the BaU scenario. Table 3 shows a part of the input parameter values determined in the workshop. The number of values of parameters changed here was 13. Participants determined values of parameters considering the storyline of scenario. For example, participants decided to diffuse EVs and replace all GVs into EVs because EVs are so popular in the scenario. The reduction of CO_2 emission estimated by the model was 35% compared with BaU scenario (see the first trial in Fig. 4). This result did not achieve the goal of SCP. Another 15% reduction was needed.
3. Because the result of quantification was insufficient, workshop participants reviewed the settings of the input parameter values and then changed some values as described in Table 3 (see second trial). More specifically, the utility rate of car-sharing service, which describes the rate of the mileage of car used in car-sharing service per year compared with owned car, to 10 from 2 in 2050 because a lot of consumers share generalized cars by customization using VR. The CO_2 emission in this situation was 49% compared to the BaU scenario (see Fig. 4), which means that the participants found a set of input parameter values to achieve SCP.

5 Discussion

The developed model supported the workshop participants' process of scenario design by quantifying SCP scenarios. Specifically, the model helped workshop participants do trial and error of three processes; 1) defining values of input parameters 2) estimating CO_2 emission founded on BaU scenario and comparing with BaU scenario 3) changing input parameters and re-calculating.

Workshop participants shared the background of each input parameter because they set input parameters discussing with each other. Through this workshop, we found that the influence of EV and utility rate of car-sharing was significant for the reduction of SCP because 15% of the CO_2 were reduced in the second trial. As a future task, after quantification workshop, the scenario designer has to develop detail scenario using these backgrounds in 3S simulator.

Table 3. Example of input parameters and values in 2050 (not exhaustive)

	Household penetration rate of car [%] (households that can use cars / whole households in the country)	Household rate of sharing households in the market [%] (households sharing cars / households that can use cars)	Utility rate of shared car (mileage of a shared car / mileage of an owned car)	Market share of EV in market [%] (number of EVs in usage / whole cars in usage)
BaU Scenario	40	0	0	10
SCP Scenario				
First trial	50	100	2	100
Second trial	50	100	10	100

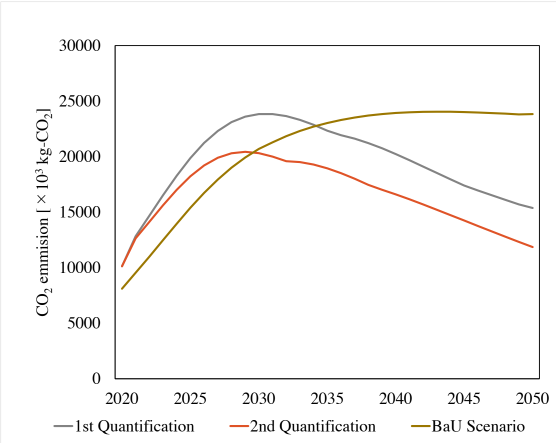

Fig. 4 CO_2 emission in SCP scenario and BaU scenario

Some challenges remain in the process of workshop. Although workshop participants quantified SCP scenarios, it is still not easy for participants to decide reasonable values in 2050 of input parameters within a workshop because time of workshop is limited. For more effective quantification, scenario designers need to offer more detail information related to parameters. Also, we need to discuss whether the quantification results are convincing or not. In future, we validate results of scenario quantification by involving more experts including those who from other discipline.

The limitation of the model should be considered. Since the model is developed based on past workshop and literature review, it might not express measure that includes completely new type of consumption and production. To clarify whether this model can quantify other scenarios or not, we will quantify other SCP scenarios.

6 Conclusion

We proposed product circulation model to support the workshop-based scenario design process. The model enabled to support the quantification process of SCP scenario from an environmental perspective. In the case study, one of SCP scenarios in Vietnam in 2050 was quantified. The results showed that utility rate of car sharing service is effective for reduction of CO_2 emission in the scenario. Future work includes conducting more case studies to further test the validity of the developed model.

Acknowledgement

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Small WEEE Recycling in Japan and Challenge after China's Import Ban

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Abstract

Due to China's waste import ban announced in July 2017, material cycles in Japan have been greatly affected. In view of this situation, we decided to elaborate the process of small WEEE recycling facilities in Japan to explore appropriate measures for more efficient plastics recovery and residue reduction. For that purpose, we conducted a questionnaire survey for designated companies with facilities for small WEEE recycling, and reviewed the influence of certain factors such as item classification in processing and process flow patterns on plastic recovery rate. The results show that plastic recovery from small WEEE is not easy. Of the companies surveyed, even the highest rate of recovery for processed amount remains about 12%, which was limited to a certain process. It is necessary to further promote advanced separation to improve plastic recovery for domestic material cycles and to reduce the amount of residues to be disposed.

1 Introduction

Due to China's waste import ban announced in July 2017, imports of mixed metal scrap and waste plastics in China were strictly controlled since the end of 2018, and material cycles in Japan have been greatly affected. As a result of the difficulty in exporting mixed metal scrap to China as well as Japan's strengthened export control by its revised Waste Management Act, small WEEE (waste electrical and electronic equipment) recycling facilities in Japan have been receiving more medium-to-low grade WEEE, some of which even cause fire accidents.

Since the residues from small WEEE and waste plastics require the similar thermal treatment or landfill facilities, Japan has been facing shortage of those facilities. In view of this situation, we decided to elaborate the process of small WEEE recycling in Japan to explore appropriate measures for more efficient plastics recovery and residue reduction. For that purpose, we conducted a questionnaire survey for designated companies with facilities for small WEEE recycling to clarify the influence of certain factors such as item classification in processing and process flow patterns on plastic recovery rate.

2 Materials and methods

2.1 Questionnaire survey for recycling companies

First, we consulted related organizations and experts about the impact of China's import ban regulations and the current state of small WEEE recycling in Japan, and examined the survey questions. Next, we conducted a questionnaire survey on business descriptions, status of processing operations, and other matters for 54 designated small WEEE recycling companies. The questions on processing operations addressed the received items and amount of small WEEE, item classification for processing, process flow, recovered amount of recyclable materials including plastic, residue amount and disposal method, etc. Other questions addressed factors such as the impact of China's import ban and related issues. In order to reduce the burden of respondents and to increase the number of responses, we also asked them whether they allow us to refer their recycling business plans and recycling performance reports as requested by Article 15 of the Small Appliance Recycling Law Enforcement Regulations. The law obliges designated recycling companies to submit to the Ministry of the Environment the recycling business plan before they start the business, and the recycling implementation report each year.

The survey form was sent to the companies by mail on April 23, 2019, and they were asked to reply within about one month.

2.2 Items subject to the Small WEEE Recycling Law

There are 28 items that are subject to the Small WEEE Recycling Law excluding 4 items subject to the Home Appliance Recycling Law. Of those 28 items, 16 items such as personal computers and mobile phones are specified target items that municipalities can hand over to recycling companies free of charge because they have resource potential and are easy to separate.

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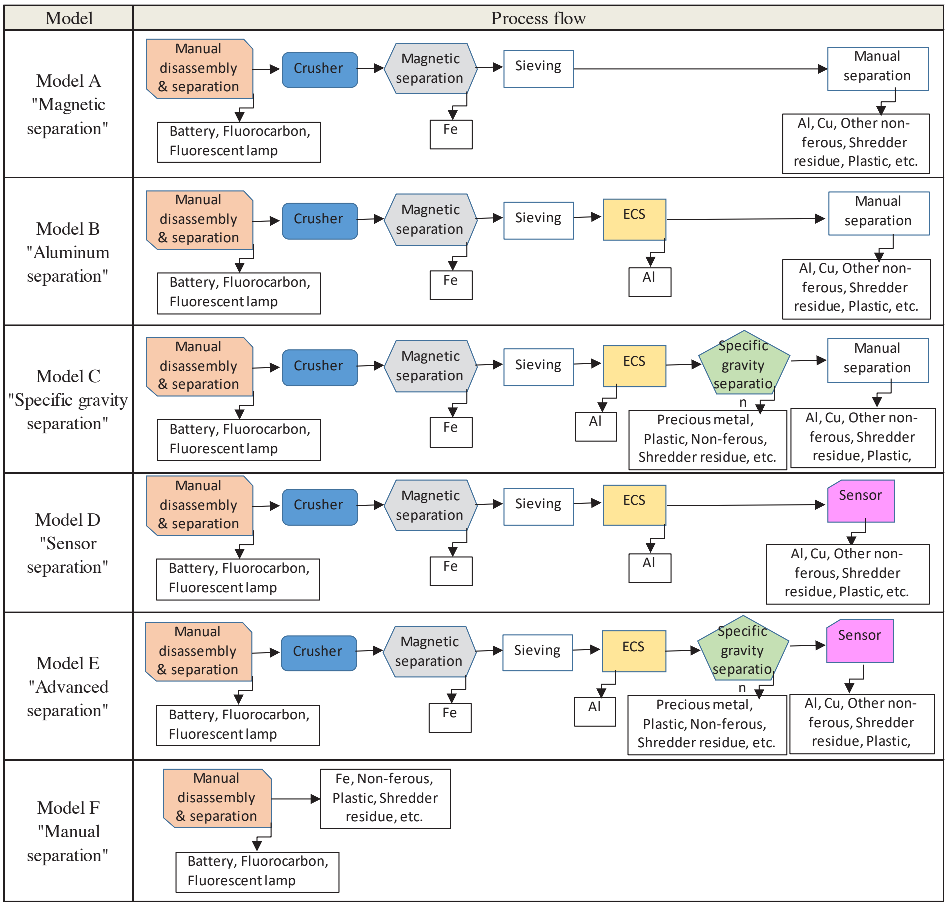

Figure 1: 7 model patterns of process flow

Specified target items are mostly categorized in high-grade items in our question.

2.3 Process flow patterns

After analysing related information in advance, we prepared 7 model patterns capturing different components of the recycling companies' processing operations for received items. Process Flow Model A (called "magnetic separation"), Model B ("aluminum separation"), Model C ("specific gravity separation"), Model D ("sensor separation"), Model E ("advanced separation"), Model F ("hand separation"), and Model G ("other") are shown in Figure 1. In order to find a way to increase plastic recycling, the relationship between process flow patterns and plastic recycling was analysed.

3 Results

3.1 The number of questionnaire respondents

Responses to the questionnaire survey were obtained from 35 companies, and the response rate for the 54 companies surveyed was 65% based on the number of companies. The response rate based on the amount of received small WEEE in FY2018 accounted for 82%.

3.2 Item classification for recycling

Regarding small WEEE items received by the recycling companies, the largest number was "all 28 items covered by the system" (24 companies, 71%), followed by "all (or almost all) 16 specified items" (5 companies, 15%).

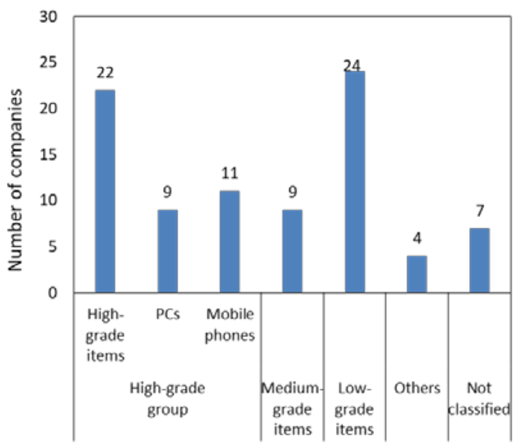

Figure 2: Number of category item classification for processing

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As for whether the recycling companies classify recyclables when processing the received items, about 80% of them do so. While there are many companies with classifying operation into 2 or 3 categories, there are also companies classifying into 6 or more categories. Some companies used their original category names and we arranged into our common names. Figure 2 summarizes the number of categories addressed by the respondents. There were 22 companies having specific process operations for classified high-grade category items and 24 companies having those for low-grade category items.

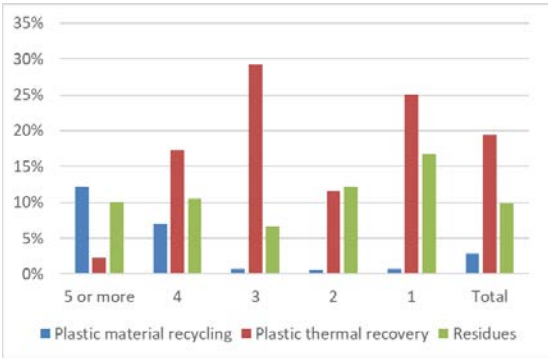


Figure 3: Relationship between classification in processing and the rate of plastic recovery and residue generation

Figure 3 shows the relationship between the classification in processing, the plastic recovery (material recycling, thermal recovery) rate, and the residue generation rate per total processed amount of small WEEE. For all the companies responded, the rate of plastic recovery for material recycling, for thermal recovery, and residue generation in the total processed amount were 2.9%, 19.4% and 9.9%, respectively. In the case of companies classifying into 5 or more categories, the rate of plastic recycling is high as 12.2%, although this result may be due to the fact that companies receive many items not from the municipalities but from retailers. Relatively high residue generation rates are found at companies without item classification for processing.

3.3 Process flow patterns

For the high-grade category, both Model B and F were mostly adopted by 6 companies, and for the low-grade category, Model E and B were adopted by 7 and 6 companies, respectively. The items classified as high-grade category tend to be processed by hand, whereas the items classified as low-grade category are often processed by sensor classification or advanced classification.

Process flow pattern	Number of companies	Processed amount (t)	Plastic recovery for material recycling (%)	Plastic for thermal recovery (%)	Residue (%)
A	1	0.0	–	–	–
B	6	2,150.7	1.2%	25.4%	3.4%
C	4	3,830.6	6.5%	25.9%	2.4%
D	5	4,655.9	1.2%	26.3%	4.0%
E	7	30,763.7	3.6%	14.4%	10.4%
F	1	78.2	0.0%	7.4%	0.0%
Total	24	41,479.1	3.5%	17.3%	8.6%

Table 1: Relationship between process flow pattern and plastic recovery and residue

The process flow pattern differs depending on the item to be processed, and it is not easy to understand the relationship between the company's process flow pattern and plastic recycling. For example, as shown in Table 1, the rate of plastic recovery for material recycling, for thermal recovery, and residue generation to the total processed amount was 3.5%, 17.3%, and 8.6% respectively for all the companies that processes low-grade items separately, but relationship with specific process flow patterns was not found.

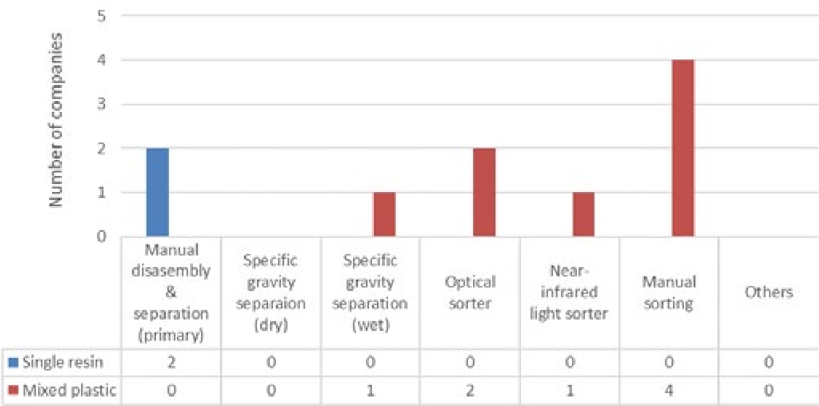
3.4 Process for plastic recovery

Figure 4 shows the process of plastic recovery at the companies processing high-grade or low-grade items. Overall, only a few processes collect plastics as single resin, and it is limited to manual separation process (before mechanical separation processes or Model F) and optical sensor process. Although collecting mixed plastics requires more processes than a single resin, it is also limited to manual separation and specific gravity separation (dry type, wet type) processes.

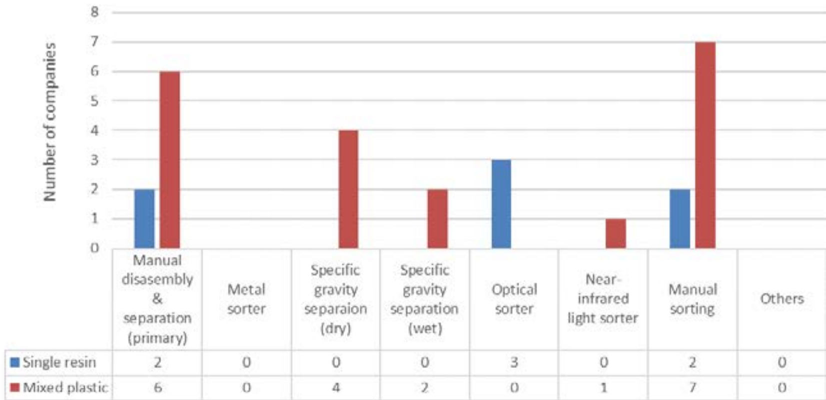
Most of the recovered single-resin plastics were recycled as materials. On the other hand, for mixed plastics, thermal recovery with production of refuse-derived fuel (RDF) and cement was common at 24 companies, and material recycling was implemented at 13 companies, but many recycled materials seem to be utilized as construction materials.

3.5 Impacts of China’s import ban

Regarding the effects of China's import ban, many of the respondents stated that the amount of processing residues increased and that plastics could not be sold because they became valueless. The lower the grade of small WEEE is, the larger the amount of plastic will become [1]. Those lower grade small WEEE remained at municipalities in Japan because of China’s import ban, and many of them are recycled at designated recycling companies. It was found that the amount of residues generated after the crushing process was so large that recycling companies suffered from increased disposal fee of residues contained plastics.



A. High-grade item



B. Low-grade item

Figure 4: Process of plastic recovery

4 Discussion

The results of a questionnaire survey for small WEEE recycling companies in Japan show that it was not easy to recover plastics from small WEEE for material recycling, and that even the highest rate of recovery for processed amount, among the companies surveyed, remained about 12%, which was limited to a certain process.

In addition, because of the difficulty in exporting mixed metal scrap, the companies engaged in the small WEEE recycling in Japan receive increasing amount of small WEEE, especially in the low-grade category. Since the destination of residues containing plastics generated from small WEEE overlaps with that for waste plastics, there is a problem that the existing capacity for thermal recovery or disposal sites are very tight and limited. According to our interviews with domestic plastic recyclers, even when plastic is recovered for material recovery from WEEE in Japan, a large part of recycled pellets from WEEE plastics are still being exported to China and other Asian countries [2]. In the future, it will be necessary to further promote advanced separation to improve plastic recovery for domestic material cycles and to reduce the amount of residues to be disposed.

5 Acknowlegment

We would like to express our gratitude to all the respondent companies that participated in the questionnaire survey for their cooperation in this research. We also thank Associate Professor, Dr. Shinsuke Murakami at University of Tokyo, Ministry of the Environment, Japan, the Association of Designated Small WEEE Recycling Companies, and Environmental Control Center for their cooperation. This research was partly supported by the Environment Research and Technology Development Funds (JPMEERF20182001) of the Environmental Restoration and Conservation Agency of Japan.

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The structure and challenges of the national E-waste Reverse Logistics System to be implemented in Brazil, according to electrical electronic sector agreement signed in October of 2019

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Abstract

In October 2019 the Electrical Electronic Sectorial Agreement, contractual act of the National Policy on Solid Waste law, was signed among the Brazilian government and private sectors, electrical electronic manufacturers and traders, in order to implement and carry out the national E-waste Reverse Logistic System in Brazil. The system goals are, in 5 years from now, collect and dispose, on environmentally sound management, 17% of the electrical electronic products placed on the market, estimated in approximately 1.8 million tons per year (2016), and involve the 400 largest cities of the country spread over a continental territory. This work presents the structure of the national E-waste Reverse Logistics System to be implemented in Brazil, describing its main characteristics, operation model, stakeholders, technical and supervision requirements and system growth planning. In particular it also analyses the main challenges to be overcome and proposes strategies to make the system implementation feasible.

1 Introduction

The lifestyle of today's society is directly related to the excessive use of technology and electronic equipment. Therefore, this equipment's useful life is increasingly shorter, and its disposal generates impressive amounts of electronic waste (e-waste). The estimates of United Nations University (UNU) [1] indicate that, in 2016, 44.7 million tons of e-waste was generated worldwide, and only 20% of this waste was environmentally sound discarded. According to the same UNU estimative, Brazil generated 1.5 Million tons of e-waste and, consequently, he is the 2nd country that most generates e-waste in the Americas and the 6th in the world. To face this scenario, in 2010, Brazil enacted Law 12.305, instituting the National Policy on Solid Waste (NPSW) aimed at environmentally sound management of solid waste, including electrical and electronic equipment waste (e-waste).

The construction of a national solid waste treatment policy in Brazil began to be legislated in 1989. However, only in 2007, the Government's proposal was the base for the establishment of the National Policy on Solid Waste (NPSW) [2]. The NPSW [3] was sanctioned as Federal Law No. 12.305, of August 2, 2010 and on December 23, 2010 the Decree 7404 was approved, which regulates the NPSW, creates the Ministry Committee to forward the implementation of Solid Waste Reverse Logistic Systems. However only, on October 31, 2019, Electrical Electronic Sectoral Agreement [4], contractual act of NPSW, was signed among the Ministry of the Environment (MMA) and the Electrical Electronic Sectors (manufacturers, importers, distributors and traders) to implement the Brazilian's Reverse Logistics System (RLS) for e-waste. Finally on February 12, 2020, the Federal Decree nº 10.240/2020 [9] ratified the Electrical Electronic Sectoral Agreement and regulated the implementation of the Brazilian e-waste Reverse Logistic System (RLS).

The NPSW [3] brings together the set of principles, instruments, guidelines, and actions for the integrated and environmentally sound management of solid waste, including e-waste. The NPSW aims to reduce environmental impacts and take advantage of the opportunities represented by the reuse, recycling, and treatment of waste discarded, in order to meet society's desires. NPSW allowed the creation of sectoral agreements, using the reverse logistics mechanism, establishing shared responsibility, and the participation of waste pickers in the selective collection process. It established the elaboration of national, state, and municipal waste management plans [5]. Likewise, NPSW created an information system and the prohibition of dumps.

2 E-waste reverse logistic system in Brazil

This work presents the structure of the national E-waste Reverse Logistics System to be implemented in

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Brazil, describing its main characteristics, operation model, stakeholders, technical and supervision requirements, and the growth plans to achieve established goals.

In particular, it analyses the challenges to overcome in the system implementation, which proposes collecting and disposing of a significant volume of e-waste on environmentally sound management and complying with Brazilian's reverse manufacturing standard. It also analyses the challenge of implementing the e-waste shipping process, which will cover hundreds of the largest Brazilian cities spread over a continental territory, which is higher than one hundred million inhabitants, and strategies that could be adopted in order to make the system implementation feasible.

2.1 Stakeholders of e-waste reverse logistic system

The e-waste Reverse Logistic System (RLS) model defined by Brazilian NPSW provides shared responsibility among the stakeholders involved in the entire process [6]. It is possible to classify them into consumers, traders, distributors, manufacturers, and importers. The model should also include Management Entities (ME) and the voluntary participation of city halls, cooperatives, and associations of waste pickers [4], Figure 1.

The Electro Electronic Sectoral Agreement for the implementation of the e-waste RLS allows the system to be implemented individually by stakeholders who are responsible (traders, distributors, manufacturers and importers) or in the collective model through those responsible associations or agreements with ME [4] [7].

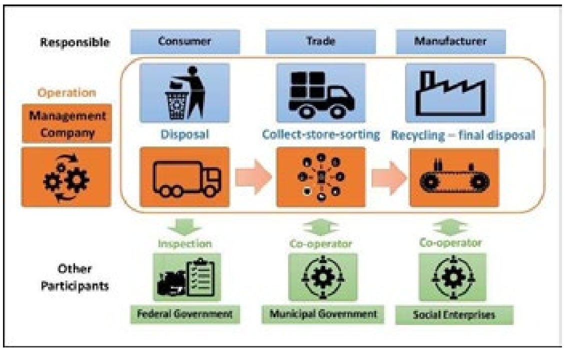

Figure 1: E-waste reverse logistic system model

The ME's purpose is to create a collective RLS like a consortium, making it possible to reduce the entire process's costs and increase the efficiency in the stages of collection, shipping, and recycling [6].

The consumers will be responsible for disposal the e-waste to the collection points, always observing the necessary precautions regarding disposal, such as removing private information and data stored in the products and disposal of the entire products cleaned.

On the other hand, the stakeholders responsible (traders, distributors, manufacturers and importers) of EEE will be responsible for structuring and implementing the e-waste RLS.

The traders should take available the e-waste collection points into their stores and be responsible for storing the e-waste until they are sent to the recycling process. These obligations are also applied to companies that sell electro and electronics equipment through distance selling, the marketplace, and electronic platforms.

Distributors are responsible for providing storage space for the consolidation and sorting points of e-waste RLS. When they do not have storage space, they are obliged to pay for it [4].

Finally, manufacturers and importers should promote the process of recycling and reinsertion of materials in the production chain, reducing the environmental impacts and the demand of raw materials, or the environmentally sound destination of 100% of e-waste collected by the RLS [4] [6] [8].

Besides specific responsibility of each stakeholder who is responsible, there are common responsibilities for all of him:

- The creation of a communication and environmental education plan, which will contemplate several ways of public awareness campaigns regarding environmentally correct disposal [4] [7] [8].
- When the responsible companies are not associated with a ME, they should make available the e-waste information and reports regarding actions under their responsibility to the competent environmental agency [4].

2.2 Operational structure of e-waste reverse logistic system

For both the Electrical Electronic Sectoral Agreement [4] and Decree nº 10.240/2020 [9] regulate the structuring, implementation, and operation of the e-waste RLS, in the exclusive scope of household equipment, not including products from industrial and professional use and high quantities from large generators [4] [9].

As explained in the previous topic, e-waste RLS's operation will include the following steps:

- Disposal of e-waste by the consumers, at collection points;
- Receipt, by traders, of e-waste discarded by consumers;
- Shipping, by traders or distributors, of the e-waste discarded to the consolidation, sorting or destination points.

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- The environmentally sound destination, by manufacturers and importers, preferably through recycling and reinsertion of materials in the production chain.

All recyclers who want to participate in the e-waste RLS must have the appropriate licenses issued by the competent environmental agencies. They also must comply with the ABNT NBR 16156:2013 [4] Brazilian standard and have to be qualified by the ME.

The RLS will create a Performance Monitoring Group (PMG) to monitor the implementation and operation of the e-waste RLS, composed by representatives of stakeholders who are responsible (manufacturers, importers, distributors, traders), and MEs [6].

The system evaluation and monitoring will be carried out by PMG, and delivered to the Ministry of Environment (MMA), should cover at least the following items:

- List of Cities served by the e-waste RLS;
- The list of the Collection Points containing the identification and addresses;
- Weight of e-waste received by the e-waste RLS;
- Weighted average unit weight by equipment type in the base year (2019);
- List of recycling companies qualified by the system, including their National Company Register (CNPJ), the weight of e-waste received, and their license by the environmental control agency;
- Information about the status of meeting the agreed goals;
- Other relevant aspects of the performance monitoring of the e-waste RLS.

In addition to the PMG actions, stakeholders must contract independent annual audits to verify the data provided and prove their performance [4].

Furthermore, the NPSW created the National Information System on the Management of Solid Waste (SINIR), a digital information system that collect public and private data on solid waste management, including e-waste. SINIR will make it possible to monitor, inspect, and assess the efficiency of the management of the e-waste RLS [3] [10].

2.3 Regulation requirements of e-waste reverse logistic system

The Electrical Electronic Sectoral Agreement has established specific requirements for the Reverse Manufacturing Companies (recyclers), the Management System, and the Education and Environmental Communication Plan (EECP), which we present below, as shown in figure 2.

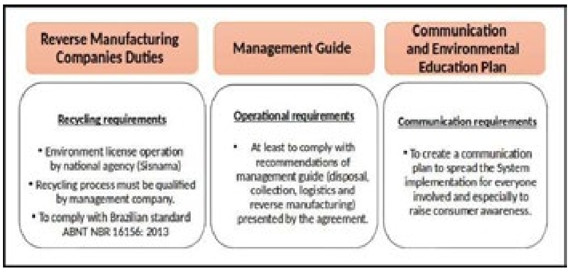


Figure 2: System regulation requirements

2.4 Obligations of recyclers

To participate in the RLS, e-waste recyclers must meet at least three essential requirements: environmental licensing, recycling process qualification, and to comply with Brazilian standard ABNT NBR 16156:2013 [4].

Concerning environmental licensing, the National Environment Council (CONAMA), in resolution 237 of 1997, regulated the aspects of environmental licensing established in the National Environment Policy. The federal agency, the Brazilian Institute, the Environment and Renewable Natural Resources (IBAMA), or state or municipal environmental departments, are responsible for authorizing, monitoring, and inspecting industrial activities that may damage the environment [4].

The qualification of the e-waste recycling process of recyclers will be carried out by the Management Entities (ME) according to the Brazilian standard ABNT NBR 16156:2013 - Waste electrical and electronic equipment - Requirements for reverse manufacturing activity [11]. The standard establishes the requirements to structure a management system for the reverse manufacturing of electronic waste. The standard is based on four (4) fundamental pillars, that is, the protection of the environment (ISO14001); worker safety (OSHAS18001), the waste recycling process mass balance and the traceability of the materials and, finally, the protection of the manufacturers' brands and digital data stored in the waste [11].

The ME will also be responsible to verifying that recyclers or shipping companies are complying with IBAMA environment regulations for the e-waste interstate shipping [4], and as well as to contract the service providers, according to the federal regulation organs requirements (SNVS and SUASA), to carry out the environmentally appropriate disposal of tailing resulting from the recycling processes [4].

The National Policy on Solid Waste (NPSW) [3] encourages Recyclable Material Collectors' Cooperatives and Associations (RMCCA) to participate in the e-waste RLS. They may formally integrate into the e-waste RLS, to collect, shipping or even recycling, as service providers through formal contracts with the ME.

2.5 System operational guide

The Sectoral Agreement for e-waste Reverse Logistic System (RLS) presents basic operational guide that includes technical guidelines for the correct handling to disposal, shipping, storage and recycling of e-waste.

Consumers are a fundamental part of the e-waste RLS, because they are the source of returning the e-waste to the collection points,. Therefore some basic handling and disposal care of e-waste is necessary, how to separate e-waste from other fractions of solid waste, as well as disposal of the entire products cleaned and remove any private information or data stored in the e-waste.

Only capacity professionals, qualified by Management Entities (ME), will ship the e-waste. The shipping must carefully handle the e-wastes, and no processing of the e-waste is allowed during the shipping stage. The e-wastes must also be shipped in closed vehicles or with covered bodies, to the storage and consolidation points.

At the storage and consolidation points could occur the screening stage, which aims to separate the e-wastes by similarity, optimizing the shipping to specialized recyclers. It is also no allowed e-waste processing at the screening stage.

Finally, the e-wastes are shipping to companies responsible for recycling and environmentally sound disposal. In this stage, the e-wastes are disassembled in order to separate their main components into different parts, such as plastics, ferrous metals, non-ferrous metals, glass, and components that need special treatment.

2.6 Environmental communication and education plan

The traders, manufacturers, importers, or their representative ME, must participate in the execution of the Environmental Communication Education Plan (EECP), to carry out information, dissemination and awareness-raising actions for Consumers and society, in general, in the scope of the e-waste RLS [4]. According to the Electrical Electronic Sectoral Agreement (EESA), the communication plan will cover:

- The mandatory of environmentally sound destination of e-waste and tailings.
- The obligation to remove, before disposal, all information and software programs stored in e-waste.
- The environmental aspects of the EEE life cycle mentioned in EESA.
- The location of the system e-waste collection points.
- Create and maintain a website and information system to publicize e-waste RLS actions.

The Environmental Education Plan aims to awareness opinion makers, leaders of entities, associations, and municipal managers to support the e-waste RLS implementation and promote actions to encourage the consumer to sustainable consumption, correct e-waste disposal, and respect for the environment. [4].

2.7 Main characteristics of e-waste reverse logistic system

The Brazilian system structure's main characteristics, for receiving and environmentally sound disposal of electronic waste, are presented below in Figure 3.

The Electrical Electronic Sectoral Agreement (EESA) considers e-waste all electro-electronic equipment for domestic use, home appliance, whose operation depends on electrical currents with a nominal voltage not exceeding 240 volts, at the end of its useful life.

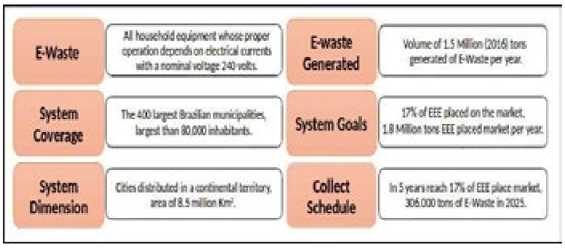


Figure 3: Main characteristics of Brazilian e-waste reverse logistic system

The system will involve the 400 largest cities (with more than 80,000 inhabitants) of the country spread over a continental territory. For each city, the system must install at least one e-waste collection point for every 25,000 inhabitants.

The e-waste RLS target proposal is, in 5 years from now, to carry out the environmentally sound management of 17% of the EEE volume placed on the market in the base year (2019).

According to international estimative from 2016 [1], Brazil place on the domestic market 1.8 million tons of EEE per year, and the country generates 1.5 million tons of e-waste per year [12]. So Brazil must collect approximately 306,000 tons of e-waste in 2025.

3 System challenges and implementation strategies

To understand the challenges of implementing the Brazilian's Reverse Logistic System (RLS) for e-waste, we analyzed some critical implementation factors, of our point of view: Reach the e-waste recycling target defined as 17% of the volume of electro electronic equipment (EEE) placed on the market; Ensure that the quality of recycling plants comply with the Brazilian standard ABNT NBR 16156 [4]; The economic impact of shipping costs on the system implementation and, finally, To raise consumer awareness in order to motivate his collaboration with the system.

3.1 Achieve the e-waste recycling target defined as 17%

To assess the Brazilian challenge of reaching the e-waste recycling target, defined as 17% of Electrical Electronic Equipment (EEE) volume placed on the market, we have analysed how higher this rate is than the recycling rate of Brazil today, as well as the volumes of e-waste involved on this rate. Finally, we compare these numbers with the recycling results of European countries, with similar targets.

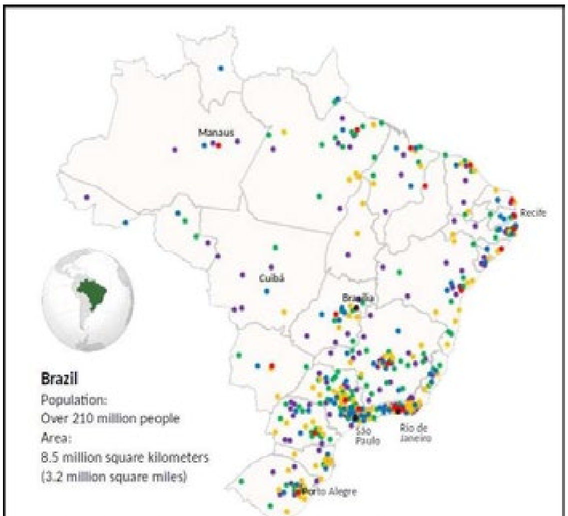
Note that the base year of the Reverse Logistic System (RLS) of Brazil is 2019, date of signature of the sectoral agreement, so after 2019 those responsible will have a period of 1 year to structure the system, and finally the target of 17% must be reached in 5 years after the system has been structured, therefore 2025.

In terms of volumes, we used the estimated data from 2016 [1] as a reference, when Brazil placed approximately 1.8 million tons of EEE on the market, so to reach the target of 17% in 2025, the RLS must recycle approximately 306,000 tons of e-waste. The estimative from 2016 [12] is that Brazil generates approximately 1.5 million tons of e-waste per year.

According to the estimate [12] in 2016, Brazil recycled 3% of the e-waste generated. Brazil has several e-waste environmentally sound recycling initiatives and recycling plants, including refrigerators recyclers established in the country since 2010, and recyclers of defected EEE discarded by manufacturers, in a business to business (B2B) relationship, these activities justify this 3% rate. To reach the final target of 17%, the country's recycling capacity needs to increase about fivefold the current rate, in 5 years; therefore, it is a great challenge.

Comparing the volume of electronic waste to be recycled in Brazil (rate of 17%, volume 306,000 tons, 2025) with European countries, according to the 2016 estimates [1], we observe that the Brazilian target is similar to the volume recycled by Italy (rate of 22%, volume 249,000 tons, 2016). However, there are great differences as the European country has reached its goal in 10 years (2006 - 2016), twice as much as the Brazilian proposal, and even more important is that the Brazilian territory is approximately 28 times larger. Although the comparison is very simple, in fact other factors must be taken into account. It gives us an idea about the challenges of the Brazilian proposal.

Considering the previous analyses, we can conclude that the Brazilian proposal seems to be bold. However, the strategy to reach the target of 17% is rational, once the system implementation will go through five stages, with a gradual increase of the recycling rate, year per year, according to the numbers of cities involved and the number of collection points installed, as shown in Figure 4: Goals and evolution of the electronic waste reverse logistics system.



Year	Cities	People involved	Brazil Populaton	Collection points	Waste colleted	Waste quantity
1st	24	52 Million	25%	2080	1%	18 ktons
2nd	68	74 Million	36%	2960	3%	54 ktons
3th	186	103 Million	49%	4120	6%	108 ktons
4th	294	117 Million	56%	4680	12%	216 ktons
5th	400	126 Million	61%	5060	17%	306 ktons

Figure 4: Goals and evolution of e-waste reverse logistic system

To face this challenge, it will be necessary to increase the processing capacity of current recycling companies and probably promote the creation of new recycling plants, including supporting the qualification of small e-waste recyclers, spread throughout the country, they can formally participate in the e-waste RLS.

3.2 Ensure recycling plants quality to comply with ABNT 16156

According to the NPSW [3], the recycling process, by definition, is one process that performs any physical or chemical transformation of e-waste. Therefore, the process exposes the hazardous substances in e-waste and poses risks of environmental contamination and worker safety.

Due to the hazardous characteristics of e-waste recycling, together with the growth of informal e-waste market in the country, the Center of Information Technology Renato Archer (CTI), Institution of Brazilian Ministry of Science, Technology, and Innovation (MCTI), has engaged in developing a technical standard, at a national level, to ensure that e-waste dismantling, recycling, and result materials management process would be done correctly.

Therefore in 2013, it was developed the Brazilian standard ABNT NBR 16156:2013 - Waste electrical and electronic equipment - Requirements for reverse manufacturing activity [11]. The Brazilian standard is based on four (4) fundamental pillars: protection of the environment (ISO14001); worker safety (OSHAS18001), the reverse manufacturing process mass balance and the traceability of the process resulting in materials, and finally the protection of the EEE manufacturers' brands and digital data stored in the waste.

The structure of the Brazilian standard is similar to international standards (ISO). The new concepts that the standard has introduced in the process are the mass balance of e-waste and materials' traceability. Therefore, it requires that e-waste input volume be equal to the materials output volume and control the destination of materials resulting from the process.

Our experience in supporting recyclers to comply with ABNT NBR 16156 in the SIBRATEC program [16] has shown that it is not difficult to adopt it, even in small social recyclers, challenge will depend on the company's culture and commitment. However, the standard's differential is that it incorporates safety and transparency to the e-waste recycling process, characteristics that convey trust to customers and, therefore, increases significantly the recycler's competitiveness.

3.3 Reducing the shipping costs

One of the biggest challenges of the Brazilian e-waste reverse logistics system (RLS) is the large extension of its coverage area, that is, the collection and recycling services should be available for the 400 largest cities of the country spread over a continental dimension territory, which is higher than one hundred million inhabitants, involving large distances between the main cities and even between cities in the same metropolitan region (the metropolitan region of São Paulo city is approximately 220 km long), as shown in Figure 5.

Typically the cost of shipping is one of the most significant components of the Reverse Logistic System (RLS) costs, therefore, to reduce the impact of shipping on the final cost of the RLS process, a strategy must be adopted to reduce the path between the e-waste collections points and recycling plants.

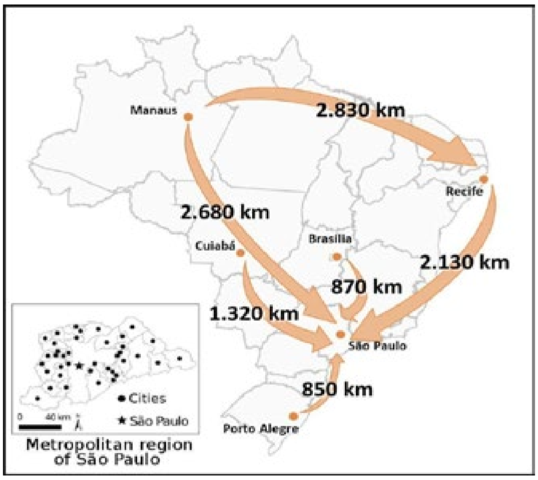


Figure 5: Continental extension of system coverage area

Previous studies carried out in Brazil, as the Technical and Economic Feasibility Analysis by ABDI in 2013 [13], and the Project JICA by MDIC in 2017 [14], indicated that using intermediate storage points, between the collection and recycling process, for e-waste consolidating and sorting process, can optimize the shipping process and reduce the system logistics costs significantly.

Another important strategic action would be to increase the collection and recycling capacity in the metropolitan regions, where most of the population is concentrated and, therefore, the place where generates the highest volume of e-waste.

However, in order to strongly mitigate the e-waste shipping costs, it would be essential to encourage small recyclers and logistics companies, spread around the country, to formally participate of e-waste RLS, to increase the country recycling capacity, reduce the shipping distances and, consequently, enhance the recycling capacity and reducing significantly shipping costs.

3.4 Raise the consumer awareness

The consumer is one of the most relevant stakeholders in the system. However, his participation is voluntary, so to raise the consumers' awareness to encourage them to collaborate effectively with the environmentally sound disposal of e-waste is one high point to make the e-waste Reverse Logistic System (RLS) economically sustainable and therefore feasible.

In general, Brazilian consumer's profile is to collaborate with good causes and to raise their awareness is usually not difficult. However, it will be important to implement an efficient communication plan to inform about their responsibility for the e-waste RLS success, as well as the relevance of e-waste environmentally sound disposal for the country's environment preservation and protecting the public health. The plan must also inform about the collection points location to facilitate consumer disposal.

Although the goal of the Brazilian LRS is based on the number of collection points installed around Brazilian cities, in general, campaigns for the e-waste collection are very successful events in Brazil, especially when its involves the participations of young people.

The Brazilian Greenk Movement [15], focused on people's environmental education about the importance of e-waste environmentally sound disposal, is based on the collaboration of generation Z youth, adept at Geek culture and passionate for technology, science, and e-games with environmental awareness. The Movement is a disruptive innovation in environmental education and awareness, and has been a success both in the young people's engagement on e-waste disposal, as well as in the volume of e-waste collected during the Greenk Techshow event [15]. This movement's experience could be adapted to implement a large communication plan, around the country, about the importance of Brazilian e-waste RLS, with incredible chances of success.

3.5 Implementation strategy proposals and expected results

According to the previous analysis, the implementation of the e-waste reverse logistic system in Brazil, presents significant challenges to be overcome, of which we can highlight the recycling target to be reached until 2025 and, mainly, the system extension involving a hundred cities spread in a continental area.

To face e-waste system's challenges, several strategies could be adopted. However inevitably they should aim the increasing of e-waste recycling capacity installed in the country, to assure the compliance of recycling process quality with Brazilian standard, reduce the shipping costs of e-waste across hundreds of cities spread in a continental country and to raise the consumer awareness to collaborate with e-waste disposal.

Perhaps one of the biggest challenges of the system is to provide services across a very large area, covering hundreds of cities spread across a continental extension country, therefore in order to reduce the e-waste shipping costs strongly, it will be necessary looking for a novel strategy, with one disruptive solution, for instance promoting the responsible participation of small collection, shipping, and recycling enterprises, spread around the county, including a social enterprises as waste pickers associations and cooperatives, whose proposal creates a capillary structure system, in order to strongly increase the e-waste services offer at a low cost, making the system feasible and sustainable, to maximize the environmentally sound management of e-waste.

Although the system's implementation is a great challenge, the significant growth of e-waste collection, logistics and recycling services, aiming to achieve the proposed goals, will undoubtedly attract investments and opportunities for new e-waste companies, and consequently promoting the economic and social growth in the country. This situation happened in 2010 when the Brazilian's NPSW [3] was approved, and several e-waste recyclers settled in Brazil, but then, as the electrical electronic sectoral agreement took a long time to be approved and the e-waste recycling demand did not grow as expected; several of them had their operations halted in the country.

Finally, the government has a fundamental role to play in the system implementation. They must monitor the system operation and inspect if the Sectoral Agreement requirements are being met, taking advantage of the excellent opportunity to make e-waste reverse logistic system in Brazil not only an action to preserve the environment, but also a powerful instrument to promotes economic and social development.

4 Conclusions

The structure of the Brazilian e-waste reverse logistics system is robust and feasible because:

- There is legislation in force with targets and inspection mechanisms,
- The goal is bold, and the coverage area is large, but the system evolution will be done in stages,
- The recycling system is based on quality standard, and the implementation can be collective,
- Control, supervision, and evaluation mechanisms are in place,
- There is basic operational guide on good collecting, shipping and recycling practices
- There is a communication plan, to raise consumer awareness and motivate their collaboration

Implementing and operationalizing the Brazilian e-waste reverse logistic system will be tremendous technological and political challenges that will demand disruptive strategies and solutions. However, on the other hand, it is a great social and economic development opportunity, which is why the main stakeholders are optimistic.

In a short time, with e-waste environmentally sound management, Brazil should significantly reduce the electrical electronic equipment impact on the environment and public health, and promote the circular economy and social-economic development, goals idealized by the NPSW.

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Jobs and E-Waste: Ireland's compliant and non-compliant treatment flows

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Abstract

The creation of employment opportunities, is an important factor in growing green and circular economies. This research investigates job creation in the Irish WEEE pre-treatment sector by examining labour requirements at Ireland‘s main compliant WEEE recycling facility. Through conducting time studies for individual pre-treatment steps and using UNU Keys for categorisation of WEEE it was determined that between 338 and 1,967 tonnes were required to create one full-time job for the categories LHA, CRT/LCD/CRT screens, microwaves, and mixed waste. Subsequently, the results were applied to accompanying research in order to estimate foregone jobs due to WEEE arising in metal recycling scrap yards. It was found that diversion of this waste to a compliant WEEE pre-treatment would result in the creation of 12+ jobs. This research opens doors to further investigate job creation across EU member states and globally using the straightforward and consistently applicable and adaptable methods developed here.

1 Introduction

Increasing demand for electronic products globally has resulted in a significant increase in the associated waste electrical and electronic equipment (WEEE), presenting a number of issues for consideration. Classified as a hazardous waste due to a composition of numerous toxic elements, WEEE poses a threat to both environmental and human health when disposed of or treated without care. Manufactured using numerous valuable and critical raw materials (CRMs), which must be initially obtained through mining with only a fraction making it through value recovery in recycling, EEE presents economic and social issues at the beginning and end of the product life cycle.

The European WEEE Directive lays out the regulatory environment for WEEE collection and treatment in the EU. Compliant WEEE treatment involves a high degree of attention to health and safety conditions, separation of materials, and selective treatments in order to reach the stipulated recycling targets. This essential preprocessing is mostly performed manually [1; 2]. These requirements add additional steps to the treatment processes required compared to traditional scrap metal recycling, which in turn results in a higher number of labour hours required. Additionally, costs for compliance standards certification, proper reporting, administration, equipment, and technology rise for compliant facilities in stricter regulatory environments [3]. Meanwhile complimentary channels do not absorb these additional costs and therefore have a distinct economic advantage through limited or a lack of reporting, a lack of required specified treatments [3]. In addition, complimentary channels, through non-segregation of WEEE and materials shredding, are relatively ineffective at precious metal recovery [1; 2], and are not providing optimal opportunity for CRM recovery [4].

While there has been increasing interest in research relating to WEEE treatment, over the last two decades a significant gap has emerged in research estimating the number of jobs created through compliant treatment. This provides an opportunity for research to produce insight by estimating the employment consequence of foregone jobs in compliant WEEE recycling due to diversion of waste into non-compliant or even informal WEEE treatment. This study develops and tests a methodology to estimate the labour hours, and therefore jobs, required in the pre-treatment of WEEE in Ireland, based on observations of a compliant facility where a significant portion of the WEEE collected in Ireland is treated. Although there is further potential for estimating jobs foregone in relation to collection and end processing, the scope of this study is focused on labour specifically involved in the pre-treatment of WEEE. The estimated labour required to treat WEEE is combined with the results from a separate study quantifying the amount of WEEE in Ireland found in non-compliant channels, specifically, scrap metal collections.

2 Background

2.1 Job creation in WEEE treatment

Estimation of job creation and labour hours required in the treatment of WEEE has surprisingly little presence in recent academic literature. While many papers focus on the environmental and health impacts of WEEE treatment in developing countries, very few mention the number of workers. Of those papers where numbers are mentioned, estimates were largely found not to have been heavily evidence-based and tended towards loose estimates used for context. Additionally, these estimates were based on regulatory and economic situations differing greatly from country to country and spanned decades. This as well as difficulty in defining WEEE or e-waste across regions and governmental bodies presents additional challenges in estimating employment potential in WEEE treatment globally [5].

Of particular importance is the creation of decent work, which encompasses employment creation, social protections, rights at work, social dialogue, and more, and is called for in Goal 8 of the United Nations' Sustainable Development Goals[1]. Recently, a review by the International Labour Organization (ILO) (2019) [5] examined existing sources of information regarding creation of decent work in the treatment of WEEE. The review consolidates available national estimates, with national estimates ranging from 5,324 employed in 62 companies in South Africa, to 690,000 employed as collectors or recyclers in China. However, the review acknowledges that the process of producing the estimates was at times unclear.

The ILO review also identified several weight-based estimates, the first of which equates 1,000 tonnes of WEEE with 40 jobs in collection and sorting in the UK [6], and another equates 15 jobs in sorting and recycling of WEEE with an additional 30 in landfills and 200 in repair [7]. Relational estimates were also presented in the ILO's analysis, estimating that 1 tonne of WEEE could support 1 job in Kenya [8], and that recycling electronics had the potential to support 10 times more jobs than landfilling approximately two decades prior to this study [9]. A number of variables differ across each of the aforementioned estimates; in addition to the difference in weight based, worker counts, or relational estimates, some represent different sectors, branches of the same sector, regulatory environments, working conditions, average working hours/annual full-time job definitions, and even time frames. Thus, while several estimates are available in the literature, few are comparable to an extent allowing replication across multiple regions, governments, economic conditions, etc. There is significant value in closing this gap through developing a globally expandable method establishing the potential of more formalised WEEE treatment to create decent work opportunities.

2.2 Compliant treatment of WEEE

European treatment requirements are laid out within the WEEE Directive, and in the transposed version, Statutory Instrument (S.I.) 149, for Ireland. Compliant WEEE treatment facilities in Ireland are required to enact measures ensuring the safety of workers, proper disposal, improved value recovery, and minimization of pollution risks, which non-compliant pathways may or may not apply to their operations. Types of WEEE equipment, previously separated into 10 categories, are now merged into 6 categories in the legislation as of 2018 [10].

These 6 categories define a number of required pre-treatments including, at minimum, a removal of all fluids and a heavy focus on depollution to reduce environmental impacts of hazardous materials. In addition to the required pre-treatments, WEEE collection is also subject to requirements relating to the reporting of quantities in order to meet set collection targets. From 2019, targets mandated within the WEEE Directive and transposed member state legislation are set at collection of 65% of the average equipment placed on the market averaged over the previous three years, or 85% of WEEE generated, along with set targets for recovery and recycling/preparation for reuse based on the new 6 categories of WEEE [10]. The Directive also permits member states to set up minimum quality standards, which led to the development of a European standardisation. Standards vary by member state and cover areas such as health and safety and treatment quality.

The report 'WEEE Recycling Economics' (2018) [3] authors Magalini and Huisman illustrate the financial cost of compliance, the label of compliance itself incurring additional costs including preparations for auditing, reporting, and other related administration. Auditing and reporting were found to result in a cost of €4-8 per tonne and €37-42 per tonne, respectively [3]. Overall, the avoidance of these regulatory requirements could result in a decrease in 20% of costs related to reporting and auditing and 50-60% of costs relating to depollution and disposal [3]. It is clear that the vast majority of these steps result in not only additional financial costs but also in additional labour requirements. Processing of WEEE in scrap yards can be best described for the purposes of this study by its lack of pre-treatments. Processing of waste in such sites does not include the careful separation, manual dismantling, or depollution as WEEE and other hazardous waste categories are not the intended waste categories, and in fact are not permitted as intake. However, WEEE ends up at scrap metal sites as part of mixed metal loads, mostly coming from construction and demolition works and home or business clear-outs. WEEE are composites of various materials, mainly metals and plastics and are aggregated with other composite materials for shredding both in Ireland and overseas. When compared with non-compliant channels of WEEE

[1] https://www.ilo.org/global/topics/decent-work/lang--en/index.htm

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collection and treatment, compliance with the legislative requirements and those within standards likely results not only in the loss of economic competitiveness and opportunity for compliant facilities, but also in job creation for the WEEE treatment sector.

According to the Huisman et al. (2015) in the Countering WEEE Illegal Trade Summary Report [11] only 35% of European WEEE disposed of over the year 2012 was treated within legally compliant waste treatment streams, as reported in official documentation for collection and recycling. Thus, the remaining 65%, or 6.15 million tons of WEEE, was found to have been exported (16%), remained in Europe but recycled in non-compliant facilities (33%), scavenged to remove valuable components (8%), or improperly disposed of in household or other waste bins (8%). Globally, by 2016, 44.7 million tonnes of e-waste was generated, but waste recycled through appropriate channels amounted to only 20% of this number, despite 66% of the world's population living under e-waste legislation [12].

Non-compliant channels, absorbing none of the additional costs of compliance, are therefore at an unfair competitive advantage and contributing significantly to the disrupted economics of the WEEE recycling trade [3]. The scavenging of whole products and components is representative of the economic consequences of non-compliant WEEE treatment in the EU. In addition to the environmental costs of improperly handled scavenged material, it is estimated that the WEEE diverted from the compliant channels of treatment amounted to 152,000 tonnes of material at a value of more than €150 million in 2018 [13].

Ireland's waste collection and treatment has in recent years reached collections targets stipulated by the WEEE Directive through collections from civic amenity sites, retailer takeback schemes, and special collection events. Ireland has previously met WEEE collection targets, reaching 51% collection in 2017, exceeding the 45% target of the time [14]. However, the increased collection target of 65%, 14% above the rate of collection in 2017, will prove a challenge for the Irish WEEE system. Research by Ryan-Fogarty et al. (2020a) [15] illustrates the quantity of WEEE arising in "complementary" channels, such as metal scrap yards. Clearly, there is a higher potential for collection of WEEE through the recapture of WEEE that is not arising in the compliant system due to disposal in household waste collections, scrap metal collections, and both illegal and legal export [16]. Additionally, lifetime extension through second-hand sales, refurbishment, remanufacture, as well as long term storage result in a delay in EEE arising in the compliant waste stream and facilities [16]. Quantifying WEEE not arising in compliant recycling systems, and therefore a portion of the missing economic potential for compliant WEEE recycling facilities (i.e., job creation potential), can contribute to the argument of enacting measures to channel WEEE into the appropriate facilities.

3 Methodology

In order to assign evidenced values to the labour input hours for each type of WEEE, data collection was conducted through time study observations at a compliant WEEE facility in Ireland treating 75% of compliance scheme collected WEEE in Ireland in six categories: mixed waste, LHA, screens, microwaves, and cooling. Time studies use observation and measurement, to determine the amount of time required to complete a particular task under particular conditions.

WEEE is already largely segregated when it arrives into the facility, as waste segregation is highly promoted at public collections to allow for efficiency in pre-treatment. However, smaller quantities of temperature exchange equipment, LHA, microwaves, and screens are also separated from mixed waste which also arrives on site. Additionally, products containing batteries are temporarily diverted from the mixed waste stream and returned following battery removal, in line with legislation and fire safety precautions.

As the facility is within Ireland, it is subject to the strict regulatory environment described in the section 2.2 of this paper, compliant with the WEEE Directive and S.I. 149. The facility also exists in a competitive economic environment.

Sampling consisted of observations of treatment operators dismantling WEEE, identifying distinct steps in the dismantling process, and recording the time required for each step either by unit of equipment or batch of items. Weights per unit of equipment were assigned based on research by Forti et al. (2018) [17] and the associated United Nations University (UNU) Keys for WEEE classification. Use of the UNU Keys allowed for a consistent and transparent method for assigning weights. Processes were then mapped into treatment flows and each step in the treatment flow was labelled with the amount of time in minutes required for that step. The steps were then summed to result in the total labour time required for a complete process. Lastly, the hours required per mass of WEEE were used to calculate the amount of WEEE associated with one full-time job in the treatment of that WEEE. An Irish full-time job is assumed herein to consist of 1,810 hours based on research by Eurofound (2017) [19] averaging working hours, paid leave, and holidays across Irish business sectors.

The methodology in this study is based on the straightforward calculations developed to determine total labour hours required to treat specific WEEE flows, whereby the amount of labour hours needed to treat a specified mass of WEEE (e.g., 100 kg/1 tonne/etc.), determined through data collection, is multiplied by the amount of WEEE that needs to be treated, resulting in the total labour hours required. Conversely, in order to determine the amount of WEEE required to fulfil the labour hours of 1 annual full-time job, these calculations were simply reversed. This data collection and the associated calculations were then applied to data quantifying WEEE in Ireland moving through non-compliant pathways [15] in order to estimate the number of full-time jobs that would be required, were this WEEE diverted into pre-treatment at compliant facilities.

4 Results

The following sections describe the processes as well as the estimated time requirements for the treatment of 6 WEEE categories at the model facility.

4.1 Mixed waste

In the model facility, an incoming mixed stream of electronic waste is moved directly from trucks into the treatment area and sorted continuously throughout the day. The first sort is conducted manually, separating equipment to be entered into streams for which there are dedicated processing lines on-site as well as removing pieces unsuitable for subsequent mechanised process such as cables, glass, and products containing batteries, the latter of which will re-enter the mixed waste stream post battery removal. The remaining waste consists largely of small household appliances and other miscellaneous products (Figure 4.1).

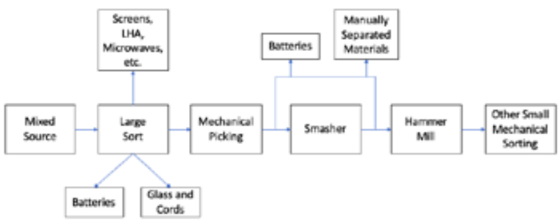

Figure 4.1. Treatment flow of mixed waste at the model facility.

The first stage of pre-treatment, as mentioned, removes unsuitable waste from the stream and reallocates it into appropriate streams. The second stage uses a mechanical claw to separate items and drop them onto a conveyor belt where the workers further identify unsuitable materials, particularly cables. In the third and final stage, waste moves through a series of machinery including a large tumbler using gravity to break equipment into pieces, shredders, and machines using material separation techniques, with a number of workers manually separating smaller parts unsuitable for the machinery such as batteries and sorting material types at different stages.

As the conveyor belts and picking of unsuitable materials run continuously throughout the work shift, estimation of labour required is not broken down into tasks for this waste stream. Rather, the estimation is calculated from the number of workers and the amount of waste treated per day. Each day the mixed waste stream is reported to treat 25-30 tonnes of WEEE, running over an 8-hour workday with the help of approximately 15 workers. Within the range of WEEE per day, 362-453 tonnes of mixed WEEE equates to 1 full-time equivalent job.

4.2 Large Household Appliances (LHA)

The separated collection source of LHA was unloaded at a rate of on average 16 seconds per unit, or approximately 0.37 minutes per 100 kg. While all LHA was segregated together and underwent largely the same treatment, washing machines underwent an additional manual treatment step consisting of the removal of the motor, purely for additional value recovery. Other LHA, along with the remaining portion of washing machines, was subsequently compacted and baled, largely for efficiency in transportation, then loaded for export for final treatment.

The LHA analysis resulted in two separate estimates, based on UNU code 0104 for washing machines, and an average of codes associated with other LHA product types. The treatment for LHA, not including washing machines, was found to require a labour input of 5.51 min/100 kg, while washing machines required 6.41 min/100 kg with the additional dismantling (Figure 4.2).

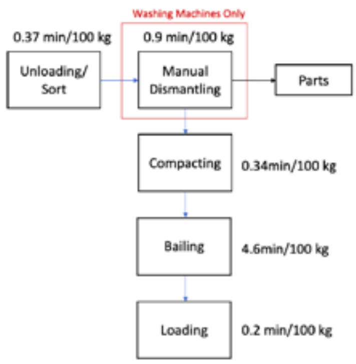

Figure 4.2. Labour flow and inputs for the dismantling of washing machines and other LHA.

The overall treatment process for LHA was estimated to equate to 1,967 tonnes per full-time job, while the treatment process for washing machines resulted in a slightly higher labour requirement with one full-time equivalent employee treating 1,692 tonnes in one working year.

4.3 Screens

4.3.1 Cathode ray tube (CRT) televisions and monitors

Separate collection occurred for a significant portion of CRTs treated, although a stream of units were separated from the mixed waste as well. CRT units were gathered in cages and moved by forklift to the workstation, where workers are located at ergonomic desks with hammers, electric screwdrivers, a conveyor belt leading to the depollution area, and easy to reach collection bins for separated materials (plastic/metal/etc.).

Following dismantling of the outer case the remaining inner glass casings were moved down the conveyor belt where the units were depolluted using a powder vacuum, and glass types are separated. Separated metal, plastic and glass was baled and removed from the area via forklift. The treatment process described here and illustrated in Figure 4.3.1 equates 476 tonnes of CRTs within 1 full-time job.

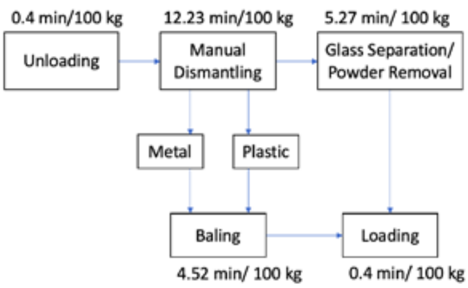

Figure 4.3.1. Labour flow and inputs for the dismantling of CRT screens.

4.3.2 LCD/LED televisions and monitors

Flat-panel display televisions and monitors with backlighting provided through LEDs and LCDs are treated separately from CRT televisions, and also are largely received through separate collections. Although LCDs require an extra depollution step, in this facility by way of a specialised machine, all other processing in the model facility was the same for LED and LCD devices. Screens were delivered in cages and pallets to the workstation by forklift, where workers removed the housings using hammers and electric screwdrivers. Based on the weight estimated for UNU code 0309, the treatment process for flat-panel display TVs and monitors overall (Figure 4.3.2) equated to 1 full-time job per 338 tonnes.

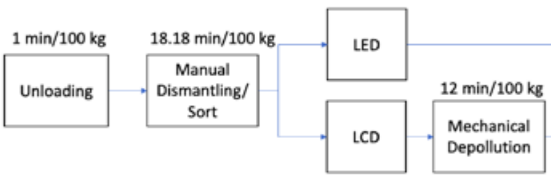

Figure 4.3.2. Labour flow and inputs for the dismantling of LED and LCD screens.

4.4 Microwaves

Microwaves were largely sourced as a separate collection in order to facilitate necessary removal of parts. A smaller portion was continuously sorted out from the mixed waste stream due to their construction being unsuitable for the machinery used to treat mixed waste. The process for treatment of microwaves included loading and unloading by forklift with a dismantling step where several component parts were removed manually in between. Manual dismantling was facilitated by an ergonomic work desk with attached tools hanging at easy reach, tools including an electric screwdriver and a hammer as the most frequently used. Pallets with units to be treated and bins for units to be taken away were placed within reach of the work desks.

Manual dismantling steps took an average of 1.5 minutes per unit, and each unit was estimated to weigh 18.21 kg according to UNU Key 0114 [17]. Thus, with the added 2 minutes per tonne for both loading and unloading, microwave treatment at the model facility (Figure 4.4) results in one full-time job per 1266 tonnes of microwaves.

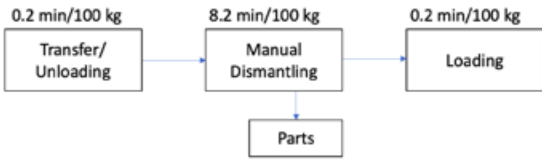

Figure 4.4. Labour flow and inputs for the dismantling of microwaves.

4.5 Cooling

The simplest process of WEEE treatment was for cooling equipment including refrigerators and freezers. This equipment requires specialist treatment, which is not conducted in the Republic of Ireland and therefore was only loaded from collection trucks and reloaded into transfer trucks to specialised treatment facilities in Northern Ireland (Figure 4.5).

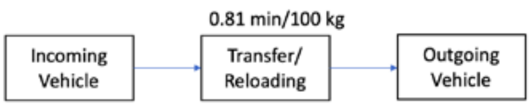

Figure 4.5. Labour flow and inputs for the dismantling of cooling equipment.

Forklifts were used to move one pallet of several units at a time. Using the weights associated to UNU-Keys 0108, fridges (incl. combo fridges), and 0109, freezers, 40 and 44 kg respectively [17], the process of moving the pallets or units from one truck to another required approximately two minutes per tonne or 0.2 minutes per 100 kg. In this case it is not particularly useful to present labour hours in terms of full-time jobs, since on its own loading and unloading of 13,407 tonnes of cooling equipment at the model facility would equate to one full-time job.

4.6 Summary of time study and observation of compliant WEEE treatment

Comprised of an overview of 75% of the processing of Irish WEEE, the results stemming from this study present an interesting and largely representative view of Irish job creation in the recycling of electronics, consolidated in Table 4.6.

Table 4.6. Summary of results, including annual full-time job equivalencies of waste treatment streams, treatment processes and equipment required at the model facility.

Category	Mass required per full-time job equivalent (tonnes)
Mixed Waste	362-453
LHA	1,967
Washing Machine	1,692
CRT	476
LCD/LED	338
Microwave	1,266
Cooling	13,407

5 Discussion

The job equivalencies for the six categories of waste considered in this study have a very wide range, from 338 tonnes of Flat Panel Displays for one full-time job equivalent as the most labour-intensive treatment category to 13,407 tonnes for cooling equipment as the least labour-intensive category. Clearly, while the transport of cooling equipment from the Republic of Ireland into Northern Ireland where it is processed will account for a larger number of labour hours, pre-treatment of refrigerators and freezers is not a significant portion of the labour in recycling of WEEE within the Republic of Ireland. On a much more relatable scale, microwaves were the next least labour-intensive requiring 1,266 tonnes of microwaves to equal one full-time equivalent job, with LHA in a similar range. Microwaves also likely represent a smaller and lighter incoming stream and as such comprise a smaller portion of jobs in recycling than the remaining streams. The remaining streams, screens (including CRTs and LED/LCDs), and mixed waste, fall roughly into a much more similar range of 400-660 tonnes per one annual full-time equivalent job. These categories also represent high volumes and/or high weights being processed in the recycling facility, with LHA being a significant portion by weight considering the high weight of each individual units. Therefore, these categories are particularly important in estimating job creation based on recycling of WEEE in Ireland.

As discussed in section 2.1, it is difficult to compare the pieces of work in the existing literature due to differing variables of scope such as economic, societal, regulatory environments, time frames, branches of the treatment process, etc. For example, although the results do not illustrate employment and labour hours in collection, administration, refurbishment, or specific waste streams collected under separate schemes such as IT equipment, these jobs should also be considered in the quantification and related considerations of employment in recycling of WEEE. Quantification of these types of jobs creates opportunity for further related research, especially comprehensive research representing the entire sector and applicable to the same sector in various areas of the world. This model will be particularly interesting for use in better estimating the potential for decent work in developing nations, where recycling jobs would require a lower amount of automation, transitioning from informal WEEE recycling.

5.1 Application of time study and observational data to WEEE lost to scrap metal in Ireland

Given that the mandated pre-treatments occur in the model recycling facility and do not occur in the scrap yards a significant labour difference in the processing of WEEE between the two site types is expected. Combining the results of both studies (Table 5.1) shows this assumption to be true for all bar temperature exchange equipment. As, the treatment of temperature exchange equipment such as refrigerators and freezers is conducted outside of the Republic of Ireland it means that this category is not of particular importance in this comparison, as there is very little labour difference between the two sites (although where the material travels to and how it is treated after leaving both sites differs greatly). However, WEEE found in scrap yards representative of the other five categories does show a significant labour difference, particularly when summed together.

Table 5.1. Application of technical coefficients representing jobs per tonne of WEEE to estimations of WEEE in scrap yards annually

Category	Annual Estimated Weight in Scrap Yards (tonnes)	Estimated job equivalencies
Mixed Waste	3,883	8.57 – 10.72
Washing Machines	2,277	1.35
Other LHA	2,570	1.3
Microwaves	430	0.34
CRTs	127	0.27
LED/LCDs	71	0.21
Cooling	1,395	0.1
Other	197	n.a.
Total	10,950	**12.14 – 14.29**

6 Conclusion

Non-compliant treatment and disposal of WEEE, especially in the form of scavenging, has been established to have an economic impact on the WEEE recycling trade. Specifically, the differences between compliant and non-compliant facility costs create unfair competition and value loss by diverting equipment away from proper treatment channels [12; 11]. It is clear that due to the preparation for, reporting of, and the practice of becoming and remaining compliant there is a significant added cost and labour requirement. Non-compliant facilities and streams are not burdened by these added costs. In the highly regulated Irish system these differences in the cost base would be expected to be stark. This study shows this to be true in the comparison between WEEE improperly disposed of in scrap yards, where WEEE has been shown to not be separated and is processed as scrap, and compliant facilities such as the observed model facility, where WEEE is carefully separated and treated under regulatory and standard requirements. The combined implications of the non-compliant WEEE quantification and the estimation of labour hours per mass of categorised WEEE provide a unique perspective on the distinctions between compliant and non-compliant treatment. The WEEE lost to improper treatment has the potential to create and support a likely minimum of 12-14 full-time equivalent jobs. It is important to acknowledge the employment potential in collection, administration, and other peripheral activities that are yet to be measured, as well as the employment potential in WEEE that is diverted into export, household waste collections (which may end up in landfills, incinerators, or plastics recycling), scavenging, and even long-term storage. Several factors further indicate that this is a conservative estimate. For instance, other waste streams enter scrap processors that contain WEEE, however, the quantities are small or specialised and it was not possible to survey these as none were witnessed at scrap yards during the sampling period. Furthermore, Ireland has introduced the polluter pays principle in Ireland through privatization of household waste, which requires each household to pay for waste collection costs, with recycling subsidised through the packaging compliance schemes. This has led to an increase in fly-tipping, or dumping waste; how much WEEE is contained in fly-tipped waste is unknown. This presents further opportunities for the research team to expand on the developed model. Based on WEEE generated in 2016 amounting to 93,000 tonnes [12], and a collection rate of 51% in 2017 [14], it can be loosely assumed that WEEE not arising due to only a portion of the above additional labour inputs could expand this estimate to more than 50 jobs. There is also significant potential for further development of this model in the EU, where many countries generate significantly more WEEE than Ireland, and 65% of WEEE generated has been found to not enter the appropriate treatment schemes [12]. Assuming a hypothetical model where WEEE generation by category and WEEE treatment across Europe were similar to those in Ireland, the implications of this study show the potential for the creation of more than 3,000 European jobs were the assumed 33% [11] of WEEE recycled in non-compliant facilities diverted into compliant streams. For more accurate estimates of the EU job potential, further research should be conducted to establish country or system specific technical coefficients and, importantly, to collate information on the breakdown by category in WEEE not arising. Currently, the estimated employment potential resulting from this study is not insignificant in the context of the Irish WEEE recycling stream and should serve as further encourage an increase in efforts to establish enforcement of directing WEEE to the appropriate channels.

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Localities of e-waste flows – a comparative study of Leipzig and Wrocław

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Abstract

This paper discusses e-waste flows in two central European cities – Leipzig and Wrocław. Mixed methods were used to position the quantitative data on WEEE within their social and spatial contexts. Initial data analysis revealed that in the years 2014-2017 more WEEE was collected from household sources in Leipzig (4.5-6 kg per inhabitant) than in Wrocław (1.2-2.1 kg per inhabitant) due to the well-developed network of civic amenity sites. However, the yearly collection rate for Wrocław increased to over 12 kg per inhabitant by expanding the geographical scope of the analysis and including B2B sources. Available data indicates that household WEEE from Wrocław was mostly processed within the region. Interviews with local waste management professionals identified aspects of resident behavior that affect the collection rates and other channels – informal collection, improper disposal, second-hand stores, online platforms, scrapyards – which also shape flows of no-longer-necessary EEE in the cities.

1 Introduction

This paper investigates flows of e-waste on a municipal level. Despite all EU member states having WEEE regulations in place, most of the EEE sold on their territories does not enter the formal collection and recycling systems [1]. Compliance monitoring, as well as large research projects such as the Urban Mine Platform [2] or the Global E-waste Monitor [3] delivered valuable aggregated data on (W)EEE on the country level. Other studies approached e-waste flows from different spatial perspectives by looking at ports [4], [5], borders [6], and regions [7]. Yet, research on e-waste flows in municipal areas of the EU, contrary to those of the Global South [8], [9] has been scarce up to date.

The goal of this paper is to address this gap by comparing e-waste flows in two European cities using a mixed method approach. The analysis is based on publicly available data on WEEE flows, spatial analyses of municipal collection points, and semi-structured interviews with five representatives of local municipal waste management companies. Firstly, I will briefly describe the two studied cities, and compare (W)EEE mass flows in Poland and Germany. I will then present my analysis of the estimated collection rates of WEEE in both cities and discuss it in the context of formal channels, as well as availability and quality of data. Basing on the interviews I conducted, I will then discuss the factors that affect the quantities of collected WEEE, as well as informal channels in the studied cities. I conclude by discussing main findings and identifying areas for further research.

2 Cities

Two cities of similar surface and population have been chosen for a comparative study of local e-waste flows. Leipzig is the most populous city of the State of Saxony in Germany (601 668 inhabitants in Dec 2019). The city is an important industrial, commercial and academic hub in Eastern Germany. Two electronics suppliers (Leesys and SINUS) run their manufacturing there. There are 640 registered e-waste collection points in Leipzig (as of May 2020), most of which are assigned to distance service providers. Only 88 are physically located in the city, out of which 73 are primarily retailer-based and 15 are civic amenity sites (Wertstoffhöfe) operated by Stadtreinigung Leipzig (SRL). The city hosts four e-waste processing plants.

Wrocław is the capital of the Lower Silesian Voivodship in southwestern Poland (611 606 inhabitants in 2019). It is an important regional academic, commercial and industrial center. Four large EEE manufacturers (Electrolux, BSH, LG, Whirlpool) have factories in or close to the city. In 2017, they manufactured 8.6 million household appliances and employed 8 thousand people [10]. Wrocław municipality lists 130 e-waste take-back points in the city (mostly retailer-based). There are also 2 civic amenity sites (Punkt Selektywnej Zbiórki Odpadów Komunalnych - PSZOK) operated by Ekosystem – a waste management company owned by the municipality. Additionally, 33 companies with different profiles (waste management, scrapyard, repair, document destruction) are listed in the governmental database as authorized e-waste collectors [17].

The city hosts six e-waste processing plants with three more located in its proximity.

3 Formal flows

3.1 Country comparison

Figure 1 illustrates the development of EEE put on market (PoM) and WEEE collected in Germany and Poland. Between 2010 and 2017, both countries reported a similar increase in the yearly amount of EEE PoM (20% in Germany and 25% in Poland). Different tendencies are reflected in the amount of WEEE collected. Whereas in Germany it stagnated at around 10 kg per inhabitant, in Poland the reported amounts of collected WEEE doubled from 2.9 kg per inhabitant in 2010 to 6.4 kg per inhabitant. Those numbers resulted in exactly same collection rate of 45% that both countries reported to the European Commission for 2017.

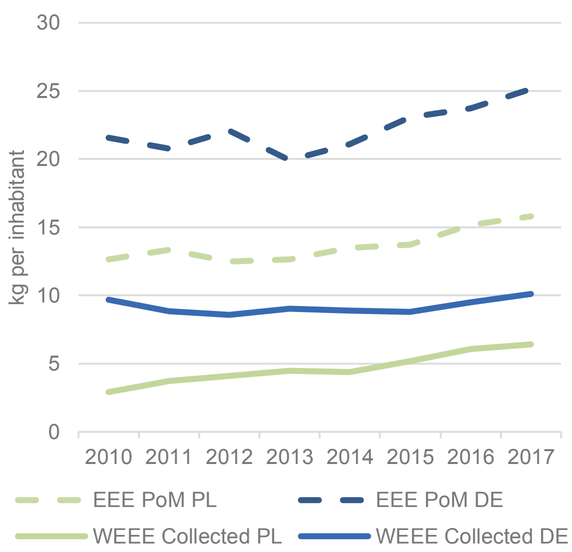

Figure 1: Developments in EEE PoM and WEEE collected in Germany and Poland per inhabitant in years 2010-2017

3.2 Data Sources

The data on EEE PoM and collected WEEE for Poland and Germany were obtained from the official reports of the monitoring state institutions [11], [12]. The data on WEEE collected in the cities were obtained from reports available online [13], [14]. Moreover, additional data on the amounts of WEEE collected and processed in the Lower Silesian Voivodship were obtained from the Voivodship Office [15], [16], to which all actors dealing with WEEE within its area must report. It was not possible to receive city-specific data from stiftung ear, the clearing house for e-waste flows in Germany. Therefore, to supplement the analysis of WEEE collection in Leipzig, I assumed an even population-based distribution of retailer, as well as B2B collection of WEEE in Germany and extrapolated the national data on these collection channels for the years 2015-2017 [11] to Leipzig in accordance with the population dynamics.

3.3 WEEE collection in Leipzig and Wrocław

Figures 2 and 3, as well as Table 1 present the evolution of WEEE collection in both cities. They demonstrate significant differences in terms of reported collection of e-waste in both cities with regard to the collection channel. In Leipzig, the amounts collected at the civic amenity sites oscillated between 4-5 kg per inhabitant in the years 2014-2017. This number increases to 6 kg of WEEE per household in 2017 when adding the estimated collection by retailers. The estimated B2B collection adds another 0.3-0.4 kg each year.

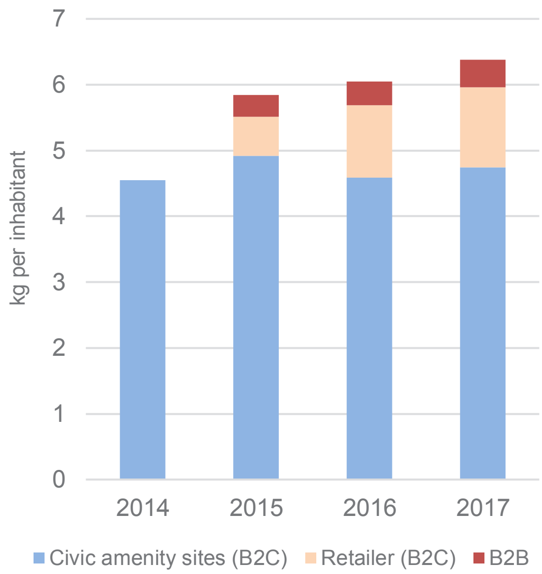

Figure 2: Development of estimated WEEE collection in Leipzig per inhabitant in years 2014-2017 with regard to collection channels

In 2015, the volume of e-waste collected per capita at the civic amenity sites in Wrocław amounted only to 0.12 kg per inhabitant. That amount doubled within 2 years, but even then, it was over 15 times lower than in Leipzig.

	2015	2016	2017
Civic amenity sites	0.12	0.19	0.24
Processing plants	0.7	0.41	1.47

Table 1: Evolution of household WEEE collection in Wrocław regarding two formal take-back channels in years 2015-2017 (in kilograms per inhabitant)

Own collection by e-waste processing plant operators has been a more important WEEE take-back channel in Wrocław. According to [14], it amounted to 0.7 kg per inhabitant in 2015, 0.4 kg per inhabitant in 2016 and 1.5 kg per inhabitant in 2017. Two local companies were the most active in e-waste collection. TKM recycling collected in total 613 t (1 kg per inhabitant) in 2017, while Wastes Service Group reported 276 t (0.4 kg per inhabitant) the same year. Thus, each company collected more on their own than what residents brought to the civic amenity sites. Basing solely on data reported by the Wrocław President [14], the collection from households in the city amounted to 0.8 kg per inhabitant in 2015, 0.6 kg per inhabitant in 2016 and 1.7 kg per inhabitant in 2017, which are much lower values than in Leipzig.

Interestingly, the data from the Voivodship Office [15] demonstrate a very different picture. There, apart from civic amenity sites and processing plants/PROs, reports from other actors authorized to collect e-waste are included. The data are based on waste codes from the European List of Waste. Thus, it is possible to distinguish between e-waste collected from household (waste codes 20 01 21*, -23*, -35*, 36 presented as B2C in Fig. 3 and 4) and non-household sources (waste codes starting with 16 02 presented as B2B in Fig. 3 and 4).

According to these data, 4.9 kg of WEEE per inhabitant were collected in the city in 2014, 4.7 kg per inhabitant in 2015, 4.3 kg per inhabitant in 2016. These values are

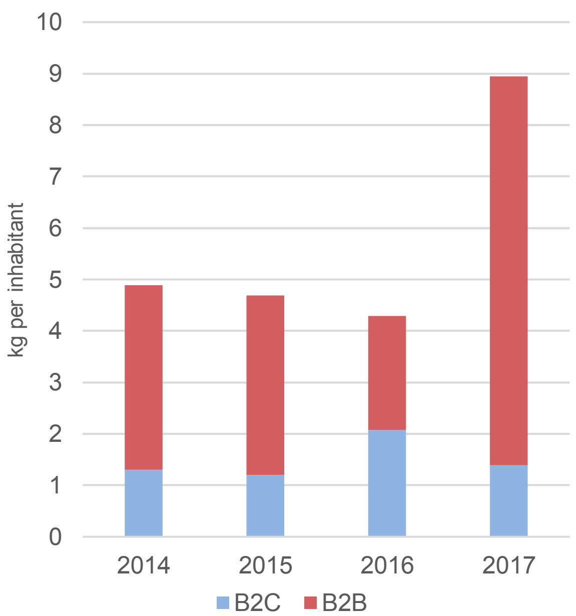

Figure 3: Development of WEEE collection per inhabitant in Wrocław in years 2014-2017 with regard to the source of collection

slightly lower than the ones reported in Leipzig. The amount of collected WEEE in Wrocław, however, peaks in 2017 at 8.9 kg per inhabitant (compared to 6.4kg per inhabitant in Leipzig). This is connected to a striking tendency in Wrocław – each year higher amounts of reported WEEE collection were assigned with waste codes starting with 16 02 used for non-household sources than with those used for household sources. In the years 2014 and 2015 that ratio was approximately 3:1, in 2017 it increased to 5:1 (or 84%). These proportions are opposite to what was reported on the national level. WEEE collected from sources other than households that year amounted only to 7.8% of the total WEEE collected in Poland [12].

According to one of the interviewed recyclers, this is connected to large EEE producers leading their operations in Wrocław and the area. Apart from the manufacturing, Whirlpool and BSH run their factory service in the city. Therefore, much of the waste codes 1602 assigned to Wrocław are appliances or parts originating either from factory service or customer returns and collected from those companies. Moreover, the surge of e-waste collected in Wrocław in 2017 coincides with BSH opening two factories of EEE in the city that year.

High collection of e-waste through B2B channels in Wrocław contrasts with low reported collection of WEEE from household sources, surpassing 2 kg per inhabitant only in 2016. In the remaining years it oscillated between 1.2-1.4 kg per inhabitant, which is almost four times less than the amount collected at the civic amenity sites in Leipzig. However, the actual formal collection from households in Wrocław is very likely to be higher, which is connected to the data limitations explained below.

The comparison between the two data sources [14], [15] reveals an inconsistency regarding household waste collection in 2017 in Wrocław. More household e-waste was reported to be collected that year through civic amenity sites and own take-back of processing plant operators than from all the collecting actors altogether. This points out to the main limitation of the data, which is related to the area to which the number refers. The spatial classification of the amounts does not relate to where e-waste was collected, but to where the actor collecting e-waste is registered to conduct business activities. In this sense, some large waste management companies (such as Remondis and Stena), as well as processing plant operators that organize own collection in Wrocław (e.g. Wastes Service Group) are registered outside of the city [17]. The volumes collected by them in Wrocław are therefore assigned to the Wrocław county (powiat) in the official data. The next section discusses these entanglements in the context of WEEE flows.

3.4 WEEE Flows

Once collected, EEE becomes WEEE, and in Poland and Germany must be given to authorized actors for treatment, further processing or preparation for reuse. However, in both countries this is organized differently which results in different levels of transparency over where which actors handle (different types of) e-waste in which way.

In Germany, obligations to pick up containers from the civic amenity site operators for treatment, processing, recycling, or preparation for reuse are redistributed to producers by a clearing house. The information on destinations of the containers is not publicly available. Therefore, it was not possible to assess what happens with most of the WEEE collected in Leipzig. However, municipality operating civic amenity sites may opt out from the obligation to hand over (some categories of) WEEE it collected to the producers. According to a representative of the municipal waste management company, in 2019 the SRL opted out large household appliances (category 4 in the clearing house system) for self-management and sold it to a processing plant in Leipzig operated by a recycling company.

In Poland, actors collecting and/or processing e-waste must report the volumes and types of e-waste to the voivodship marshal. These data contain solely aggregated amounts of collected or processed WEEE within a certain administrative area reported under different waste codes. Establishing direct links between collected and processed WEEE is thus not possible basing only on the data. Nevertheless, taking the registered places of various actors in e-waste flows into account, the data analysis can reveal interesting geographical patterns.

For that purpose, I compared WEEE collection and processing data on the municipal, local (Wrocław and Wrocław county), and regional (Lower Silesian Voivodship) level [15], [16]. Taking data on WEEE collection and processing assigned to the city of Wrocław into account, in the years 2014-2017 only 1931 t of WEEE were reported to be processed there, compared to 14540 t of WEEE collected. This picture changes after adding data assigned to the Wrocław county (powiat), where 24 companies collecting WEEE as well as three e-waste processing plants are registered [17]. Additionally, LG Electronics runs household appliance manufacturing (washing machines, refrigerators) in that area.

Taking the larger area into account results in much higher collection levels. This is mostly due to 15170 t of WEEE reported as collected from household sources in Wrocław county (population 130-140 thousand) in the years 2014-2017 (compared to 3813 t collected in the city of 635-639 thousand inhabitants in the same period). The average reported WEEE collection in the area amounted to about 6 kg per inhabitant for both B2C and B2B sources, totaling 12.1 kg per inhabitant altogether (the sudden drop of household collection in 2017 is likely connected to the implementation of the Recast WEEE Directive in Poland that year). This is significantly higher than the previously assessed amount for Wrocław. It is also higher than the national average, which for the years concerned amounted to 5.1 kg per inhabitant from household sources and 5.5 kg per inhabitant totally.

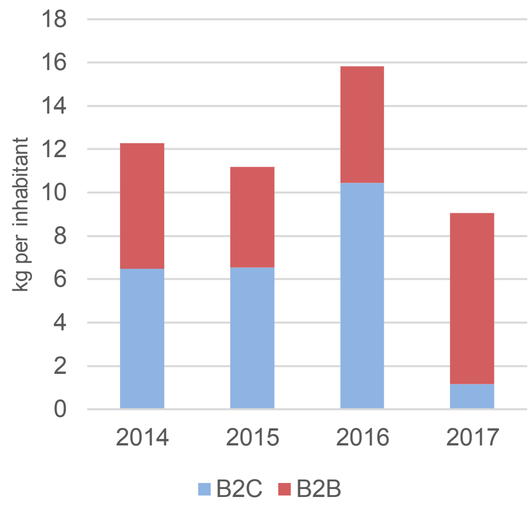

Figure 4: Development of WEEE collection with regard to the source of collection in the Wrocław area (city and county) in the years 2014-2017

In the years 2014-2017, 19174 t of WEEE were processed in the Wrocław area (yearly average of 6.2 kg per inhabitant). Interestingly, most of the processed e-waste originated from B2C sources (14571 t or 4.5 kg per inhabitant per year) with an equivalent of only 25% (4603 t or 1.7 kg per inhabitant per year) of total B2B WEEE collected in the area being processed there. In terms of B2C, the processed volume equaled 77% of WEEE collected from the household sources in the area in the same period. The data indicates that none of fluorescent lamps and other mercury containing WEEE (20 01 21*), as well as CFC-containing devices (20 01 23*) were processed in the Wrocław area nor in the Lower Silesian Voivodship. This is confirmed in Wrocław President reports [14], which mention destinations for these types of WEEE in the Greater Poland, Lesser Poland and Masovian Voivodships. On the voivodship level, only the equivalent of 47% of the B2B WEEE collected in Lower Silesia was processed there, whereas for the B2C WEEE that rate amounted to 55%.

3.5 Spatial analysis of the civic amenity sites distribution

The data demonstrated that civic amenity sites are much more important for WEEE collection in Leipzig than in Wrocław. Figures 5 and 6 illustrate the spatial distribution of the civic amenity sites. The primary difference is that Leipzig hosts 15 such places, whereas in Wrocław there are only 2 of them (as of May 2020). Additionally, the maps depict an area within 10- and 15-minutes' drive from the civic amenity sites. Assuming that 10 minutes is the maximal distance a resident is willing to drive one way to dispose of domestic e-waste [18], Leipzig offers very good e-waste disposal possibilities with only small parts of the city outside of that coverage. The situation is very different in Wrocław, where only residents from the center and a small area in the North-West of the city can reach municipal amenity sites within that time. This situation improves by adding 5 minutes to the assumed convenience. However, even then many densely populated areas of Southern and Eastern Wrocław remain outside of this range, whereas the civic amenity sites are reachable from practically any point of Leipzig.

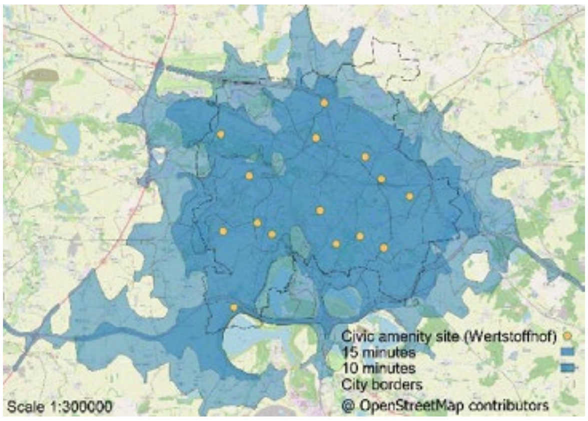

Figure 5: Map of areas reachable within 10- and 15-minutes drive from the civic amenity sites (Wertstoffhöfe) in Leipzig

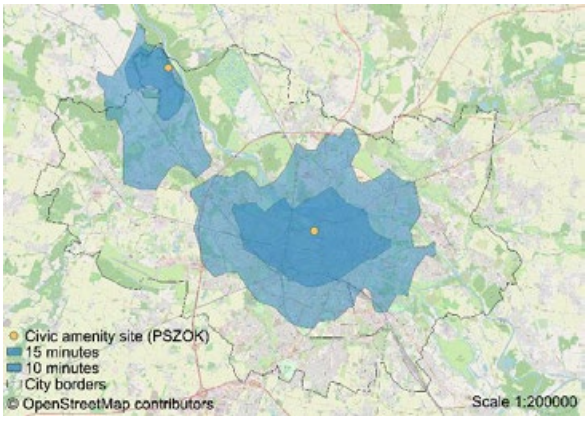

Figure 6: Map of areas reachable within 10- and 15-minutes drive from the civic amenity sites (PSZOK) in Wrocław

4 Resident behaviour and informal flows

A comparison of the amounts of WEEE collected per capita in Leipzig and Wrocław (Fig. 2-4) with the EEE PoM in Germany and Poland (Fig. 1) demonstrates that only a part of EEE found its way to the formal collection systems. The question arises as to what happens with the remaining amounts in both cities. The next section draws on the accounts of the local waste management professionals (the interviews were anonymized for data protection purposes). With many years of work experience in the local setting, they bring valuable insights into local characteristics of WEEE flows. Hence, several issues connected to residents' behavior, as well as to the actors that collect and process unwanted EEE outside of the formal system were identified.

4.1 Perspectives on resident behaviour

Reluctance of residents to throw away old but still functioning devices was mentioned as an important factor in low WEEE collection by the representatives of SRL. From the perspective of my interlocutors, that concerned especially older generation, as well as younger generation, which is becoming more environmentally aware. The result is similar – those groups of residents are assumed to prefer keeping an old appliance at home, giving it away or selling it than bringing it to the civic amenity sites.

Convenience and lack of awareness were mentioned by the representatives of municipal waste management company in Wrocław as main factors influencing the low collection rate there. In their eyes, people in Wrocław are often busy and strapped off time and prefer to have unnecessary stuff picked up from their homes, at best with some financial gratification. On the other hand, from the perspective of my interlocutors another important issue is that many people are still not aware of the options for EEE disposal, nor of the legal status of throwing EEE away.

This is connected to ignorance as another significant factor to which my interlocutors in both cities pointed out. According to them, most of the residents should be aware of how to dispose of their unwanted EEE. For example, at the beginning of 2019, the SRL sent an informative flyer about no possibility to dispose of small EEE with household waste to all households in Leipzig, but many people continued to throw away small electrical and electronic devices that way. In Wrocław, that practice, as well as leaving unwanted (often large) appliances by the household waste collection points in residential areas was also confirmed by my interlocutors. Even more striking example brought up in that context was a notorious practice of throwing away

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WEEE at wild trash heaps in uninhabited areas (also confirmed in e-mail exchange with the city office).

Different factors identified above can affect the way the residents choose to part with their EEE. For example, convenience (combined with a poor coverage of civic amenity sites) possibly plays a crucial role in much higher amounts of WEEE collected from households by processing plant operators than the volumes brought to the municipal amenity sites in Wrocław (as they offer free pickup of EEE from homes). In combination with reluctance to throw away still functioning devices, it might also play an important role in the informal channels.

4.2 Informal channels

In Leipzig, an SRL representative identified informal collectors of unwanted EEE as the main unofficial channel. They were said to operate mainly in front of civic amenity sites, where they target EEE brought by residents. My interlocutor claimed they use slogans about reuse, but in fact they pick up valuable items and throw the rest away. In this context, other studies addressing informal EEE collection in Eastern Germany demonstrated that big part of the appliances which are collected that way are exported (mostly to the East) [6, 19] or indeed scavenged for valuable parts and scrap metals [19].

In Wrocław, second-hand stores, online platforms as well as scrapyards were mentioned by the local waste management company representatives in the context of informal local flows of unwanted EEE. In the city, there are 3 large stores with second-hand EEE. Two of them offer a mix of locally sourced and imported products, whereas one specializes in UEEE imported from Germany. Among other means, these stores use online platforms in trading their products.

According to my estimates based on two exploratory one-week surveys of large household appliances (washing machines, dishwashers, ovens, refrigerators) offered on popular online second-hand platforms (ebay-kleinanzeigen.de in Leipzig and olx.pl in Wrocław), the yearly volume of these appliances can reach up to 1030 t in Leipzig, which corresponds to 1.7 kg per inhabitant or 37% of all WEEE collected at civic amenity sites in the city in 2017. In Wrocław, that volume was significantly higher due to the activity of second-hand shops on the platform, averaging at estimated 1700 t per year (2.6 kg per inhabitant) or 1100% of all WEEE collected at civic amenity sites in the city in 2017. Taking only the share of appliances offered by private users into account, the yearly estimate for Wrocław would reach 950t (1.5kg per inhabitant or 600% of all the WEEE collected at the civic amenity sites). The appliances offered on the online platforms were mostly traded as functioning, with only about 8.5% being described as defunct in Leipzig and 7% in Wrocław.

Finally, scrapyards were identified as a destination for the part of EEE. Historically, scrapyards played a crucial role in flows of large household appliances in Poland [20], and they are still reported to capture significant part of the WEEE flows [21]. The crucial difference to Germany is that in Poland scrapyards are allowed to collect (only complete) WEEE. In Wrocław, eight scrap dealing companies authorized to collect e-waste [17] run 11 scrapyards. Unfortunately, none of the companies I approached for an interview expressed interest in contributing to this research.

4.3 Education

Both municipal waste management companies claim dedication to educational efforts, particularly at schools. As one of my interviewees in Wrocław told me, engaging with children not only develops their environmental sensitivity, but is also an effective form of influencing their parents. Exemplary is here the educational activity of Ekosystem at one of the civic amenity sites they operate in Wrocław. The company organizes interactive workshops on waste, combined with a visit to the museum of old electronic and electrical equipment (picked up from the WEEE brought to the civic amenity site). E-waste is also an entry ticket to the museum. These workshops were visited by about 8000 children in 2018.

5 Discussion and conclusions

This paper demonstrated that the collection of WEEE is organized very differently in the studied cities. In Leipzig, it is mainly based on civic amenity sites, whereas in Wrocław much more actors are involved in the collection. This certainly has its roots in how the WEEE Directive was implemented in both countries but also depends on the available infrastructure. The spatial analysis (Fig. 5 and 6) illustrated that the lack of civic amenity sites in Wrocław makes the WEEE disposal inconvenient for most residents. Further research could address how distribution of civic amenity sites (or other channels of WEEE collection) influences the collection levels by comparing a larger number of cities.

Assessing the subsequent flows of WEEE has proven difficult in both cities. Much more information was publicly available (and obtainable from the monitoring institutions) in the case of Wrocław, giving the flows partial transparency. It was possible to determine that CFC-containing devices, as well as fluorescent lamps and mercury containing WEEE from Wrocław were treated/processed outside of Lower Silesia, whereas almost all the remaining WEEE was dealt with within the region. It was not possible to determine post-collection WEEE flows in Leipzig, due to the lack of transparency (stiftung ear's redistribution system is based on confidential trade data), with the exception of large household appliances (excluding temperature exchange equipment), which were opted-out and handed over to a processing plant in Leipzig in 2019.

The lack of harmonization in data reporting constituted another challenge. In Germany, data on WEEE is categorized into 6 groups (from 2018 harmonized with the WEEE Directive), in Poland both local and regional data were aggregated with regard to waste codes from the European List of Waste. Moreover, the data posed interpretative challenges due to the counterintuitive spatial references. In terms of data on WEEE collection in Lower Silesia, spatial classification was based on the area of company registration and not on where the take-back took place. Harmonization of data reporting with increased transparency could greatly improve the comparability and overview of the WEEE collection and flows in different administrative areas. That could also facilitate research on other connected issues such as treatment and processing standards or preparation for reuse practices.

The data indicated that the operations of EEE producers in Wrocław and its surroundings result in significantly higher collection of WEEE reported from non-household sources in that area. Although that phenomenon is largely linked to post-consumer WEEE originating from customer returns and factory service, it also directs attention to waste generation by EEE producers. In this context, further studies could expand on different types of waste generated from EEE production, which is rarely brought up in the context of WEEE. Moreover, research on localized hubs of EEE production could investigate links to circularity by asking where the materials come from, how much of them are sourced locally and regionally, and how much of them are secondary materials. This could improve the understanding of how circular economy is enacted in geographical space.

The presented data demonstrate that relatively low amounts of EEE from households found their way to the official take-back channels in both cities. In this context, exploring factors behind the consumer behavior with regard to the unwanted EEE, as well as informal channels through which those appliances change hands will be crucial for understanding of the low collection in various geographical contexts. The interviewed local practitioners representing waste management companies in Leipzig and Wrocław identified a number of behavior-related aspects such as reluctance to throw away functioning devices, convenience, lack of awareness, as well as ignorance that are linked to still relatively low formal collection of WEEE from households in both cities. They also identified other actors, such as informal collectors, second-hand stores, online exchange platforms and scrapyards that play an important role in what happens with redundant EEE in the cities.

In this context, further studies inquiring in how different consumer practices are related to formal and informal channels of U/WEEE flows in various geographical contexts are necessary. Still little is known about the role of informal collectors or online second-hand platforms in the context of what happens with EEE in European countries. Various methodological challenges are posed here, as those channels are not visible in official data and informal actors might be reluctant to participate. Another challenge is how to assess the role of digital spaces in relation to different fates of EEE. This paper explored potential methods of inquiry into online platforms used to part with the EEE that people no longer need. The yearly volumes of large household appliances offered on just one of the popular second-hand websites could reach up to 1030 t (1.7 kg per inhabitant) in Leipzig and 1700 t (2.6 kg per inhabitant) in Wrocław. These numbers are only rough estimates based on an exploratory survey, but they indicate the importance of online platforms in the way residents deal with no longer needed EEE. Further investigation of the volumes offered on, as well as actors (private, informal collectors, second-hand stores) operating on this type of platforms could bring important insights into the fates of 'missing' W/EEE in different places.

6 Acknowledgments

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Quantifying used EEE exported from Ireland in roll-on-roll-off vehicles

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Abstract

This study has developed/utilized a method to quantify amounts of UEEE leaving Ireland in roll-on-roll-off vehicles through the sampling of 279 vehicles and documentation prior to vehicles being loaded onto transport ships. The value of UEEE in Nigeria for each shipment has also been estimated based on Nigerian second-hand websites. Each unit of UEEE was assigned a weight based on the weight of that category of EEE in the UNU codes. The study estimates an average of 17,319 kg of UEEE annually shipped from Ireland in roll on roll off vehicles, valued on the Nigerian market at approximately €147,225. Sampled vehicles showed that 20% of vehicles contained UEEE, suggesting a significant reduction in UEEE being exported from Ireland in roll-on-roll-off vehicles.

1 Introduction

Increased demand, high obsolescence rates, innovation, and shorter product lifespans contribute to the growth of discarded electrical and electronic equipment (EEE). Popularly referred to as the fastest growing solid waste stream, around 50 million metric tonnes (t) of waste EEE (WEEE) is generated globally at an estimated 6 kg per person and this is projected to rise to up to 111 million tonnes per annum in 2050 [1]. In particular, the transboundary flows of used electrical and electronic equipment (UEEE) and WEEE are a focal subject of growing research in relation to a number of concerns [2]. For example, the export of WEEE from developed countries to developing countries [3; 4] affects rates of collection in the origin countries. For instance, only 22% of generated wastes in the USA is collected where European countries collect up to 35%, and 16% was exported, largely in undocumented exports [1; 5].

Recent research has indicated that the US, China, and 6 countries in the EU (Germany, the UK, Belgium, Netherlands, Spain, and Ireland) are responsible for the import of the largest amount of used electronics to Nigeria [6]. Subsequently, this research ranked Ireland as the 8th highest exporter of used electronics with over 98% via roll-on roll-off (RoRo) shipments [7]. The term 'RoRo' shipments, used throughout the remainder of this paper, refers to cargo shipments where individual, whole vehicles and their contents are driven on and off the cargo vessels, unlike container shipments where items are loaded into a container then transferred onto the vessel. Ireland, with a share of 3.77% of annual imports to Nigeria, was highlighted to contribute 3,660t in RoRo vehicles and 40t in container imports of UEEE [7]. During the period of assessment, 105 of 170 imported vehicles were observed to contain UEEE. Items imported consisted mostly of screens, large equipment and small appliances where 60% was referred to as clean and suitable for direct reuse, but 40% improperly packaged and dirty [7]. For Ireland, this has the potential to affect WEEE collection rates and potentially impacts ability to reach collection targets. Furthermore, with the present focus on advancing a circular economy, the transboundary shipment of WEEE may lead to a loss of materials recoverable by advanced recycling end processing, which the destination countries may lack.

This research seeks to evaluate the quantities of used electronics exported from Ireland, particularly the volume and type of UEEE contained in RoRo vehicle shipments. It will also examine the financial factors that drive this trend. A presentation of quantitative data provides a deeper understanding of the transboundary shipment of WEEE from Ireland to other countries, especially countries in the global south. This is important as well-collated data reduces the generation of e-waste, prevents illegal shipments, promotes recycling, creates green jobs, and curbs global emissions [5].

2 Background

2.1 Export of UEEE to West Africa

Substantial price differences do not deter consumers in developed countries from going for new electronics whereas the opposite is the case in developing countries [8]. Due to such disparities in economic situations, discarded electronics often find high reuse value when shipped to developing regions. This equipment often holds economic and/or use potential for other individuals or communities, especially those in developing countries. The reuse market improves access to information and communication technology (ICT) via the availability of lower priced equipment [8]. The demand for used electrical and electronic appliances in developing countries such as Nigeria is on the rise.

While the local generation of e-waste in developing countries is rising, imports contribute a large amount to the numbers. West Africa serves as a major trading route of used electronics [9] for equipment shipped in containers and RoRo vehicles to Lagos, Tema and Benin [10; 11] Over time there have been attempts at quantifying the amount of U/WEEE imported into West Africa, especially Nigeria and Ghana. *The Digital Dump* report by Basel Action Network (2005) [12] estimates that around 400,000 used computer scraps are imported into Nigeria monthly in containers and the growth of obsolete PCs in developing countries is estimated to increase to 400-700 million units compared to 200-300 million units in developed countries [13].

Findings from *the Basel Convention E-waste Africa Programme* equally show that about 150,000 tonnes of UEEE is imported into Ghana annually [9]. Of that amount, 15% were repaired and resold while the other 15% was irreparable [9]. In Nigeria, of the 100,000 tonnes UEEE imported into the country illegally in 2010, 30% was non-functional [14]. Such imports have led to a flourishing industry of informal recycling in West Africa [10]. In addition to imports, the growing demand of new ICT in developing countries contribute to the increasing numbers of locally generated WEEE and with the correlation between growth of gross domestic products (GDPs) and generated WEEE, the numbers will see up to a threefold increase by 2050 [1].

Illegal and unlicensed exports of UEEE to developing countries with ineffective recycling results in the loss of valuable metals like palladium, gold, silver, indium, and germanium [9]. However, the trade of imported UEEE in good condition has the potential to provide significant socio-economic value. Still, the major challenge remains to be the import of e-waste and near end-of-life equipment [10]. The opportunities in the processing and trade of used electronics such as computers offers a high degree of reuse, employment and in the long run provides socio-economic benefits due to factors such as increased accessibility to technology of low-income earners [15].

2.2 Regulations on transboundary shipment of WEEE and enforcement of WEEE regulations in Ireland

The principal regulations that prohibit the transboundary movements of waste with hazardous components, particularly from countries in Europe, are as follows:

- the Basel Convention,
- the Organisation for Economic Cooperation and Development (OECD) council decision (2001) 107/FINAL,
- and the European Waste Shipment Regulation [16].

In Ireland, Statutory Instrument (S.I.) No. 149 (2014) ratified the European WEEE regulatory instrument, the WEEE Directive, into national law. The Environmental Protection Agency Office of Environmental Sustainability is responsible for the regulation of WEEE in Ireland [17]. In 2017, Ireland surpassed the 45% target for the collection of WEEE by collecting 51% of EEE placed on the market (Environmental Protection Agency 2019[1]). However, new targets set from 2019 require an increase from 45% of EEE placed on the market to 65% of equipment sold. Such ambitious targets present a challenge for Ireland and other EU member states.

The National TransFrontier Shipment Office (NTFSO) of the Dublin City Council, established in July 2007, is the national authority on the regulation of exports, imports, and transit of waste shipments in Ireland [17]. Formerly, enforcement and regulation of exports was conducted by local authorities, resulting in a fragmented approach to requirements and reporting. The consolidation of authority in the TransFrontier Shipment Office allowed for consistency in the regulation and enforcement of WEEE transit, along with other wastes. WEEE is considered one of its priority wastes, and its core objectives include the enforcement of the regulations stipulated under S.I. No. 149 [17]. The Waste Regulation and Enforcement unit of the NTFSO is charged with the management of waste shipments including e-waste. To ensure that UEEE shipped in RoRo vehicles from Ireland are for direct reuse, a series of procedures and inspections in line with global, regional and national regulations are carried out by waste enforcement officers from NTFSO. Pre-shipment checklists as outlined in the guidance document [18] include:

- appropriate packaging to protect UEEE from damage during transport,
- roRo vehicles should be accessible and unsealed to allow visual inspection by Waste Enforcement Officers,

[1] https://www.epa.ie/nationalwastestatistics/weee/

- and UEEE should have reuse market value stated.

Moreover, documents to be mandatorily attached for inspection include:

- proof of ownership such as receipts,
- evidence of functionality like electrical certificate,
- a detailed packing list with essential details such as UEEE type, value, quantity and serial number,
- and other relevant transport documents such as a 'bill of landing.'

Waste Enforcement Officers regularly visit the port of export, Ringaskiddy port in Cork, to inspect RoRo vehicles. Vehicles are selected for inspection at random and the contents of selected vehicles are inspected before being cleared for shipment.

One of the issues surrounding transboundary shipment from developed countries is the lack of functionality tests at the countries of origin [6]. To ascertain functionality of the equipment billed for shipment in Ireland, electrical certificates are required. These are duly completed and signed/stamped by an electrician or technician after testing is conducted. This is a mandatory procedure as without the attachment of this certificate, vehicles containing UEEE are placed on hold by waste enforcement officers and cannot leave the port. Additionally, the NTFSO operates a system whereby the electrical certificates obtained must be from the accredited list of personnel approved to undertake such testing prior to the shipment of UEEE. The electrical certificates are only issued when the UEEE is proven to be shipped with an intent of reuse hence UEEE primarily shipped for recycling or major refurbishment works is controlled.

Also, upon inspection, it is observed that equipment is in good condition and that measures were taken to prevent damage of equipment in transit. Electronics, such as televisions, were required to be properly placed and secured to avoid damage.

In addition to inspection of UEEE carried within the RoRo vehicles, the vehicles themselves are inspected. Vehicle documentation is checked certifying ownership and road worthiness, as well as the functionality and that required safety measures, such as removal of oil from engines, of any car parts shipped within the vehicles as cargo. Vehicles with verifiable, complete, and accurate documentation are cleared for shipment. Vehicles lacking one or more of these requirements are placed on hold and will not be shipped until such time that the discrepancies are addressed.

3 Methodology

The research team accompanied waste enforcement officers for monthly, on-site inspections of roll-on roll-off vehicles in the export compound of the Ringaskiddy port in Cork. Although this is not the only port in Ireland, this port is reported by inspectors to be the only major route for the export of RoRo vehicles out of Ireland, with largely insignificant flows of RoRo vehicles leaving other ports in the Republic of Ireland. The export compound for RoRo vehicles serves as the receiving location for owners to drop off vehicles to be shipped, secure storage of vehicles awaiting shipment, and the location of compliance inspections prior to shipment . While the in-depth compliance inspections are carried out on only a random selection of vehicles, the research team was able to conduct visual inspections of each vehicle contained within the yard on the given sampling day and its accompanying list of packed contents.

Suggested by the 'person in the port' research by Odeyingbo *et al.* (2017) [7], RoRo vehicle shipments from Ireland serve as the principal route for the movement of used and waste EEE, finding that 98% of the UEEE exported from Ireland was found in RoRo vehicles. Based on this research as well as interviews with waste enforcement and port officials RoRo vehicles were chosen as the focus of observational inspections.

The research scope covers all categories of EEE listed within Annex IV of the recast WEEE Directive. Often, studies on the flows of WEEE focus mostly on the streams of televisions, monitors, and computers due to the presence of valuable metals and ease of refurbishment and reuse [19]. For this reason, this research is unique as it not only focuses on electronics and IT equipment such as laptops, desktops, mobile phones, and televisions but also encompasses all categories of WEEE.

3.1 Data sources and collection

Enforcement documents, namely the packing list documenting the vehicle's contents, and included a visual inspection of the vehicle to confirm that the documents reasonably represented the content. Vehicles whose packing lists were found by waste enforcement officers to not be accurately representative of the contents of the vehicle during compliance inspections, or vehicles containing equipment but lacking a packing list, were stopped by inspectors until cleared with the appropriate paperwork. These vehicles were marked noncompliant in the data collection as they were on hold and not being shipped at the time of data collection. Duly completed documents were evaluated and photographed. Information recorded on packing lists includes item names with a description and the make, quantity, and declared value of the item. Additional paperwork included information such as destination, and in the case of UEEE, proof of functionality. These additional documents were noted as present but were not analysed in-depth.

Vehicles contain a variety of items such as clothes, furniture, vehicle parts, used tyres, and UEEE. While all contents were recorded, only data relating to UEEE was analysed in line with the aim and objectives of this research. Each vehicle was given a unique identifier upon sampling in order to prevent duplicates in the data. Unique identifiers and the collected data associated with each were then collated and analysed to ascertain quantities of vehicles which contain or do not contain UEEE, profiles of which vehicle types are likely to contain or not contain UEEE, and the types and quantities of UEEE present in shipments.

In conjunction with the methods quantifying the UEEE exported from Ireland in RoRo vehicles, the value of the exported electronics was researched in the Nigerian reuse market. An in-depth evaluation of the monetary value of the UEEE found in the vehicles was undertaken. The values of the equipment when resold in Nigeria was obtained using personal communication and from Nigerian websites with listings of used electronics such as Jiji.com and OnlineAlaba.com. Lower and higher end values were obtained, and the averages were computed and recorded.

Data on the number of vehicles shipped the previous year was obtained and analysed in order to determine the appropriate sample size necessary to statistically represent the shipped vehicles. To convert the units of UEEE recorded to weights, the indicated average weight of the EEE by UNU-Keys category was used. The UNU Keys for EEE allow for a consistent and publicly accessible method of weight estimation, which can be replicated by future studies regardless of where those studies are based. Based on the likely life span of UEEE prior to shipment, the weights of EEE placed on the market in 2016 were used for the analysis in this study.

4 Results and discussion

The following section presents the results found over period of study, beginning June 2019 and ending March 2020. Overall, a total of 279 vehicles were sampled, which represents about 35% of the number of vehicles shipped annually. When broken down into vehicle types, the sample represents 28% of cars and vans, and 44% of trucks. The statistical significance of the sample size was based on historical data collected from the shipping company.

4.1 Quantities of UEEE

The results of data collection on the 279 sampled vehicles is laid out in Table 4.1.

Table 4.1. Sampling data by type of vehicle and weight of UEEE per vehicle.

Vehicles Sampled	279
Vehicles Containing EEE	52
Weight of EEE Sampled (kg)	5542
Average Weight of UEEE per vehicle (kg)	17
Average Weight of UEEE per vehicle containing EEE (kg)	106

Cars and vans represented 63% of RoRo vehicles, while trucks represented the other 37%. Upon inspection of these vehicles, 16.88% were found to contain some form of UEEE whereas the remainder had none, either containing other used equipment such as clothing, furniture, or car parts, or were shipped empty. Despite trucks representing roughly 1/3 of the sample size, cars and vans were more than 5 times more likely to contain UEEE, with 90% of vehicles that contained UEEE being cars or vans. Cars and vans also contained approximately 87% of the documented UEEE by weight.

Notably, this data suggests that of the total number of RoRo vehicles exported out of Ireland, 1 in 5 vehicles (cars, vans, and trucks) contained used electronics, with each vehicle that contained UEEE carrying approximately 106 kg. The total weight of UEEE recorded in the study was found to be 5,542 kg, from approximately 300 units of UEEE. Calculated using the size of annual shipments found in the historical data, this expands the estimate to 17,319 kg shipped from Ireland per year in RoRo vehicles.

4.2 Value of used electronics

As discussed in previous sections, the demand for used electronics in Nigeria is a growing development. The availability of used electronics affords people of lower economic means and disadvantaged backgrounds to improve their standards of living. For example, some of the EEE observed include essential modern conveniences, such as fridges to elongate the lifespan of foods, considering the humid weather akin to tropical regions like Nigeria, and IT equipment allowing for internet access. By having a cheaper option, people can more readily afford electronics to improve their social status and quality of life. Additionally, with factors such as job creation, income from preparation of reuse as highlighted in the literature review, these products improve the standard of living of affected individuals in developing countries. Information gathered indicate that the products in this research shown to be frequently exported had a strong correlation with the demand and ready market for it in Nigeria such as the market for used TVs and washing machines. Refrigerators, televisions, freezers, washing machines, and cookers dominate UEEE exported from Ireland to Nigeria. On this basis, these items were selected and the associated values on the Nigerian resale market were determined. This is illustrated in Table 4.2.

Table 4.2. Price range of select used electronics based on perceived demand in Nigeria.

Note: 402 NGN = 1 Euro

UEEE Type	**Average value as declared on shipment (€)**	**Used Market Price Nigeria (€)**
Television	112 - 131	242 - 372
Washing Machine	124 - 326	199 - 273
Fridge	50 - 76	118 - 186
Freezer	87 – 184	100 – 112
Cooker	112 - 165	131 - 149

Prices differ with manufacturer, model, size, and second-hand value. A comparison of the obtainable value in Ireland and in Nigeria show that these used electronics hold promises such as profit from sales.

5 Conclusion

This study presents the first comprehensive estimation of UEEE shipments exported from Ireland in roll-on-roll-off vehicles conducted at the port of exit. The data presents a unique expansion of insight into the shipment channel from Ireland to West Africa, and suggests a stark change in export behaviour in the years between the Person in the Port report and the period of study ending in March 2020. As previously mentioned, 60% of RoRo vehicles exported from Ireland and entering the port in Lagos were found to contain UEEE. This study found that 20% of RoRo vehicles sampled at the port of exit contained some form of UEEE, equating to an estimate of 15,833 kg of UEEE exported in RoRo vehicles for 2018/19. This change in behaviour is speculated to source from several key factors over the past several years. Regulatory enforcement of UEEE shipment has increased, with waste enforcement officials reporting a stricter environment surrounding inspections of vehicles and a subsequent decrease in the amount of UEEE declared and found. Directly related to the increase in regulatory enforcement is safety concerns regarding the shipment of UEEE and WEEE, escalated by incidents of fires and the sinking of a cargo ship transporting exported goods.

However, further results illustrate that the potential value of UEEE on the resale market in Nigeria continues to drive demand for import. The potential resale value of UEEE directly sampled was estimated to amount to €47,112, which equates to €147,225 of UEEE in annual shipments. Despite the costs of certifying functionality with electrical certificates, this economic value in Nigeria, where used goods are in higher demand than in Ireland, is a significant driver of export. This is particularly true in that there is no additional fee for shipment of goods inside of a vehicle, only a fee for the vehicle itself. An opportunity for further research exists in an examination of the process, cost, and verification of electrical certificates. Additionally, surveys of the perspective and behaviour of the exporters and owners of the RoRo vehicles would also provide valuable insight in future studies.

The methods developed and employed in this study allow for future estimation of UEEE exports in Ireland based on number of vehicles and vehicle types in a particular shipment or over a period of time. Additionally, the straightforward methods are expandable across EU and global shipments to provide better understandings of UEEE flows. This is of significant value to all stakeholders concerned with the regulation, enforcement, and safety of UEEE shipment. Notably, the results of this study and further studies using these methods also contribute valuable statistics for the calculation of WEEE collection targets, which may adjust based on high or low quantities of EEE exported and therefore no longer available for collection.

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E[co]work: A social enterprise solution to catalyse the informal e-waste recycling sector

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Abstract

E[co]work is a novel concept based on the co-working concept of shared infrastructure that addresses the issue of integrating the informal sector into formal take-back and recycling systems currently being implemented in the global south. Envisioned as a self-sustaining business model, the E[co]work facility is a compliant e-waste facility that rents its infrastructure to informal micro-entrepreneurs, giving them access to a formal workspace with proper equipment and tools, without requiring extensive capital investment upfront. We are employing a participatory design process to refine this concept and adapt in to the local needs in Delhi, India. This process has been valuable to show that the E[co]work concept has merit, as there is an extensive overlap between the micro-entrepreneurs needs and legal requirements. The same process has also crystallized key challenges that need to be addressed for the adoption of the E[co]work concept within the community.

1 Introduction

Due to the pervasive digitalisation and growth of the global economy, electronic waste or e-waste is one of the fastest growing waste streams in the world [1, 2]. Its functional requirements means that e-waste contains both valuable material and hazardous substances.

Many economies in the global north have established somewhat successful take-back and recycling systems, which ensure the appropriate disposal of hazardous substances and the recovery of raw materials [3, 4, 5]. These approaches are often based on the extended producer responsibility principle (EPR), which extends the legal responsibility of a producer to the e-waste occurring due to its economic activity [6]. Any systems require a strong rule of law to function appropriately. Some actors may want to externalize the costs of disposing hazardous substances against the common interest. This creates a critical need for effective control mechanisms [7]. Wherever such mechanisms are difficult to implement (e.g. in the case of transboundary movement), there will be actors looking to stretch or circumvent the legal framework [8].

The global south, where most of the growth of e-waste occurs, has often struggled to implement take-back systems following the examples of the global north [9]. A weaker rule-of-law, weaker control mechanisms, existential poverty and different social and economic realities render the issue more complex, introducing new actors and interests. One key feature of economies in the global south is the presence of a strong informal sector in the whole economy, especially in the waste sector.

The informal sector consists of micro-entrepreneurs (small businesses and self-employed persons) that have little or no legal recognition [10]. It provides livelihoods and social security, where few or no alternatives exist and is a core element of many communities. The presence of an informal sector circumvents governmental authority and thus threatens official power structures, often leading to conflicted, distrustful and at best indifferent relationships between governmental bodies and the informal sector. As a result, official bodies often implicitly expect or demand that micro-entrepreneurs formalise, while the conditions to formalise are at least unfavourable or – given the requirements – almost impossible.

In India, informal micro-entrepreneurs handle 95% of the e-waste [1, 2]. They often use dangerous and polluting processes while providing a livelihood to many urban poor in large cities. Recently introduced and enforced EPR mechanisms have led to the formation of producer responsibility organisations (PROs). PROs need to reach collection targets, thereby diverting the e-waste away from micro-entrepreneurs and ensuring environmentally friendly recycling [11]. Micro-entrepreneurs, except aggregators, have little opportunity to benefit from these new requirements and may eventually be out the work they have been doing for decades with few alternatives available. The requirements for formalisation are high, and are typical for other countries in the global south:

1. The process of formalisation, establishing a facility and obtaining the permits required can take more than a year, incurring high expenses with limited income opportunities.
2. A registered dismantling needs to have a minimal size of 300 m2 [12]. Most micro-entrepreneurs work in spaces smaller than 40 m2 and do not possess the capital required to grow their business to this size.
3. Cooperatives, a mechanism that has historically been very successful for improving whole industries such as the dairy products in India [13], have no place in the established legal framework [11].
4. Micro-entrepreneurs operate in clusters designated as housing zones. They wold need to move to commercial or industrial districts, losing the link to their existing network [14].
5. PROs need to obtain ownership of whole devices. Hence, a micro-entrepreneurial dismantler willing to follow safety requirements and sell his dismantled material to PROs are not able to do so [11].

Despite these barriers, the integration or at least beneficial relationships between micro-entrepreneurs and the wider economy is a widely accepted element of sustainable development [15, 16, 17]. It enables social mobility, safeguards livelihoods, and contributes to the vision of an equitable circular economy. More directly, it enables societies to benefit from the long-term experience, innovative drive and networks of micro-entrepreneurs by adopting them into formal structures.

Given the growing quantities of e-waste, multiple benefits of integrating micro-entrepreneurs, and existing barriers, new and innovative approaches are needed that can be a model for the future. Our work focuses on the E[co]work concept as a potential solution. This approach offers shared infrastructure in the form of a coworking spaces as a social enterprise. In this paper, we first introduce the concept and its theory of change. We then report how we shared and improved the concept through a participatory design process.

2 Concept and Methods

2.1 The E[co]work concept

Co-working, i.e. the use of shared infrastructure, has become increasingly trendy among tech workers and freelancers. The E[co]work concept adapts this idea to micro-entrepreneurs in the e-waste recycling sector. By providing a legal work environment, E[co]work obtains all required permits and thus a legal work environment without requiring micro-entrepreneurs to formalise themselves in advance. This allows them to familiarize with the legal conditions and requirements, grow within the space and gradually formalize if they see the benefits. Micro-entrepreneurs can rent part of the space and equipment for specific times.

This effectively pools the dismantled e-waste of several micro-entrepreneurs, making a shared dismantling unit with the space of 1000 m2 financially viable. The pooling also enables access to more efficient technologies that increases profits for dismantlers and justifies the utilization of the E[co]work facility. As E[co]work only provides space and services and does not necessarily buy or market the products of dismantlers, it fulfils a similar function to that of a cooperative. While E[co]work cannot replicate the existing informal networks in a new environment, the simultaneous utilisation of the facility by several micro-entrepreneurs will create a smaller community of particularly enterprising micro-entrepreneurs. PROs are provided access to dismantlers and may elect to obtain ownership of devices entering the E[co]work facility, trusting that the dismantling is performed within a licensed space.

E[co]work aims to work as a catalyst that does not directly interfere with the business of micro-entrepreneur and allows for a gradual growth. It is envisaged as an incubator and academy of training and experience, where graduates having learnt new techniques and business practices can go on to scale their businesses. It is a hub of resources through the community it creates and access to services it enables (banking, medical check-ups, insurance, and registration). It is a platform to interact with PROs, recyclers, and potential investors on an equal level.

Every E[co]work facility is, once established, expected to run as a self-sustaining social enterprise. A part of the surplus the beneficiaries generate through E[co]work and additional services cover its operational expenses. Supplementary revenue options (e.g. external funding, data collection) may temporarily represent an important source of income. Such income may help in growing the concepts reach e.g. by offering trial packages at reduced costs. However, E[co]work is a *product* that is designed for and marketed to micro-entrepreneurs. While this might make establishing the first E[co]work facility more challenging, it also improves the chance of its long-term success and viability.

Figure 1: Theory of Change for the first E[co]work facility in Delhi

An effective implementation of the concept needs to be informed by a deep understanding and relationship with its customer base and the right boundary conditions. Preparatory work to establish the first E[co]work facility as a proof-of-concept is underway in Delhi, India, where we can rely on long-term contacts with the informal micro-entrepreneurs. Also, recent legal developments put additional pressure on micro-entrepreneurs, rendering them more open for new approaches. This includes adapting the concept to the specific local context, including repeated verification and trust-building efforts with the targeted communities. The developed theory of change (Figure 1) lists the key assumptions and steps needed in this process.

Based on a functional proof-of-concept, the working business model and key learnings can be condensed into a template for replicating the E[co]work concept. In India alone, the market potential of replicating the model is substantial, considering the 1 million people involved in manual e-waste recycling operations [18]. Other countries in the global South may similarly benefit. The E[co]work Association was founded to provide long-term support for anybody looking to replicate the model.

2.2 Participatory design of an E[co]work facility

An E[co]work facility does not only provide services, but also a specific environment of trust and mutual acceptance. It needs to replicate some of the positive aspects of an informal e-waste recycling cluster, while providing better alternatives in other cases. Hence, collecting factual data, e.g. through data-driven questionnaires is insufficient. Instead, interactions need to focus on obtaining a deep understand of the people and the communities.

We employ a participatory and inclusive design process to design the facility. The process repeatedly engages with micro-entrepreneurs, from early until the final stages in the design and recognizes them as equal stakeholders. This ensures that not only the demand for such a facility in the market can be assessed, but also builds a relationship of trust, mutual understanding and establishes a client base.

As a first step, we identified local people who were interested in working with us as community representatives (CRs) and saw some potential and a need to change. The diversity of the community is well replicated in this group, as it consists of students looking to enter the business, young dismantlers, experienced traders and established businessmen.

Next, we organized and held a variety of interviews and discussions with our CRs in their homes or workshops (Figure 2). We could quickly understand which topics generated interest, as this would translate into the CRs inviting their friends, contacts and confidants into these discussions. The following topics were of particular interest for the design process:

- *Needs and aspirations:* What part of your work do you enjoy? What is the first thing you think of when you wake up in the morning? When are you happy? What is a recent success or achievement you are proud of? The workshop participants had

Figure 2: Impression of a workshop held in a dismantling shop

rarely considered such questions given their environment. The answers helped us to identify which key elements need to be preserved and what aspirations E[co]work can help to fulfill.

- *Networks and business:* What is your business? Where does the material you trade with come from? Who buys your material? Where does it do? Such questions were used to jointly fill in maps, understand the specific business models and gauge the level of trust we had obtained. The results of these discussions are not described in this paper, as the informal networks within India and Delhi have been described previously [14]
- *Personal challenges due to informality:* The sharing of how other countries handle e-waste recycling and how it is perceived internationally caused the participants revealing important insights how they experience being informal micro-entrepreneurs and strengthened their conviction that change to the better is possible.

Once we felt that there was sufficient interest for further interaction, we organised a design workshop (Figure 3): We rented an empty industrial space for a day that could be a potential location of the E[co]work facility. In the workshop, we encouraged the participants to reimagine their place of work. With tapes and chalk as tools, the 15 micro-entrepreneurs present at the workshop started visualizing their future of work in groups.

Due to COVID-19 restrictions, no further physical interactions were possible. Regular video conference calls with the community ensure that the engagement is continuous and that specific questions can still be discussed. For example, we could discuss and iterate on visualizations of E[co]work based on the inputs collected in the design workshop.

3 Results

3.1 Needs and Aspirations

Based on the discussions, we could identify the following key themes regarding the micro-entrepreneurs needs and aspirations:

- *Providing for family:* The participants stressed their clear commitment to provide for family. For example, they see the ability to generate enough income so that family members can attend school as one of their main achievements.
- *Friendships and networking over profits:* The participants also noted the importance of their established friendships and network for their well-being and economic success. They also felt that it might be challenging to leave behind their community in search for bigger profits.

3.2 Challenges of Informality

The micro-entrepreneurs were quick to point out some personal challenges that they experience regularly:

- *Source of stress:* The participants often mentioned the uncertainty of their situation, i.e. not knowing whether they can continue working even the following day. Also, as their work is illegal, they often had to resort to working at night, e.g. when

Figure 3: Impression of the design workshop

loading and unloading trucks, in order not to be caught. The irregular sleep schedule and noise generated has negative effects on them, the laborers as well as the community as a whole.

- *Lack of institutional support:* Intrigued how other countries have organized e-waste recycling and at the benefits of recycling, the participants voiced concern in the lack of support they received from institutions in order to improve their situation. Some who were in a semi-formal state, e.g. by operating a registered business but not having the right waste treatment permits, were especially disappointed. They pay taxes but did not see them utilized to their benefit.
- *Weak rule of law:* When discussing interactions with government representatives, the participants noted that they felt that loopholes and favoritism impeded both the professionalization of their industry and resulted in an uneven playing field that disadvantaged the existing actors in the e-waste recycling sector. In addition, they often felt treated as a source of money rather than people by officials.

3.3 Facility Design Workshop

A large share of their future workplace was allocated to the key revenue driving dismantling and storage areas. In addition, the micro-entrepreneurs also identified two features that could greatly impact their business:

- *Secure storage spaces:* In their current environment, the micro-entrepreneurs are often worried about the security of their material storage, i.e. through seizure. A new facility should have a CCTV installation and enable them to lock their materials securely.
- *Weighbridge:* The micro-entrepreneurs currently depend on third-party weighbridges to obtain the weigh in- and outgoing shipments of material. Given the restrictions they work in and the traffic situation, they would welcome an accurate recording of weights at the facility.

The workshop participants also identified the following auxiliary elements that they would hope to have:

- *Office space and meeting room:* In order to conduct business meetings and enable them to do their accounting, the micro-entrepreneurs would require an office space and meeting room.
- *Safety installations*: Being experienced with the dangers of e-waste dismantling, the participants identified safety elements as a key requisite for a workplace. Emergency exits and first aid kits were somethings that came up in the facility design workshop.

The participants also identified some quality-of-life elements of their future workspace:

- *Washrooms:* In the community, access to washrooms is often limited and is seen as a basic right that should be available.
- *Resting areas:* Resting areas for the micro-entrepreneurs and the laborers as well deemed as essential, possibly even with a small garden space:
- *No Air conditioning (AC):* Despite AC being very prevalent and coveted in Delhi due to the climate, the participants stressed that having AC was not a prerequisite for any workplace. Some identified AC as a luxury they would not feel comfortable with, given that their family would have to stay behind in areas without AC and sometime even limited connection to electric power.

The visualizations (Figure 4) of the workspace created based on the described expectations caused significant interest in future interactions

4 Discussions

4.1 Alignment of expectations

The expectations of the micro-entrepreneurs with regards to a E[co]work facility overlap extensively with the legal requirements such as weighing equipment and safety installations. Interestingly, COVID-19 has caused a shift in perception on aspects that had previously been topics where alignment was insufficient. The crisis has increased the awareness regarding hygiene. The idea of using personal protection equipment are more widely accepted now. As the lockdown associated with the crisis had excluded industrial areas, the micro-entrepreneurs have now also started to see direct business continuity benefits if they were to establish the business in industrial zones.

4.2 Utility of participatory design

In our experience, participatory design is highly useful when developing a concept such as E[co]work. Microentpreneurs need to see an overall benefit to using E[co]work despite the associated costs and additional requirements. This requires that E[co]work solves specific pain points the micro-entrepreneurs are faced with daily and does not introduce new ones.

Due to the micro-entrepreneurs belonging to disenfranchised communities, there is very little information, market research available that would allow for an appropriate targeting of the E[co]work product. Only through the continuous engagement and asking elementary questions on need and aspirations could we begin to relate and understand our future customers. In fact, our questions initially often caused some confusion. It is possible that nobody had asked the micro-entrepreneurs before what their aspirations and needs are.

4.3 Acceptance of E[co]work

The participatory design process has raised several key obstacles for the acceptance of E[co]work by informal micro-entrepreneurs. We describe them below and provide some specific adaptions or considerations that will need to be considered in iterating the concept and implementing an E[co]work facility.

- *Rental model:* The more established and senior micro-entrepreneurs often own the property they work in. The younger micro-entrepreneurs want to own their own property in the future. Thus, the E[co]work product, that is a rental-based model, needs to be carefully positioned towards potential customers (younger micro-entrepreneurs with a long-term vision for themselves) and stress the benefits of using it as a stepping-stone to owning an own facility in the future.
- *Personal networks:* Moving away from the cluster disrupts personal networks and may thus limit the access to materials for dismantling. Particularly younger micro-entrepreneurs depend- on more established players to supply materials and handle the sale of materials. Buy-in for E[co]work thus also needs to be obtained from more established players, so that material flows can be guaranteed, even if they may not benefit directly form E[co]work.
- *Logistics:* Indian informal E-waste clusters provide similar benefits to its members as regular industrial clusters. This includes the availability of support services such as logistics providers that have industry-specific expertise. Micro-entrepreneurs interested in E[co]work need to be supported in adapting their transport networks and pass on scale-related benefits enabled through cooperation where possible.

In addition to the points raised by the micro-entrepreneurs, E[co]work also needs to consider the expectations of OEMs, PROs and governmental institutions to ensure that the integration is successful and that it can meet the necessary legal requirements. In order to create trust and a willingness to move, E[co]work needs to minimize its impact on the material flows of its micro-entrepreneurs, that is not interfering greatly in the established business networks for the downstream treatment of materials, as these contact may be part of the same community or even family relations. At the

Figure 4: Example visualisation of an E[co]work Facility

same time, there are stringent requirements with regards of downstream treatment to be considered. Work is underway to develop a model of gradual improvement in critical materials streams that is both credible and acceptable to all involved stakeholders.

5 Conclusion and Outlook

The E[co]work concept could be a viable approach to support micro-entrepreneurs in improving their situation. It could provide functional protections from the challenges of informality and provide a replicable mechanism for the integration of micro-entrepreneurs into the global e-waste recycling industry.

The results of the participatory design process are promising enough to warrant an implementation of the concept. Some key questions regarding the acceptance of the solution will have to be addressed in future work that will include:

- *Demo spaces:* The working environment and the technology currently available to the informal micro-entrepreneurs is differs completely from the expectations of a formalized dismantling company. Elements such as seating and tables for ergonomic working conditions, organization of the work area and semi-mechanical treatment alternatives that increase efficiency are all absent. The next participatory design steps will employ demo spaces within the community to introduce and test such elements and improve on the business plan for the E[co]work facility.
- *Formal representation of micro-entrepreneurs*: The economic restrictions caused by COVID-19 has shown the community the risks of not having a united voice, e.g. in the form of an association, that can represent their interests publicly. In addition, the next steps of the participatory design process for E[co]work could also benefit from such an organization. While we were able to obtain sufficient access to the micro-entrepreneurs, it remained challenging to hold a directed discussion of the E[co]work concept as it was challenging to continually engage the same micro-entrepreneurs. We will thus support the community to establish their own officially registered association.

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CIRCULAR DESIGN AND EXTENDING LIFETIME

C.1
CIRCULAR ECONOMY:
REPAIR, REUSE, REMANUFACTURE, MAINTENANCE

Exploratory insights into the ‘consumer repair journey’ and opportunities for sustainable business innovation

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Abstract

Product repair, through the process of maintaining the functionality of items, has the potential to improve resource security and material efficiency. The repair journey that consumers go through when deciding whether or not to fix an item is, however, a set of complex decisions and actions. The journey comprises identification of product faults and repair need, information search and evaluation of alternatives, repair in action and post-repair evaluation. This paper aims to provide a synthesis of this sequence and address the complexity of the consumer's repair journey and the significance of current business practices during it. In particular, the barriers to translating consumers' intentions into behaviours are identified at each stage of the repair journey. The paper then investigates whether businesses could support consumers in their repair journeys. Finally, it proposes innovative business opportunities for the promotion of repair practices.

1 Introduction

Previous studies suggest that there has been a decline in repair associated with a throwaway culture and unsustainable consumption [1], [2] even though 77% of citizens in the EU claim to prefer to attempt to repair their products to buying new ones [3]. Research by the Joint Research Centre funded by European Commission [4] indicates that the main reasons for low engagement of consumers in repair are high costs and inconvenience caused by inappropriate design, a lack of repair manuals and difficulty in obtaining spare parts. A survey by the European Commission reported that 80% of consumers believe manufacturers should make digital devices more repairable [5]. However, repairability can be characterised not by only the product and context but also by the owner [2]. In other words, owners may be locked into unsustainable behaviour despite their own best intention [6]. For that reason, this study aims to identify repair journeys that consumers experience, considering the obstacles to and enablers for translating their intention to repair into actual repair behaviour. Moreover, the paper explores innovative business opportunities relating to the introduction of a ‘Right to Repair’ and the promotion of sustainable, repair-oriented businesses as a new norm [7].

2 Research methods and key questions

A focus group design was chosen for this study as this method facilitates discussion amongst participants and encourages building upon ideas through ‘piggybacking’ [8]. The focus group process replicates more accurately than interviews how opinions and ideas regarding repair journeys are formulated and exchanged. Participants were able to work together to identify and map out common challenges to and opportunities for translations of intention into behaviour at each stage of their repair journeys. The group discussions also allowed the investigator to identify consumers' support needs from businesses at each stage.

The literature recommends the number of participants in a focus group should range between six and ten [9]. A larger group can be liable to break up and talk in sub-groups. In contrast, in a smaller group it may be too difficult to keep the conversation going in enough depth for participants not to feel intimidated by the situation. Thus, each group session aimed to recruit, on average, eight participants. Table 1 shows number of participants in the four focus groups and their demographics.

Table 1: Focus groups and their demographics

Group	Size	Generation		Sex	
		X	Y	Male	Female
1	10	1	9	2	8
2	7	1	6	2	5
3	8	4	4	5	3
4	9	9	0	5	4

Total	**34**	**15**	**19**	**14**	**20**

This study focused on Generation X consumers, who were born between 1965 and 1981, and Generation X consumers (or 'Millennials'), between 1982 and 1998, to investigate differences and similarities in their repair journeys. The rationale for choosing these two generational cohorts were their substantial consumption power and major roles in the current workforce. Moreover, these generations appear to have different experiences, values, attitudes and preferences that significantly influence their shopping behaviour and consumption patterns [10], [11].

Four consumer focus groups were designed to last not more than 120 minutes and carried out in Nottingham. A saturation point was identified in the fourth session at which no new information or themes appeared and emerged. All the focus groups were audio recorded, transcribed and analysed, making use of thematic analysis and NVivo software. The data collected were coded following four key questions which were used to ask participants in discussions about each stage of their repair journeys: (i) what they intended to do, (ii) what they finally decided to do, (iii) what, if anything, made them change their minds, and (iv) what businesses could do to support them.

3 Key findings

3.1 Consumer repair journey

The 'consumer repair journey' was inspired by and developed from Dewey's Five-Stage Model [12]. These five stages are a framework to evaluate consumers' buying decision process. While many consumers often pass through these stages in a fixed, linear sequence, some stages, such as evaluation of alternatives, may occur throughout the purchase decision process [13].

Table 2: Repair routes

Repair route	Key actors
Self-repair	DIY user
Commercial repair	Retailer
	Manufacturer
	Insurance provider
	Authorised repairer
	Independent repairer
Non-commercial repair	DIY family member/ friend
	Voluntary DIY repairer at community event/ facilitated repair event

In the consumer repair journey, four stages, instead of five, were defined: (i) identification of product faults and repair need, (ii) information search and evaluation of alternatives, (iii) repair in action and (iv) post-repair evaluation. Products were either repaired by the owner, a commercial repairer or a non-commercial repairer such as a friend or volunteer. These three repair routes and the key actors are shown in Table 2.Table 1

3.2 Barriers of translating intention into behaviour

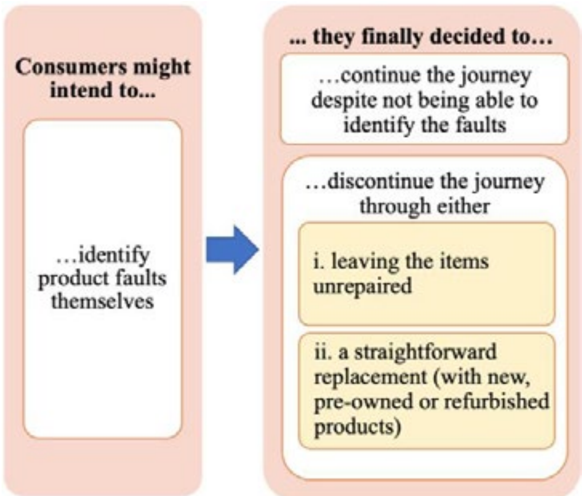
Potential intention-behaviour gaps and impact factors upon decisions were identified at each stage of the consumer repair journey and are discussed in the following four sub-sections.

3.2.1 Identification of product faults and repair need

Most focus group participants initially discovered the faults of broken items themselves. When asked about their experience at this stage, relatively more male participants than females indicated that they had identified the faults. Two female participants had contacted their insurers; they had registered digital devices (a laptop and a mobile phone) in insurance schemes which covered repair needs. In other words, they could identify a need for repair but left identification of the products' faults to the insurers.

Figure 1: Intention-behaviour gaps at stage 1 shows potential intention-behaviour gaps at this stage.

Figure 1: Intention-behaviour gaps at stage 1



Some participants continued their repair journeys even though they had not been able to identify the product fault or, as expressed by one participant, *'did not even know where to begin'*. They sought information and help from other actors to make a more informed decision at the next stage. Common obstacles to identifying faults were a lack of skills, knowledge or confidence. Some participants were afraid that diagnostic work might lead to further functional, or aesthetic, damage. Fear of data loss was a considerable concern for those intended to self-identify problems with digital devices, particularly when disassembly was necessary. Moreover, lack of tools was found to hinder the intention-behaviour translation at this stage. For example, screws with an uncommon size or shape, such as those with a triangle-shaped head, might require time and money to find and buy an appropriate screwdriver.

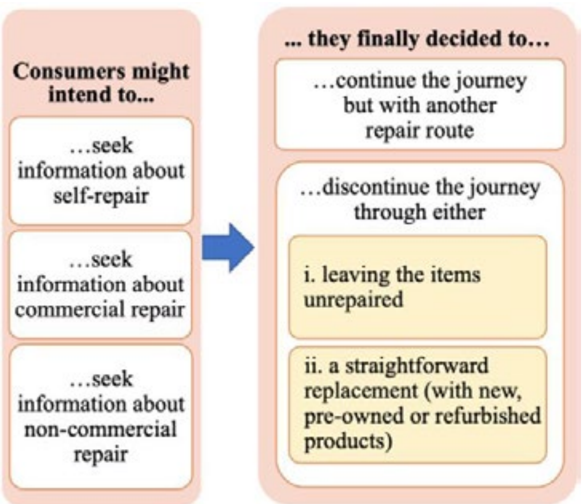
Other participants gave up on the journey, leaving their items unrepaired or purchasing a replacement. In addition to the challenges mentioned above, in some cases the perceived cost of repair appeared expensive and uneconomical, especially for low cost items such as toasters or kettles. In other cases, owners left broken items unrepaired when faults were considered minor, such as aesthetic damage or a slightly downgraded performance. Repair or replacement would only be undertaken if the product did *'actually stop working'*.

A few participants said that the availability of substitutes was a consideration. For instance, an owner might have more than one phone or be able to use a spare desktop computer rather than spend time fixing a broken laptop.

3.2.2 Information search and evaluation of alternatives

During this stage consumers seek information to inform their repair decisions. Nevertheless, potential gaps between intention and behaviour were captured in the discussion, as shown in Figure 2: **Intention-behaviour gaps at stage 2**

Figure 2: Intention-behaviour gaps at stage 2



Participants indicated that normally they intend to read manufacturers' manuals, although some complained about usefulness of the information provided. Some assumed that this might be linked to manufacturers' or retailers' monopolisation of repair services.

Most participants sought instruction or advice from the internet or from people who were friends, family members, repairers at local shops, or customer service staff at the manufacturer or retailer. The group discussions suggested that it was challenging to find reliable repair service providers. In each session at least one person did not trust a repairers' or engineers' competence at local shops, manufacturers or retailers. Although some relied on reviews such as those on Google Maps, others doubted the reliability of reviewers. There was a consensus that referrals from family, friends or acquaintances would provide an expectation of reliable repair services. A few participants sought repair advice or help from Repair Cafés.

Across all of the group discussions it was apparent that both Generation X and Y participants actively engaged in online searches to seek repair instructions. Common channels listed included YouTube and iFixit (the latter being an e-commerce business supplying spare parts and publishing free repair guides). Nonetheless, several participants drew attention to repair competence gaps between instructors such as vloggers (creators of online videos) and their audience. For that reason, even though consumers can complete this stage with more information, they may still give up on the repair journey due to perceived obstacles. Moreover, these challenges were reported to be added to by complicated product design, irreversible closures or vulnerable components. Some people left the items unrepaired after foreseeing high repair costs or a time-consuming repair process:

'I don't feel comfortable doing that [self-repair], I'd rather pay somebody, so I don't break it.'

Referencing online complaints about the high cost of repair, one participant consequently left his phone unrepaired:

'I can't bear to throw it [a phone] away, but I also don't dare to take it into Apple for a quote. It's going to cost me a lot of money.'

At the same time as looking for information, participants generally considered alternative options, including different repair routes or replacing the product. It was evident that fear of repair failure stopped some consumers from continuing their repair journey or shifted their intention from self-repair to non-commercial or commercial repair, or the reverse. Most participants identified repair costs as a factor when considering whether or not to choose commercial repair. Independent repair shops were often preferred to authorised businesses due to cheaper prices. Some participants refrained from self-repair through a concern that disassembly, causing further damage or using non-original components would void the manufacturer's warranty.

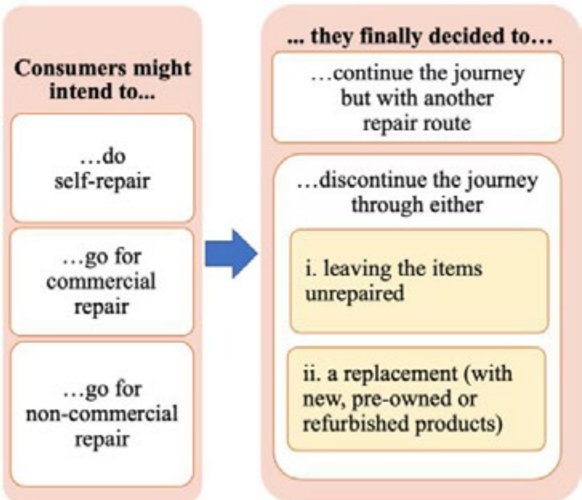
When considering replacements and the financial and environmental costs of new items, several participants preferred to replace broken items with pre-owned products (i.e. those bought in second-hand markets or given by parents or friends), including refurbished products.

There was evidence that some consumers would skip this stage if they already had knowledge or experience of fixing a product with the same or similar problems.

3.2.3 Repair in action

Consumers might intend to choose one of the repair routes but later decide to discontinue or to continue the journey with another route. **Error! Reference source not found.** illustrates these potential gaps.

Figure 3: Intention-behaviour gaps at stage 3



There was some consistency in obstacles to repair, including high costs and lack of time and skills, at this stage compared to the previous one. These were sometimes associated with unexpected situations such as out-of-stock spare parts or tools, accidental damage in the disassembly process, long-queues for customer service, or synchronisation problems with non-OEM components. There were also several instances where participants reported an intention-behaviour gap resulting from other commitments or an urgent need to use the item.

However, some products could have been repaired by consumers if they had been designed for ease of repair and spare parts were available to the public:

'Variability and complexity in parts are the biggest challenges to repair electronics.'

'New items are designed and built to be cheap, not repairable. You can't get repair done without damage.'

One participant ended up seeking help from her friend, a skilled mechanical engineer:

'I took the washing machine apart... then I realised I couldn't do it. I got a friend around to help me deal with that one.'

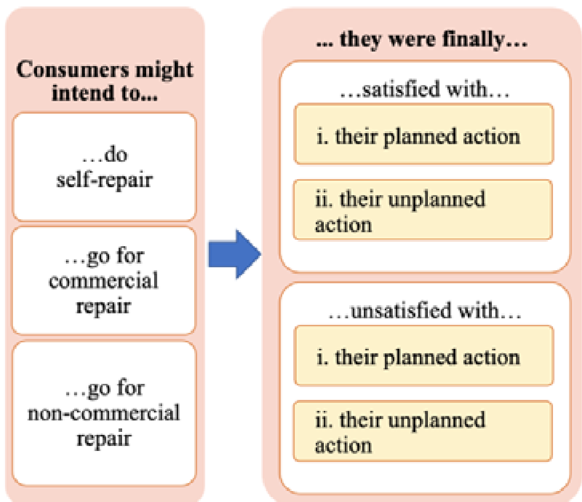
The group discussions also indicated that some participants felt that they there had been a lack of practical skills (such as mechanical and mending competences) taught in their schooling compared with that of older generations.

In every discussion group at least one or two participants doubted the competence of repairers in either independent shops or retailers. In one case this concern had resulted in a replacement being preferred.

3.2.4 Post-repair evaluation

At this stage participants reviewed the entire journey to identify differences before, during and after repair between their expectations and satisfaction with repair, or between their plan at the beginning and action taken that led to the final outcome. Figure 4 presents these differences.

Figure 4: Expectation and satisfaction gaps throughout the repair journey



Satisfaction with self-repair decisions was reported to be generated from the enjoyment in undertaking self-repair, the lower cost and extending the product lifetime. What mattered most to participants was whether the functionality of products returned after repair. There also appeared to be a difference by generation: relatively more Generation Y participants expressed a link between their motives for repair and environmental sustainability.

Most participants who succeeded in fixing a broken item indicated that they would be willing to self-repair the same or similar items in future. Several regretted their decision, however, and wondered if commercial repair would have been a better choice. The key reason for this was a recurrence of faults. Furthermore, two participants criticised manufacturers for the high cost of spare parts for DIY repair, which made this repair route uneconomical and forced them to use authorised services. Others indicated that repetitious faults were caused by *'low quality second-hand parts'* or the fact that items had *'nearly ended (their) lifetime.'*

Regarding commercial repair, several participants had been frustrated when they had spent money on repair services or spare parts, but the quality of the repair did not meet their expectations. In some cases, the same faults recurred after repair work.

It was evident in all of the group discussions that previous experience can influence future decisions and actions undertaken in future repair journeys either positively or negatively, and regardless of the repair route. For example, a few participants preferred self-repair due to losing trust in commercial services. One participant admitted not being willing to self-repair electronics again:

'What do I think about repairing electronic products? No, I do not have good experience of trying to repair those myself.'

3.3 Consumers' support needs from businesses

Three types of support need for consumers were identified: (i) improved availability of and access to repairable products, (ii) repair services, and (iii) product-service integration.

Group discussions suggested that standardisation and simplification should be considered at the design phase as these would improve the repairability of products and support repair decisions at the first three stages. For example, at stage 1, identification of faults and repair need, disassembly should be easily achieved. Subsequently, informative repair manuals should be provided at stage 2 and spare parts supplied efficiently and cost-effectively at stage 3.

There was a consensus in the expectation that improving the repairability of products might support the provision of repair services and thereby leverage a 'repair economy'. For instance, several participants indicated that if independent repairers had access to original spare parts consumers would have more options of service providers at their convenience. They also noted that if more people used commercial repairers, such repairers would benefit from more stable incomes.

Lastly, group discussions indicated that an integrated product-service offering provided by manufacturers and retailers could facilitate consumers' repair journeys. For example, several participants recommended that manufacturers provide repair services paid for either per repair or through a regular payment for ensuring the product's functionality.

4 Discussion and conclusion

This qualitative research study enabled a detailed exploration of consumers' decisions and actions throughout their repair journeys. The findings revealed that consumers may discontinue the journey at any stage due to a range of perceived and actual challenges. Some perceived obstacles might only be confirmed at a later stage of the journey. For this reason, it is essential to increase consumers' awareness of product repairability, its potential benefits and risks, and the feasibility of different repair routes.

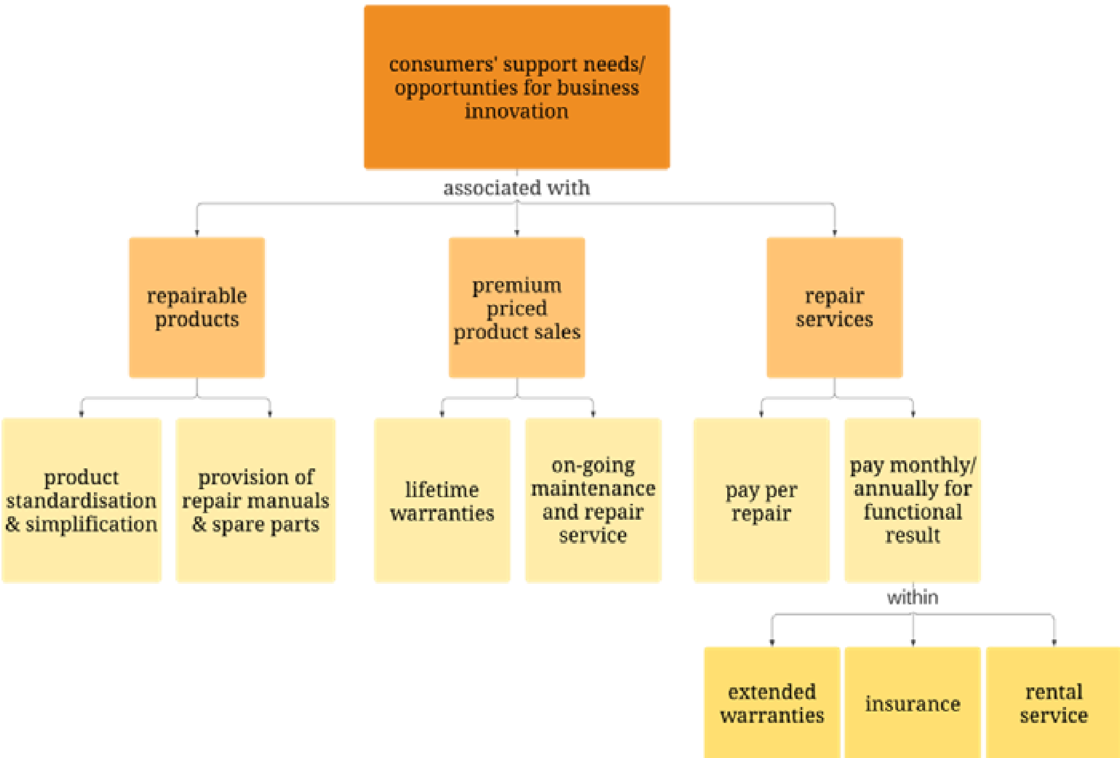
Appropriate and sufficient interventions and support from businesses are crucial if consumers are to make informed repair decisions, and their competence, sex and age need to be taken into account.

In particular, consumers may, in some instances, skip either or both of the first two stages. For example, if product owners have a clear understanding of who might offer them help or a repair service, they may not need to go through stage 1. Stage 2 can also be eliminated, if consumers have already experienced similar product faults and have necessary competencies to process later stages.

There appeared to be differences according to the sex of participants. Many men seemed to engage more actively in the entire repair journey and enjoy self-repairing electronic and electrical products. Although males also express more interest in purchasing these product types [14], their passion for technology and hardware seems to be a fundamental motive for repair behaviour.

Regarding Generations X and Y, there was no clear evidence of differences between each generation's preferred repair routes. Both generations expressed a preference for looking for repair instructions and recommendations for reliable commercial services online. Generation Y participants more often indicated that repair behaviour decisions were motivated by environmental sustainability. This finding shares a similarity with a previous study in which frequent use

Figure 5: Consumers' support needs and opportunities for sustainable business innovation



of social media and the presence of environmental issues on these channels resulted in Millennials' interest in sustainable consumption [15]. Nevertheless, due to limited sample size of this qualitative study, these explorative findings should be confirmed through further, quantitative research.

Findings from this study are also in line with those of two large-scale studies [4], [16] which address common challenges to repair behaviour and the requirements of businesses offering a repair service.

Figure 5 offers a summary of consumers' support needs from businesses and proposes business opportunities for sustainable innovation through improving the availability of and accessibility to repairable products, repair services and product-service integration.

In particular, a focus on design characteristics is vital for product repairability, through which simplification and standardisation of components should be taken into consideration. Access to repair manuals and spare parts could be provided by manufacturers as they help to increase confidence of consumers and repairers, save time and money, and enable a smooth and safe repair process [17], [18]. Repair services could be offered on a demand basis, either paid per use or included in extended warranties, insurance or rental services. Further, repairable products could be sold at premium prices that incorporate lifetime warranties or, at least, a high level of maintenance and repair. Lastly, sustainable business model innovation should consider benefits distributed across different stakeholders in the supply chain [19]; future research should take this into consideration.

Overall, this study provides a basis for business innovation, through product repair, as a part of companies' strategic development and offers practical evidence to underpin political discussion on the Right to Repair and the EU circular economy action plan.

5 Acknowledgements

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Right to Repair: the Present and the Future

Kyle Wiens
iFixit, Troy, USA

Unfortunately the manuscript for this lecture was not available by the editorial deadline.

The Raw Engagement for Sustainable Technology and Repair Talk (RESTART) Project – Findings from Participants Viewpoints

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Abstract

This paper explores the experiences of attendees at electronic repair events hosted as part of an SFI-Funded RESTART project in 2017 in Limerick, Ireland. The project explored the potential influence and capability of outreach through repair, using the medium of electronic repair events in order to inform the general public in Ireland on matters of Science, Technology, Education and Mathematics (STEM). The project also aimed to stimulate the general public's appetite for repair as a means of waste prevention and recycling for electronic appliances.

The repair events took place in the form of "iPhone Restarter" parties. Members of the general public were invited to attended with their broken iPhones and assist in repairing them. Attendees from the community and repairers discussed solutions to repair issues, exploring questions such as the need to keep devices in circulation and reducing e-waste. Adopting a "learning-through-doing" ethos, the public were given the opportunity to have their devices repaired whilst learning repair skills, gaining insight into the complexity of modern electronics, discovering how STEM enables much of this technology and discussing e-waste in the process. Related discussions also dealt with the scarcity of resources in technology, the importance of appliance re-use and the idea of repair as a sustainable waste management practice.

As part of these workshops, a series of questionnaires explored participants' experiences of the RESTART repair cafes as an educational project and as an environmental intervention. This article presents the findings of those questionnaires. Feedback indicates that participants successfully learned about repair and the materials in their devices. However, it was clear that future events need to further emphasize the scarcity of certain materials and the impact of e-waste on the environment.

1 Introduction

Nowadays we live in a 'disposable' or 'throw-away' society, with all of the associated environmental impacts of over-consumption and waste caused by the disposal of appliances, consumables and associated packaging. If these issues are not tackled, societal and economic degeneration will prevail [13]. Overconsumption has been a growing issue in Irish society for some time [2], however it has been compounded of late by the introduction of Waste Electronic and Electrical Equipment (WEEE) or e-waste - refuse brought about by the increasing uptake of technological equipment and appliances, their shortening lifetimes and thoughtless disposal, particularly nowadays with respect to mobile phones [7].

This historical consumption model of make-use-dispose is commonly referred to as a linear economy model [8]. By contrast, a circular economy model refers to the re-use of such appliances with a more efficient material re-use plan to reduce the production of waste through extended product lifecycles and use phases, since the prevention of waste production is preferable to other waste management solutions [16]. In order to move toward this circular economy model in society, it is vital that people have an understanding of the background, importance and technology behind e-waste management. Pro-environmental behaviour [15] and education around waste management policies, solutions and organizations [12] are critical in creating a circular economy. McCallie et al. [10] propose the exchange of knowledge, ideas and perspectives in a manner that includes the participation of the researchers, the general public and those in power. University engagement and community partnership with waste management are key factors in environmental progression and guiding future policies [3].

The RESTART project proposes the idea of repair events where people from the community, academics and repair technicians can discuss solutions to repair issues and explore why keeping devices in circulation and reducing e-waste is necessary. Problem solving and active engagement are important in education [4], since such repair driven workshops are an ideal learning environment. Keiller and Charter [8] noted that repair projects are steadily becoming popular with the general public of late. Repair websites such as iFixit (www.ifixit.com) and repair initiatives such as the Restart Project focus on providing and sharing repair skills, networking and connecting like-minded repair individuals - instilling the confidence to carry out repairs in the future.

The goal of the RESTART project is slightly more ambitious, aiming to open up a socio-scientific debate about e-waste management to tackle disposable society issues using public engagement, with repair offering an incentive which provides individuals with new skillsets and financial savings. Exploration of the experiences which these participants had at these RESTART repair workshops is a key aspect of this paper, as there is presently a lack of comparable research in the field examining the effectiveness of this type of e-waste management education. Additionally, STEM innovation is the foundation of many of these developments in environmental practices [1]. It has become necessary for everyone to understand the importance of STEM as innovation and technological advances continue [17]. The RESTART project provides an opportunity to highlight the role of STEM in the area of electronic appliance repair, re-use and e-waste management.

The goal of the RESTART project was to develop a dialogue between researchers and the general public around issues of technology, sustainability and the environment. This paper describes the repair workshops/events which formed the core delivery of the project and explores the potential influence and capability of outreach through repair. The next section of this article presents a literature review of the importance of re-use of the materials comprising modern-day electronic appliances and the growing importance of repair events as a means for communicating this message. This is followed by a description of the RESTART repair events which occurred as part of the project, their organisation and implementation as well as the feedback surveys used to collect participant data. The Questionnaire Results section provides information on the findings of the review of this data from a qualitative and quantitative viewpoint. Finally, the Conclusions section contains the closing remarks for the paper and summarises the main findings of this work.

2 Literature Review

This review considers some comparable STEM-related papers in the literature, looking at repair events and repair cafes such as those held during the course of this project.

STEM policy and education is a recurring theme in the literature, such as that presented in [9]. Here, 22 separate global STEM policies and practices are compared and contrasted, before highlighting findings and recommendations for the adaptation of a STEM participation strategy. Some relevant findings include the fact that the role of STEM is more important at doctoral level than first degrees, the severe gender imbalance in tertiary enrolments in STEM (especially in engineering) and the fact that the most successful countries have instituted active programs of reform in STEM curriculum and pedagogy that are focused on making science and mathematics more engaging and practical, through problem-based and inquiry-based learning, with emphases on creativity and critical thinking.

In America, the National Research Council [11] has considered K-12 STEM education at a national level, aiming to identify effective approaches for STEM education and dissemination. Gonzalez and Kuenzi [6] present a report serving as a primer for outlining existing STEM education policy issues and programs in the continental USA. It includes assessments of the federal STEM education effort and the condition of STEM education in the United States, as well as an analysis of several policy issues central to the contemporary federal conversation about STEM education.

In the UK, Silva and Bultitude [14] look at the communications skills necessary to successfully engage the general public on STEM and STEM education. The key findings from the research study into communication training programs for public engagement with STEM focus on training in direct communication methods. The study included trainers and trainees, scientists and explainers. The findings indicated that training courses are effective at increasing involvement in science communication events and trainees feel more confident and able to engage due to training. An interactive style was found to be a key element of such training courses.

Electronic Repair Workshops and Repair Cafés have also been widely considered in the literature. Repair may be thought of as 'the process of sustaining, managing, and repurposing technology in order to cope with attrition and regressive change' [27]. Charter and Keiller [18] analysed the motivations of 158 volunteers in repair cafés in nine different countries as part of a quantitative study. They found the top three reasons why participants engage in repair to be encouraging others to live more sustainably, providing a valuable service to the community and being part of the movement to improve product reparability and longevity. The authors draw the conclusion that volunteers act altruistically and that their personal gain is not important to them.

Kannengießer [19] also considers repair workshops and cafés and the driving motivation behind them, identifying them as a new format of events in which people meet to work together on repairing objects of everyday life such as electronic devices. While repairing is an old practice, argues the author, what is new is that the act of repairing becomes public in such events, with the actual repairing as well as the repair events being staged as societal actions which strive for cultural transformation aiming at sustainability. The author considers questions such as why do people participate in repair cafés and repair items? What do these events and the practice of repairing mean to the participants? And what relevance do the participants see in the Repair Cafés for society?

Dewberry et al. [19] present a report on research exploring the role of repair in creating new models of sustainable business, considering the lifecycle stage of repair and examining the nature of local and dispersed repair activities. From this, the authors look to better understand how the relationship between products and people can help shape new modes of consumption. From this, narratives of repair are collected to identify diverse people-product interactions and illustrate the different characteristics of, and motivations for, repair. Building a landscape of repair creates new opportunities for manufacture and for slowing resource loops across product lifetimes, which together provide a framework for a sufficiency-based model of production and consumption.

Not all repair efforts are limited to repair events and workshops. Graziano and Trogal [20] focus on the emergence of repair ‘shops’ across Europe, aiming to compare the transversal practices and political impacts of their different organisational setups. Here, the authors identify ‘repair shops’ as being projects and social enterprises that trade repaired and restored goods from furniture, white goods, to textiles and electronics. Significantly, these ‘shops’ are undertaken not purely as businesses, but rather as initiatives that aim to confront the environmental impacts of consumer waste, support ethical and affordable consumerism, alongside aiming to provide new trades and opportunities for employment.

Some literature researching the repair movement consider aspects such as the motivation and drive behind the repair initiative. For example, Graziano and Trogal [21] look at repair as an emergent focus of recent activism in affluent societies, identifying a number of groups are reclaiming practices of repair as a form of political and ecological action. Such actions range from groups fighting for legislative change to those groups who are trying to support ecological and social change through everyday life practices.

Resource efficiency, appliance re-use and the role of Critical Raw Materials (CRMs) is one of the key discussion points within the RESTART project. The recycling and recovery of CRMs from WEEE has received increased attention in scientific and policy-related debates over the last decade. For example, Hofmann et al. [22] have consider CRMs from a material science viewpoint. They introduce the topic of materials criticality and observe how the criticality of raw materials is perceived and handled. The authors present examples of critical raw materials in advanced technologies, summarise some definitions of criticality, outline the topic of critical raw materials by highlighting relevant outcomes of a survey on critical raw materials for materials scientists, and present a literature research on “Critical Raw Materials” and “Criticality”.

Other research publications focus on new technologies and methodologies for recovering CRMs from resources such as WEEE. Işıldar et al. [23] consider the recycling of end-of-life devices and WEEE as a secondary source of CRMs. Current technologies employed include pyrometallurgical processes; however, these are deemed imperfect, energy-intensive and non-selective towards CRMs. The paper considers alternatives such as biotechnologies, biologically induced leaching (bioleaching) from various matrices, biomass-induced sorption (bio-sorption) and bio-electrochemical systems (BES).

In their publication, Hennebel et al. [24] give a comparable overview of some of the microbial strategies that are currently applied for full scale bio-mining; they also identify new and emerging technologies, currently under development, which have the potential for large scale metal recovery and the needs and challenges on which future bio-metallurgical research should focus to achieve this ambitious goal.

Elsewhere, some publications present results of case studies and trials on CRM recovery from WEEE and comparable sources. Buchert et al. [25], for example, describe the findings from the German project "Recycling critical raw materials from waste electronic equipment". The project's aims included the production of a life cycle inventory of the occurrence of the critical raw materials in four selected groups of electronic devices – flat screens, LED lights, notebooks and smartphones – and the development of recycling options for the waste equipment to recover the critical raw materials. The study found that many of the critical metals examined, especially the rare earths (lanthanides plus scandium and yttrium) as well as tantalum, gallium and indium show total end-of-life recycling rates of less than 1%. The recycling situation for precious metals (platinum, palladium, gold and silver) and cobalt was significantly better with rates above 50%.

All of these CRM/recovery examples highlight the need to better educate and inform the general public about the existence of CRMs, their importance for the modern technological world and what can be done to help conserve, recover and re-use these important resources. Repair events such as the RESTART project are one way of directly helping to conserve and recover these resources while educating the general public at the same time.

3 The RESTART Repair Events

The RESTART project established a series of educational-driven, repair-based events focusing on STEM outreach and education. These events functioned as a vehicle for general public engagement with the complex scientific and societal issues which STEM raises. The events were aimed at the general public, allowing people to bring their small household appliances such as tablets or phones to be repaired. Attendees sat down with expert repair volunteers and staff to understand how the technology works, identify their device problem(s) and repair them. Supported by a range of educational resources developed for the project, these interactions allow discussions on the nature of the technology, the range and amount of STEM involved, as well as attempting to demystify the area of STEM for the attendees.

Electronic devices are an excellent conduit through which to approach the general public about abstract topics such as STEM. WEEE is the fastest growing waste stream in Europe, growing at 3-5% per year [26]. The RESTART project worked to increase public engagement on the topic of STEM using this novel model of active participation through the medium of these repair events and workshops. Inspired by the broader community repair movement, it promoted engagement among the general public on abstract topics such as the appliance technologies, the manufacturing materials and their associated challenges as well as product lifecycle considerations, from extraction through to use, repair, collection, pre-processing and recycling.

Education, discussion and engagement around the STEM topic with the general public is facilitated through this unique opportunity. By offering people the option of fixing their own appliances during these repair workshops, the project aimed to engage people in discussion and discourse over the issue of STEM and its importance to all modern electronics. Additionally, repairing products also has an environmental impact, by enabling people to repair/maintain their own appliances going forward, thereby slowing material loops as part of a transition to a circular economy [26]. People not only learn about STEM, but are actively engaging in strategies to address STEM challenges. Furthermore, these repair cafes were used to highlight how our growing reliance on technology is placing an inordinately high demand on these scarce resources and tackle some of the questions associated with addressing the issue.

The RESTART project ran from January to December, 2017 and saw the electronics repair events being hosted at 3 different venues in Limerick, Ireland. These “iPhone Restarter Parties” were hosted at 3 geographically and societally distinct locations, including the University of Limerick, The Limerick FabLAB in the city centre and the Limerick Learning Hub in Thomondgate, Limerick.

The events focused primarily on iPhone repair, with participants afforded the opportunity to collaborate on the repair of their own phone during the workshops. By targeting iPhone repair, the project developed the skills, equipment and supplies to provide the workshops in the relatively short lifetime of the project. Given the popularity of iPhones amongst the general public and in particular the younger generations, the offer of “free” screen, battery or charging port repairs for iPhone offered a compelling “hook” to draw many people to the events who would not normally consider frequenting such workshops. In total, 90 phones were repaired over the course of the project, with between 5-14 people attending each of the 12 events during the year.

At each repair event, participants arrived with their electronic appliances to be repaired, where they will be met by hosts and introduced to the repair/restarter event process. When ready, they sat down with experienced repair personnel and participated in the repair process, helping to effect the repairs on their appliances first-hand. Attendees gained an understanding of how the technology worked through the identification of problems with their device. Supported by the range of educational materials developed for the project, this allowed discussions on topics such as the nature of the technology, the range and amounts of CRMs and other scarce resources used and actions to address the lack of these resources.

The repair café/restarter party setting created an engaged dynamic, making participants far more likely to get involved in the discussion stage of the process. These repair workshops were intended to be the triggers for larger conversations pertaining to science and technology; engineering and the environment; product life cycles; materials needed for appliance manufacture; how much energy this manufacturing process uses and what happens with these devices once they become waste. Through the time that participants spend in the repair workshops and events, these and other related topics could be examined and discussed with the individual participants in a relaxed and comfortable setting. Participants engaged in the repair process, gained a better understanding and appreciation for the role of STEM in their personal electronic appliances and effected a change in their perspective towards STEM and the circular economy as well as the repair/recycle/reuse of electronic devices within society.

Most of the event advertising happened through electronic media, with volunteers and participants recruited via advertisements on partner websites, email notifications/lists and social media feeds. Word of mouth was key to accessing the networks of people in all three locations. Photos, videos and outcomes from the events were posted to social media, along with relevant and pertinent information about the specifics and importance of repair and re-use for extending product lifetimes. Participant uptake and interest in the events was immediate with all events being over-subscribed. Over the course of the year, 180 people have followed the project on Facebook and Twitter with approximately 3,500 people being reached by project posts and tweets online during a typical single event.

Twelve repair volunteers/facilitators were recruited and trained during the course of the project. These repairers were predominantly people with engineering or technical backgrounds who were interested in developing iPhone repair skills. The project collaborated with a local phone repair provider, PAIR Mobile, to provide repair training, technical support and the supply of replacement/spare iPhone parts. Approximately one days' worth of training was required before most repairers were comfortable with working on the iPhones for repair.

The typical RESTART event workshops ran for three to four hours, with each repair scheduled for one hour. Participants arrived at their pre-arranged timeslot, presented themselves and their iPhone for repair with the aid of the repair volunteers. During the course of this hour repairing their phone, the repair facilitators engaged the participants on a range of STEM topics, repair and re-use, all relating to the disposable society. As the repair facilitators worked to diagnose the issue and prepare the relevant parts for the repair, the participant was invited to interact and participate in the repair. Through the medium of iPhone repair, topics such as the scarcity of critical raw materials for phones and engaging in repair rather than disposal were naturally discussed as part of the process. The participants learned about the component electronics and parts inside their phone and the steps necessary to repair them.

People attending the workshop were asked to complete a brief questionnaire before they participated in the event and another after the finish of the repair. A separate, follow-up questionnaire was sent out eight weeks after the event to those who provided contact details at the workshop. These questionnaires contained a number of Likert-type items and qualitative questions relating to repair, waste and the relationship between repair and science. Some of the items were similar across these questionnaires in order to create a comparative index from before and after the workshop events. Most people (N=73) filled out the pre-event questionnaire and the post-event questionnaire (N=70) at the workshop events. About a quarter of people who attended the events (N=18) completed the follow-up questionnaire.

4 Questionnaire Results

Thematic analysis was the primary method of analysis for the qualitative data. The procedure recommended by Braun and Clarke [28] was rigorously followed using an inductive approach. This method seeks to find themes throughout the data using codes to categorize the responses. An iterative approach was adopted, where responses were coded, codes were grouped into themes, and themes were used to as the basis for recoding. This cycle was followed until a stable thematic structure described most of the responses. From the questionnaire findings, overall percentages were calculated to indicate whether the statements typically found agreement or disagreement with the audience. Given the small non-random sample, it made little sense to run significance tests on the data.

Learning about phone repair was most prominent of the three main themes identified in the qualitative data. Participants consistently mentioned the phone repair skills they had learnt, for example, 'I have gained skills on how to repair a screen', and as a result, that they were more likely to repair in the future, '[I'm] more likely to carry out simple phone repairs'.

Responses also indicated the education received in relation to phone technology, 'Saw the inside of a phone & saw how the battery, charging port & screen works'.

Participants reported their reaction to the skill level required in phone repair, ‘It’s not as hard as you would think’. As a result of these patterns, three subthemes were identified; learning how to repair phones, learning about phones and learning how achievable a repair is.

The quantitative data further highlights the third subtheme, learning how achievable a repair is. Participants felt that repairing their items was more possible after the event (67%) and they learned something that would help them repair things in the future (86%). No participants reported becoming more intimidated about repair, but some (44%) reported that they learned that specialist knowledge is required to repair things. The transferable nature of repair skills learned was evident also. When participants were asked about the items they would repair next, most answered affirmatively, listing phones, computers/laptops (N=7), iPads/tablets (N=6) or a range of miscellaneous technological items (N=13) such as a hair straightener or whatever broke next (N=2) as potential candidates.

The second theme discovered was the environment and was much less prevalent than the first. The participants indicated they learned about the reusability of the parts of their phones, ‘Never to discard your phone as its parts, although not all 100%, they could be re-used again to repair another phone’. The importance of recycling and materials was also noted, ‘I now understand the environmental impact of wasting precious metals, and also would feel more confident in researching and trying general diagnosis & repairs of electronics’. Participants also suggested in the future they would, ‘Get things fixed rather than throwing them out’, and ‘Get things fixed instead of buy a new one’.

This theme was also supported by the quantitative data. Before the event, a substantial amount of participants agreed that they were aware of the impact of throwing things away (63%) and were aware of the benefit that repairing things could have on the environment (71%). After the event participants indicated that they had learned something about the impact of waste and repair on the environment (75%). Some people who attended have kept something that would otherwise have been thrown away (45%). Half of the participants who filled out the follow-up questionnaire indicated that since participating repairing their stuff feels more important (50%) and that participating made them more aware of how to recycle e-waste (50%). A large proportion of participants (78%) indicated that the repair made them more aware of the materials inside their technology and a smaller number of participants became more aware of the scarcity of some raw materials in technology (38.9%).

Money was the third theme identified through thematic analysis. The participants enjoyed the gratis nature of the event, however, money was also discussed as a limitation to future repairs, ‘The expenses that are involved in fixing this item’, ‘The price of repairing’. Participants also indicated that the cost of acquiring parts would limit their repairing, ‘Possibly the high cost of replacement parts (mainly the loudspeaker)’, ‘Cost – I’ll buy new if replacement costs too much’.

Over half of the attendees agreed that they were aware of the links between science and repair (55%) before the workshop began and a substantial amount of participants learned about how repair relates to science in the workshop (70%). The link between science and repair was mentioned by three participants in the qualitative section, ‘Science is strongly linked to repair’, ‘I have learned that science can be linked with electronic devices in order to fix them’, ‘Science is progressing in its role and involvement in technology and new resources and elements are proving capable of new things’.

Participants learned about materials and the environment. Attendees confirmed that their behaviour toward waste management would change and stated that they would reuse items rather than throw them away or buy new items. An awareness of critical and scarce materials was also evinced, with participants speaking about repair and waste management. Participants enjoyed learning about the parts and materials inside the phones however only a small number of participants mentioned their scarcity.

The repair events were enjoyed by the vast majority of attendees (89%). No one was bored by the process of repair. Participants were proud of their repairs (72%) and were happy to show their repaired item to people (67%). Some participants shared the repair on social media (45%) and others told people about the repair (83%). The effectiveness of an engagement and problem solving suggested by Fisher et al. [4] was evident as many participants communicated their intentions of future use of their skills in repair, despite the limitations encountered.

However, only 56% of participants reported that their item still worked in the follow-up questionnaire. One participant reported their dissatisfaction with the service, ‘Since the screen on my phone was fixed the battery of my phone no longer lasts so I presume its due to the phone being opened to put the new screen on I was very unhappy with this as the phone was perfect before I got the screen fixed. I told my friends what happened and recommended they go to an apple store to get their phone fixed if there was something wrong and don't do it yourself as this is what happened to me [sic.]'. It is worth noting here that participants are generally more likely to respond to the follow-up questionnaire if they have a special motivation to e.g. dissatisfaction in this one particular case out of the 92 surveyed.

This also highlights the difficulty in gathering responses to such events and ensuring the survey sample size is sufficiently large to enable meaningful patterns to be identified. The satisfaction of participants in relation to staff, atmosphere and enjoyment of the workshop was evident from the survey feedback. However, the technical skill level of the repair facilitators required improvement according to the survey participants. Repair success was the hook element of the project and this was not prevalent enough in the follow-up questionnaire. This could be explained by the small number of follow-up participants, and their motivations for engaging with the follow-up questionnaire may have been to highlight this issue. A larger response rate for the follow-up questionnaire is necessary for future inferences and the issue highlights a challenging future area of research, response rates and motivations.

Given the short duration of the workshop (~1 hour per attendee) and the need to repair appliances as well as educate/inform participants, one shortcoming identified is the lack of focus on environmental impact and materials in the workshop environment. Interactive material(s) and more focused discussion is necessary to improve general knowledge of the scarce/critical raw materials used in modern appliances and technology and the implications of their use on the environment, as well as how reusing, recycling and repair can tackle these issues and the role STEM plays in the process. For example, some questions from the pre-questionnaire were closely related to those on the post-event and follow-up questionnaire. However, it would be much more useful if scales were used to create before and after measures for such questionnaires going forward. For future workshops of this nature, a more inclusive, representative scale should be distributed at different time points to accurately explore the effectiveness of the project.

5 Conclusion

This article has presented research conducted as part of the RESTART project in 2017, aimed at educating the general public and creating discussion around how the use of technology depends on scarce, diminishing materials and encouraging movement towards a circular economy via re-use and repair. The project employed a "learning by doing" pedagogical approach in order to educate and inform them on issues of STEM and resource efficiency in today's technological world.

The RESTART project events succeeded in stimulating discussion with people about waste management and how their use of technology is depleting resources. People learned repair skills which could help them manage their waste more sustainably in the future. Attendees were educated about the materials in their phones and the appropriate management of these materials however raw materials and environmental impact will be more focused on going forward in order to highlight its importance. It is clear that an intervention which includes active participation and discussion, although not without fault, is favourable. In order to more thoroughly review its effectiveness, a more reliable scale is necessary.

In order to ensure that our world can deal with the ever-growing problem of e-waste, it is vital that steps are taken to promote a circular economy. Repair events such as the ones described in this research provide a unique opportunity to indicate to everybody the disposable nature of our society in particular regarding technology, whilst also outlining the importance of STEM in providing solutions to environmental issues.

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A Future of Fixing: Upscaled Repair Activities envisioned using a Circular Economy Repair Society System Framework

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Abstract

Repair constitutes an essential circular economy (CE) strategy that enables the extension of product life. Having access to repair is essential for sufficiency: via repair, individuals are able to "make do" with the products and equipment they have, and this opens the opportunity to also decrease environmental impact, improve sufficiency, increase financial autonomy, and provide for meaningful employment in the repair sector. A vision for a repair society must be co-created by all relevant stakeholders to align interests and avoid unintended consequences. The key features of a realized, futuristic CE Repair Society, in which repair is normalized, are distinguished using literature review on e.g., current repair barriers and alternative consumption. Then, the features are viewed through the lens of the CE Repair Society Systems Framework (Figure 1) to discern the levels of a Repair Society, and their interconnections.

1 Background

The concept of a Circular Economy (CE) is still emerging and is founded on the premise that the inherent value in materials and products ought to be sustained and recovered through the creation of circular material and product "loops" [1]. Repair constitutes a strategy for "slowing" product loops (i.e., extending product lifetimes) and thereby enabling sustainable consumption and preventing waste. Upscaling repair and creating a Repair Society must be the priority in a CE and constitute the focus of this paper.

In our view, a "CE Repair Society" is one where repair is a cost-effective, convenient, and mainstream activity. Its realization requires a dramatic upscaling of repair services and activities compared to the current state. This upscale is currently hindered by a range of barriers, including obsolescence (Table 1). Consumers have become "normalized" to the breaking of their devices and the belief that the only option is to discard and replace[1]. Overall, the transition to a CE Repair Society is contingent on overcoming existing barriers, innovation and change [3], and preservation e.g., rebuilding of repair and maintenance skills that have become "endangered" [4].

Currently, upscaling of repair is influenced by various diverse stakeholder interests with little understanding of the implications of favouring some interests over others. Given that the majority of sustainability challenges we face today stem from unintended consequences of innovation [5], an appropriate role for repair within a CE must be approached strategically to ensure that the 'solutions' are viable for all stakeholders, and do not lead to future unintended consequences. As part of this strategic planning, a vision for a repair society must be co-created by all relevant stakeholders. The key stakeholders (Figure 1) in a repair system can be divided into the demand and the supply-side of the repair transaction. The supply-side consists of Original Equipment Manufacturers (OEMs), Independent Repairers (IRs) and consumers performing repair themselves (do it yourself - DIY). On the demand-side are individual consumers. The overall framework conditions for market actors are ultimately dictated by governments. Ultimately, the repair system is limited by planetary boundaries.

Participation in repair involves a) being able and willing to conduct a repair *transaction* (i.e., selling or purchasing), and b) performing *the repair*. Consumers with a broken product generally have four possible courses of action: 1) consult the seller, the OEM's repair division, or authorized repair service provider; 2) 'Do-it-yourself' (DIY) repair; 3) seek out an Independent Repairer; or 4) dispose of the broken device and purchase a replacement product. This choice is

[1] E.g., the battery of wireless headphones cannot be swapped, so by the time the battery runs out the headphones become e-waste [2].

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impacted by a range of factors, such as personal preferences and physical and financial access [6].

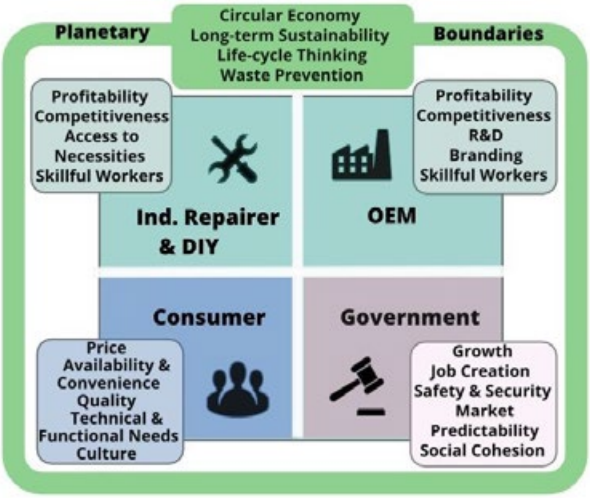

Figure 1: Repair Key Stakeholders [6]

Regarding the supply of repair, the interests and determining factors are more complex, since they differ between OEMs (and OEM-authorized repairers), independent repairers, and DIYs. Common for all is the need to have access to the required tools, firmware, schematics and spares (hereby collectively referred to as 'necessities') in order to be able to conduct the repair [6].

For repair activities to reach their full potential and role within an effective CE (i.e., to achieve the desired environmental outcomes), there is a need for repair to be normalized. This study explores the possibilities of a realized CE Repair Society vision, drawing from historic and cultural contexts of repair, the current state of repair, and thought-leadership regarding the role of repair, as desired for the future.

2 Method & Disposition

To understand the opportunity and implications of a repair society, we reviewed both academic and grey literature, using an inductive coding approach which yielded three categories: 1) Current barriers and enablers; 2) Historical and cultural accounts of repair; and 3) Repair Society Visions. The first category is legal, economic and technical issues, focusing on reviews [3], [6]. The second and third category reviewed literature, using search terms such as "repair" and "society/ "culture"/"economy", as well as relevant references in these works. The review only included research explicitly applied to repair. Potential benefits and negative effects of normalized repair activities are explored. Following the research approach, the three tables below have been organized into the emerging themes in order to describe and discuss facets of a future repair society.

3 Literature review

The following tables outline the findings of the review, organized into Current (Table 1), Historical and Cultural (Table 2), and future Vision (Table 3) perspectives on a Repair Society, respectively. In Table 1, primary barriers to normalized repair, as identified in the literature, are presented.

Current Barriers
Socio-cultural
• Design preference for concealment of the functionings of devices [7] and lack of knowledge on how products work [8]. • Newness-fixation and high speed of design changes [7] create perceived obsolescence, reducing consumer interest in repair [9] • "Maintenance lacks the glamour of innovation" [10]. • Material decay, due to lack of maintenance and repair is symptomatic of a devaluation of the present moment, in favor of the future promise of novelty [11]. • Lack of time and attention [7]. • Lack of ethics/morals of care and responsibility for one's biospheric impact [7]. • Consumers lack economic and emotional attachment to products, leading to poor care and lower willingness to repair [8]. • Lack of recognition (i.e low social value of repair) makes repairers change career [12].
Economic
• Increasing presence of new, low-quality, low-cost product options [3]. • OEM profit-orientation focused on higher-cost replacement and avoidance of cannibalized sales [8], [6], [3]. • Consumers are "punished" for choosing to repair (instead of replacement) in the form of costs and inconvenience [6], [8]. • Repair perceived as risky [6]. • Aftermarket profitability through monopolization for OEMs- "decoupling" consumer ownership in a manner that interferes with repair [13],[6]. • Lack of quality repair service [6].
Technical

- Convenience of disposal options [3].
- Lack of reparability in product design [6],[8].
- Repair skills are neglected and devalued in formal design, technological and engineering education [12].
- Lack of access to spare parts tools and other necessities [8], [6], [3].
- Repair enabling continued (undesirable) use of lower-efficiency devices [6]
- Safety and security issues stemming from non-expert/unsupervised repairs [14].
- Manuals and repair information can be inaccessible for low-literacy repairers; translations to local languages and instruction videos are needed [12].

Policy and Law

- IP-laws favoring incentives for innovation over repair, blocking repair [6].
- Warranties and guarantees under Consumer Law are not enforced [6].
- Contract law enforces repair restrictive clauses [6].
- Lack of design laws towards more repairable products and accessible necessities for repair [6]

Table 1. Current Barriers

Contrasting the current state with evidence of successful repair cultures from around the world, Table 2 captures conditions and characteristics of these cultures that enable(d) a form of Repair Society.

Current and Historical Repair Cultures

People and their objects

- Material scarcity incentivized people to "make do" and repair what they already owned coupled with a sense of loyalty to objects beyond loss of functionality [15],[16].
- Pragmatic relationship to material things, "free of fetichism, alienation and commercial calculation", focused on functionality (as opposed to individuality) ([15] pg. 62).
- Commitment to understanding and being able to modify and repair, and having a more ethical and mindful relationship to one's possessions [17],[18] Breaking, maintenance, and repair is meaningful and engaging [19].
- Increased visibility of the workings of things enables appreciation of its intricacy, inspiring awe in the user and inviting a stronger connection to an object [18], [16].
- Visibility of function enables "democratization of mastery" - inviting non-professional to partake in creation and fixing [17], [18].
- Investment into customization efforts of new goods made people reluctant to discard [15].
- Breakage is an "intermediate stage", not a "final state". "Functioning" consists of a wide span of "adaptations and variants" [20].

Repair as innovation

- Repair and repurposing, despite lacking the proper necessities or skills, are met with creative and improvised "everyday innovation" [21].

Product design

- Devices are designed for "fluidity" of functioning - consisting of a span [20].
- Simplicity, durability and ease of maintenance in design, with access to manuals and instructions, makes a device "survive" [20].

Perspectives on repaired devices

- Kintsugi, a tradition where gold or silver is used to repair broken ceramic items, increases the object's beauty, and repair becomes a valued aspect of the object's history [22].

Social implications

- Repair as a form of creativity and lifestyle regardless of socio-economic background [15].
- Media and government provide knowledge and ideas for repairs [15].
- Propensity and ability to repair is part of the moral and social assessment of individuals, affecting status/authority in the community

[15].
The socio-political meaning of repair
• Repair culture as a way to resist commodification of human creativity [21]. • Repair as local empowerment [23] and "localization" of repair skills to safeguard and strengthen local culture and technical skills (i.e., to counter foreign intrusion of technology, knowledge and culture) [12].
Repair skills
• Repair training is offered, teaching explicit, tacit and social skills of repair [12]. • Strong repair community sharing knowledge [12].
Ownership structures
• Granting ownership of an object contributes to its "success" (i.e., life length) [20].

Table 2. Current and Historical Repair Cultures

Finally, in Table 3, conditions and characteristics of a viable vision for a CE Repair Society are presented and organized by the role that repair plays in the Repair Society context.

Repair Society Visions
Repair <u>and</u> innovation
• Repair processes are considered and facilitated in product design [24], and efficacy of innovation is evaluated based on the reparability of the device [19].
Repair <u>as</u> innovation
• The act of repair *is* innovation, thus, repair constitutes an engine of innovation that leads to development [19], [24]. • The common view of innovation is not accurate; Instead, innovation is "incremental" and involves invisible breakers, tinkerers, repairers and maintainers [16], [19], [25]. • Repair and maintenance embrace disorder, not seeking merely to bring the device "back" to order but instead move it forward to a new, "repaired" order [20], [24].
The human & objects/technology relationship
• Material vulnerability generates a shared concern that ensures maintenance and repair are common practice [26]. • A departure from the Technosphers' view of technology, manufacturing, repair and discarding as "autonomous" from humans, and "natural" in their current state towards humans having agency and decision-making in product systems [27]. • An ethics of mutual care and responsibility connects people and their objects; repair enables deep, meaningful and long-lasting relationships to things [19]. A sense of responsibility, as "custodians" of things [13]. • Acknowledgement and responsibility for the negative impacts from everyday consumption [28],[19] through industrialization and commodification [27]. • Rejection of meaningless innovation that fails to contribute to progress, in favor of repair and maintenance that support sustainable societal progress [28], [29],[11]. • Product aging is understood and accepted; not all things are new and/or perfect [25]. • Troubles and malfunctioning must not be considered a breakdown [25].
Product design
• Design is timeless [19].
Social implications
• Repair is a social practice in the local community and distinction between work and leisure time is blurred [13]. • Repair economies are more harmonious, kinder, inclusive and resilient [30]. • The boundary between making and using is erased, making room for repairing and maintenance activities as an accepted aspect of the product life-cycle [31].
A repair economy

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• Material things are not seen as expendable [30]. Unwanted objects are moved "into situations amenable to their repair..." ([32] p. 96). • Ethical repair e.g., livable wages for repairs, enhanced worker well-being and resource conservation [32].
The role of repair in the economy
• Repair creates high-skilled [33], steadier, local jobs, as its operations cannot be off-shored as easily as manufacturing of new devices [13]. • The maintenance and repair sector is acknowledged for its size and economic importance [29] and seen as an "engine room" of modern economies and societies [24]. • Repair reduces cost of living [33].
Self-sufficiency or provision
• Repair opportunities create enhanced financial access to technologies for individuals [32]. • Individuals possessing repair skills are less dependent on formal wages, increasing self-reliance and self-sufficiency [13], [32].

Table 3. Repair Society Visions

4 Key Features in a CE Repair Society System

Interpretations of repair - within socio-cultural, economic, and environmental contexts - have been integrated in the literature long before the advent of CE research. Fundamentally, a Repair Society seemingly requires a sense of responsibility, or "ethics of care" for the material objects in our lives [7], [13], [19] that is at odds with the contemporary culture of "success" as being mass consumption, novelty, and growth. In this regard, a Repair Society requires a reassessment of the purpose of technology, the definition of societal "progress" and a clear approach to these new priorities [29], [27], [28].

Given the potential strategic importance of repair as a cohesive and clear pathway towards CE, we explore the key features of a repair society, as revealed through the literature review, using a systems-perspective of our CE Repair Society System Framework [34], [35] (Figure 2).

The macro-level in a Repair Society System consists of the economic system determining the market conditions, and overarching ideology around consumption and politics (i.e., the overarching, or underlying, social and economic dynamics). The meso-level is composed of three aspects: a) infrastructure and systems (e.g., policy and access to repair necessities); b) business and industry (e.g., profitability in repair and product design); and c) culture and market (e.g., media content, and access to information and knowledge). These components are heavily interconnected.

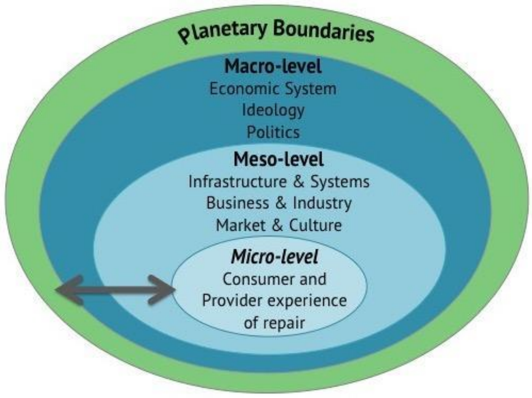

Figure 2. Repair Society System Framework

Finally, the micro-level is reflective of the individual (consumer or provider) within a CE Repair Society, and consists of the intermediate setting, and the roles, activities and relations in the implementation of repair activities.

At *the micro-level* of a Repair Society, Graziano and Trogal argue that repair initiatives stem from "a growing desire to revisit, through fixing, our relationship with the objects and machines that make up our daily lived environments and sustain our mundane activities within it." ([13] pg. 4). In a disposable society, to repair is to rebel [10]. Implicitly, then, the exploration of repair entails the uncovering of perspectives that are otherwise largely hidden and/or ignored by the individual [19], including: the devastating impacts of throw-away culture, and the value of the materials and products already in our possession, that are allowed to decay without maintenance or repair efforts. This micro-level shift in awareness and realization is inherently connected to the economic systems and ideology around consumption at the macro-level. These insights constitute potential drivers as well as potential system-wide impacts that may result from the normalization of repair. For example, the elimination of "friction" (time, cost, access) that otherwise prevents an individual from engaging in repair is as much a solution of meso-level infrastructure, and macro-level economics (among other factors) as it is of micro-level individual preferences and sensitivity. An important distinction and understanding concerns the entirety of the product/object life cycle beyond a

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binary "broken (end-of-life) vs. functioning (in-use)" framework; the state of functioning can exist along a spectrum. In addition, consumer expectations of repair work could extend beyond restoring functionality, to adding value, functionality, uniqueness, and/or other desired attributes; The role of the repair professional could be reimagined, as an opportunity to unleash creativity and ingenuity, embedded within the fixing process. Repair also then constitutes a key consideration of any innovation and design, along with the elements that make repair possible, e.g., availability of spare parts, tools and information.

Further demonstrating the complexity of a Repair Society, two current *meso-level* repair cultures have been identified [7], firmly connected to micro- and macro-level conditions and influences: 1) The industrial economy-inspired "entrepreneurial maker culture" in which repair operations are industrialized and grounded in mass-production ideologies (meso-macro alignment); and 2) "innovative repair culture" in which a wide range of people engage in repair activities (meso-micro alignment). A significant contrast in motivation, the innovative repair culture embraces a mindset of using what is "at hand" out of necessity, personal satisfaction, or ethics of care, i.e. sense of responsibility for a device. Such cultures demonstrate a non-binary view of the product, such that it can be more than just 'broken' or 'functioning' [19]. Where repair prevails, culturally, a social acceptance, and even appreciation, for "imperfections" (aesthetic and/or functional) is often present. This is observed in e.g., the Japanese tradition of "kintsugi" [22], in Steampunk's appreciation for unique items [17], [18], and in the improvisation of "everyday innovations" in the Brazilian repair culture "Gambiarra" [21],[7]. In this sense, repair is viewed as a creative, value-adding process that gives rise to something new and valuable, and the profession of repair holds status.

Historic evidence demonstrates that *macro-level* conditions, including famine, war, and regime-based oppression often create conditions that facilitate a repair-emphasis [7]. In these cases, the "make do" mentality arguably stands in sharp contrast to current conditions in markets saturated with low-cost products, i.e., most of the Global North. However, although the growth-oriented ideologies and economic systems of developed countries do not impose limitations to consumption and production, resource scarcity imposed by planetary boundaries remains an important consideration (Figure 1). As such, the conditions of material scarcity in the USSR and post-war Britain that necessitated repair, still remain very relevant and tangible in today's context, and for envisioning a future repair society that is pursued, not imposed. To this effect, alternative macro-level models that orient policy and ideology to the achievement of material conservation and value-retention, through repair, as well as through other CE mechanisms, are needed.

5 Future Research

An important remaining question is what the roles of the stakeholders are (see Figure 1) at the different levels of a Repair Society System (Figure 2) and who it is that conducts the repairs; The "distribution of repair" [26] or "repair market governance" [6] can be centralized (i.e., where there is a clear boundary between occupational communities and users, the OEM handles repair and maintenance, while the consumers barely considers it) or distributive (i.e., users have a role in the longevity of the device and are also empowered with repair skills and thus opportunities for self-sufficiency and "democratization of mastery"). These are two different repair societies, much like Schultz's two repair cultures [7] and their implications must be better understood in terms of roles, responsibility, and agency. Further, the features of the Repair Society System shows that repair is influenced at different stages of the product life cycle - there are critical time dimensions of repair, e.g., pre-breakage and at the moment of repair. Identification and facilitation of these dimensions need to be further understood, especially from a market governance perspective.

Our future research includes development of a CE Repair Society Vision and the Framework (Figure 2), including deepened literature studies, coupled with key stakeholder consultations to ensure the exchange of dialogue and feedback regarding design, content, and implications of a vision for a repair society.

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Extended Product Lifespan Abroad – Assessing Repair Sector in Ghana

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Abstract

Informal e-waste recycling in the Global South is a well-known phenomenon thoroughly described in the literature. So far, there are only few studies focusing the repair and the associated reuse of electronic devices. This contribution is trying to fill this gap with an empirical field study in Southern Ghana. Methods are proposed that facilitate the investigation of repair activities, the training of repairers and costs and success factors for repair businesses. 29 interviews with repairers and 6 experts of the repair sector have been interviewed with semi-structured interviews. In addition, a method for analysing the extended service lifespan abroad was developed and tested with 86 data points. Results reveal that around 83% of all repairers interviewed had no formal training in the field. More than 80% of all devices can be repaired and thus the serviceable life can be significantly extended, in some cases even tripled. Spare parts are mainly obtained from old equipment. The cost of a repair is low, so devices are repaired several times before they are replaced with new ones. Future research must show how inexpensive new products specifically designed for developing countries influence repair presence and practices.

1 Introduction

After the first use phase, electronic devices are often exported to countries of the Global South for being processed. Media reports occasionally report on this practice and link it to informal recycling practices.[1] Furthermore, the consequences of informal recycling of electrical appliances are the subject of many scientific studies (Osibanjo and Nnorom, 2008; Osseo-Asare and Abbas, 2015; Yu et al., 2017).

So far, little mention has been made of the repair and the associated reuse of the equipment. There are no reports if or how long second-hand imported devices are used, especially since typical lifespan estimates are not functioning due to the lack of data and missing methods for estimating the lifespan of used equipment. Also, it is unclear under which conditions and at which costs devices are repaired. For example data on qualifications of the repairers, their income and their skills and capabilities are not present in literature.

The aim of this contribution is to shed light on the aforementioned questions. After a review of literature, the methods for this study are explained. In total six experts and 29 repairers of electronic equipment were interviewed in the south of Ghana. The results are presented and further discussed. In addition, an age sample of 86 electronic devices was taken to analyse how long second-hand imported devices are used before they are dismantled and recycled.

2 Literature Review

The first mention of informal e-waste recycling in Ghana dates to 2008, when the environmental organisation Greenpeace analysed soil samples from scrap yards in Agbogbloshie in Accra and Koforidua. The samples revealed very high levels of contamination, especially of toxic chemicals and metals in the places, where plastics and other materials were burned (Brigden et al., 2008).

Since then there have been many studies that have investigated the effects of informal e-waste recycling (Beecham, 2016; Chama et al., 2014; Feldt et al., 2014; Yu et al., 2017). Little information is available on the repair of electrical appliances. In the "Ghana e-waste

[1]https://www.theguardian.com/sustainable-business/gallery/2017/feb/01/nairobi-kenya-electricals-e-waste-recycling-safaricom-ibm-samsung-in-pictures, unenvironment.org/news-and-stories/story/turning-e-waste-gold-untapped-potential-african-landfills

County Assessment" of 2011 it is assumed that there are 1200 repair shops throughout Ghana and that about 70% of the repairs are successful, which extend the lifetime of the appliances by 1-2 years (Amoyaw- Osei et al., 2011).

The repair sector is often mentioned in a marginal way. In Nigeria, the "Person in Port Project" examined a total of 60,000 tonnes of goods imported into Nigeria over two years. (Odeyingbo et al., 2017) This is also the first time that reliable data on the proportion of goods in working order are available. A total of 750 units from various categories were examined for functional capability and 26% were found to be defective. It is assumed that most of these goods are repaired and not directly disposed and recycled, contrary to what many media reports claim. More exact data on the repair sector was not generated during the study. However, these are relevant when assessing how the import of defective equipment should be evaluated.

Internationally there are only few studies on repair, in particular in countries of the global south. Corwin (2018) examined the repair culture in Delhi, India and concluded that individual parts are transferred from the scrap cycle to further use in newly assembled appliances, which contradicts the frequently reported focus on recycling (Corwin, 2018).

In two publications, Jackson examined the repair of computers and mobile phones in rural Namibia. He identifies a great deal of creativity in dealing with old equipment and describes the repair sites as places of local innovation and expertise (Jackson et al., 2012, 2011).

In order to enlarge the knowledge as well as methods for repair research in countries of the Global South we are focusing on the following research questions:

How long is the lifespan of a second-hand exported device? What role does the repair play in this context? Which are typical reasons for failures of equipment? What is the repair success rate? How are the repairers in Ghana trained and educated?

3 Methodology

The research presented here used a mixed-method approach to the role of repair for product lifetimes: Semi-structured interviews were used to characterize the repair sector and repairers as main actors in this sector. A quantitative approach was used to analyze the extended lifespan of second-hand exported devices.

3.1 Repair

For the study of repairing practices, semi-structured interviews as well as questionnaire-based interviews have been conducted. Therefore, an interview guide as well as a questionnaire was developed. A qualitative approach was chosen to gain a more true-to-reality impression of repair practices. This was supplemented by a semi-quantitative approach.

The following groups where interviewed:

- 6 semi-guided expert interviews
- 6 semi-guided repairer interviews
- 29 questionnaire-based repairer interviews

In order to make the business model and the capabilities of repair shop measurable, various success indicators were developed, applied and empirically validated. The income of the repairers will be used as the first factor. It is calculated on a monthly basis and consists of total revenue, running costs, the cost of spare parts and the number of employees.

$$\text{Income per Person} = \frac{\text{Revenue} - \text{running costs} - \text{sparepart costs}}{\text{Number of employees}}$$

Another factor is the Repair Ratio (RR). It is the percentage of successful repaired devices based on the repairers estimation.

$$RR = \frac{\text{Number of successful repairs}}{\text{Total number of repairs}}$$

3.2 Device Lifespan

In order to determine the lifetime of electrical appliances in Ghana, the age of the equipment at the dismantled or recycling stage is determined with decoding the production date from the serial number and then subtracted from the average age of the equipment at import. In addition, the age can be determined at the intermediate stages of use and repair for validation purposes. However, since one method cannot provide satisfactory accuracy, two methods are used here and compared to obtain more accurate estimates. The two methods are the estimation by the repairer and the determination of the age using the type plate.

The device categories selected were cathode ray tube (CRT) screens, flat screens (all technologies), computers and notebooks.

The underlying model is shown in Figure 1. After the import, the device is stored before it is being used. After failures, the device might be repaired multiple times before it is prepared for dismantling or recycling.

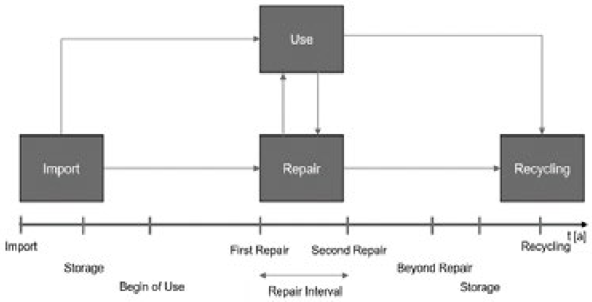

Figure 1: Lifespan Model for Second-hand Markets

4 Results

The results of the interviews provide a wide range of analysis options. In the following, some relevant results are summarized on the topics of typical device errors, education, success factors and costs. In addition, the total lifetime data for the category flat screens are evaluated.

4.1 Lifespan sample

In the course of the study, the lifetime of 82 devices was determined using the method developed in section 3.2.

The results are presented for flat panel displays only as one of the four device categories examined. In Figure 2, the data for imported flatscreens is widely scattered, 50% of the devices in the sample are between 2 - 7 years old. When looking at the dismantled televisions, the data is clearer. No flat panel display has been scheduled for dismantling before the age of 10 years. 50% of the flat screens are scrapped at the age between 11- 13 years. The age of flat screens in the repair shop is the most widespread. If the medians are used, a flat screen was 4 years old when imported, 8 years old in the repair shop and 12 years old when scrapped.

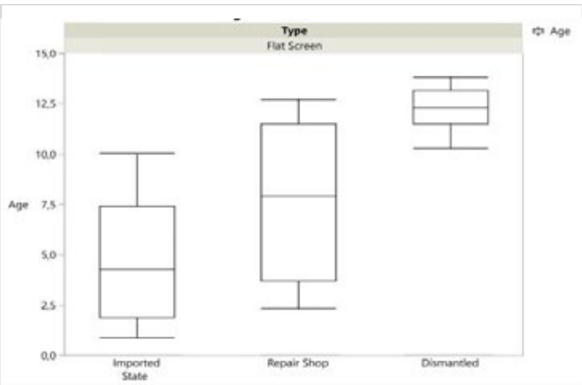

Figure 2: Flat Screen Age(n=25)

The repairers were able to determine a typical repair interval based on their experience. Sometimes the repaired device comes back shortly after a repair due to either not sufficient repair or a new fault related to the previous repair. The typical repair interval is based on successful repaired devices coming in with a newly developed fault.

Repair Interval	Average + Std.Dev
CRT Screens	5,8 ± 2,7 a
Flat Screens	1,8 ± 0,5 a
Notebook/Computer	4,0 ± 0,8 a

Table 1: Repair Interval (n=27)

Table 1 shows that CRT screens require repairs much less often than flat screens. Computers run an average of 4 years bevor there is a repair needed. Repairers stated they repair a device a multiple times before the owner replaces the device. No repairer assumed that there is a bathtub curve with many increasing aging failures and therefore the repair is no longer worth it. Most of the time a device is replaced when the owner buys a new one to get more functionality or better technology and not when the old one is beyond repair or breaks down too often.

4.2 Typical Failures and Repairs

The most common repair issue reported by the interviewed repairers was the power supply of the device. There are several reasons for this:

1. Inside the power board there are the highest currents in the whole device and therefore a lot of heat generation, which leads to higher failure probabilities of the electronics.
2. The quality of service in Ghana's power distribution network is poor, with frequent power failures, large fluctuations in grid frequency and voltage and inadequate lightning protection. This leads to faster degradation of power supply components.
3. The general humid and hot environment together with dust leads to faster failure.

The power printed circuit boards (PCBs) are often made with discrete through hole mounted capacitors, resistors, and integrated circuits with a low level of complexity. Therefore, it is relatively easy to diagnose failures by optical inspection or measurement with ordinary multimeters. Replacing the non-functional parts is also possible with a soldering iron. The mostly standard spare parts can be obtained easily. Figure 3 shows the typical failures based on 29 repairer statements.

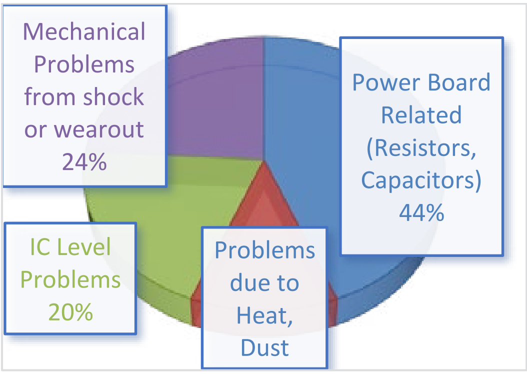

Figure 3: Typical Failures (n=29)

After the failure the repairers reported that the need to choose between exchanging an individual discrete component or an entire functional unit or PCB. But the acquisition of needed spare parts is always a challenge, as there are only few commercial spare part dealers in Ghana.

Spare Part Origin	Percentage Mentioned (%)
Harvesting from old devices	62%
Shops in town	56%
Driving to Accra (t>2h)	20%
Online (in addition)	12%

Table 2: Spare Part Origin (n=29)

As Table 2 shows the repairers rely on different strategies to organise spare part. The majority uses harvesting of spare parts from defective devices in their storage. This is by far the most often used and cheapest option. In case of special function integrated circuits (IC's), repairers rather search for another identical device instead of buying the spare IC online. The cost of online orders is very high due to shipping and a credit card is needed, which is expensive and difficult to obtain, as many Ghanaians don't have a bank account.

4.3 Education

The average professional experience of the interviewees is about 14.4 years. Junior repairers start working in a workshop as an assistant or apprentice after their school education at the age of 17-24 years, typically completed after 3 years. After a phase of 3-10 years, they either start their own workshop or take over the business when the leading repairer retires. The average age of the interviewees was 37 years, which is relatively high compared to the Ghanaian average age of 20,7 years in 2015. 80% of the interviewed persons have attended a senior high school and most of them have even successfully completed high school, which is an extremely high number in relation to 14.7% high school attendance in the Ghanaian population as a whole.

The sample data revealed that 83% of the repair workers interviewed have only been informally trained. The Ghana Living Standards Survey shows that 85% of all workers in craft or trade business have been trained informally on the job (*Ghana Living Standards Survey Round 7 (GLSS 7)*, 2019). This is very close to the number found for the electronics repair sector which is 83%.

Only 4 of 29 interviewees have attended formal training in electronics or repair either with a Higher National Diploma or a certificate course at a private institution. They often work as experts in larger stores or are providers of complex special repairs. Specialist training leads to a significantly higher income.

4.4 Repair Costs and Income

Most repair costs are related to spare parts. Repairing a cathode ray tube TV very rarely costs more than 10€, as all components are easy to handle mechanically and once the fault has been found, they simply need to be replaced. The situation is different for technologically complex main boards of flat screens or computers. Here, only specialised experts can diagnose and solve the problem. Often the complete circuit board is replaced, which leads to significantly higher costs for the spare part.

Device and Fault	Cost [€]
Television (Flat/CRT)	
Power repair	5-10
Mainboard exchange	20-50
Computer/Notebook	
Power, simple IC faults, CPU reflow	6-10
Complex IC reprogramming	<20
Phones	
Button faults	3
Charging System, Microphone, Battery	5-10
Display change	<16

Table 3: Typical Repair Costs (n=25)

The minimum income observed of 42€ per month, while the maximum observed income was 216€. The minimum income of 42€ per month is below the 2$ per capita per day poverty mark of the United Nations

(UN). The maximum observed income of 216€ was well above the average gross domestic product per capita of 115€ in 2018, which is given by the UN for Ghana as 1,517$ per year.

4.5 Factors of Success

The repair ratio (RR) is an indicator for assessing the performance of the repair sector. The average repair ratio is 83%. Each interviewee had a success rate of more than 60%. It can therefore be assumed that repairers who can repair less than half of the equipment will resign their activities sooner or later. RR is also significantly related to the problems being worked on. The highest success rates of 95% are reported for Cathode Ray Tube (CRT) screen repairs, as these hardware repairs are technologically simple. For complex software problems, especially on computer mainboards, the RR is in the range around 70%.

5 Discussion

In the following the results are discussed. First, the success factors are assigned to the research and compared with other studies. Then the lifespan data obtained and the methods are critically questioned and examined. Subsequently, improvement factors and criteria for new purchase and repair are discussed.

5.1 Factors of Success

The introduced Repair Ratio works best for understanding the complexity of repairs rather than individual qualification of the repairer. An experienced senior repairer working on overly complex problems might have a lower RR than an intermediate repairer working on CRT screens.

However, the estimation of the Ghana E-waste country assessment from 2011 was that 70% of the repairs are successful, which extend the lifetime of the appliances by 1-2 years. This estimation seems to be too low, as this research shows a success rate of 83%. The discrepancy may be due to the different composition of the repaired device types, as the success rate varies depending on the device type. Unfortunately, the exact sample composition is no longer traceable, therefore the reason for this variance can hardly be found.

The more useful factor than the RR, would be the income and the availability of tools for special repairs. Formal education in the field of electronics leads to a higher income and the repairers work on more complex problems.

5.2 Lifespan Sample

Due to the small sample size and uncertainties about storage times, the results have limitations. Also, results are depending on technologic differences. Since data of multiple product and technology generations are considered, they are highly dependent.

The aim of this analysis was not analysing the lifespan accurately but rather showing that devices are exported with the intension of using them. Media reports often suggest that electronic waste is exported for recycling. The aggregate data indicate that this is not the case, but that the focus is on further use.

Neglecting the scattering of the values in Figure 3, as well as possible storage times, tripling of the lifetime of a flat screen is possible. Including the typical repair interval from Table 3 the flat screen is repaired three to four times during the extended service life in Ghana. These results can be additionally verified by the fact that end of live devices almost always show signs of repairs. However, it is difficult to estimate the number of repairs from a dismantled device as not all repairs are clearly visible and it is not noticeable how often the device was opened and repaired.

5.3 Improvement Potentials for Repair

About one third of the interview partners critisised the quality and availability of spare parts. There are almost no quality controls on new imported spare parts. Some repairers state that they prefer harvested spare parts from old CRT televisions over the brand-new ones because they last longer.

More than two-thirds of the repairers need special tools to carry out more types of repairs. These include, in particular, analysis equipment that can easily diagnose faults on circuit boards, but also special tools for repairs.

Education is crucial in this field. Some repairers stated that they need further training in order to be able to repair modern devices with complex technologies. Learning on the job is daily business but might not be sufficient for dealing with every new technology.

5.4 Repair or new purchase

A number of factors play a role in the end customer's decision whether to repair a defective device or purchase a new one instead. In most cases the device is repaired until the owner has enough money for a new (used) device. The costs for a repair are significantly lower than for a new purchase, which is why this procedure seems to be reasonable. The other factors for a new purchase are technical actuality, functionality, optical design and others.

5.5 Outlook

The results found in this work apply specifically to the South of Ghana and may not be transferable to other countries of the global South. The results for the lifetime evaluation are not accurate due to the small number of samples and require comprehensive further evaluation. In LCA calculations, reuse in the global South is currently only being introduced in a few cases. If this area is investigated further, the data could be incorporated into the considerations and allow a more refined analysis.

Increasingly, even in Ghana, repairs are no longer cost-effective compared to new purchases. This is especially true as manufacturers also offer inexpensive new products specifically designed for developing countries. Possibly this will lead to the disappearance of commercial repair as was the case a few decades ago in Europe and North America. Further research is needed to find out whether this trend will continue and what solution strategies the repairers are using to tackle it.

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The Role of Trade-in Programs to Close the Inner Loops in the Circular Economy

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Abstract

The concept of the circular economy requires a closed loop and consequently the establishment of a controlled flow of (physical) products, parts, components, and materials.
As of today, usually this flow becomes disconnected at the very moment the final user decides to turn a particular device into e-waste or to put it into hibernation mode without ever being re-activated. The implementation of the concept of Extended Producer Responsibility calls for such waste equipment to be collected and recycled responsibly, under the financial responsibility of the producers. However, in practice third party companies – such as take back schemes or compliance systems – most often conduct these activities.
Producers contract these parties, possibly audit them and their downstream partners on a regular basis, but rarely (re-)direct the flow of processed materials, or recover "own" secondary raw materials from their "own" products at End-of-Life (EoL). Instead, a common path is to purchase recycled material from the market, if manufacturers decide - or might even be required - to use such in proprietary manufacturing processes.
The authors locate this execution by third parties within the "outer loop" in the circular economy, while considering activities and flows moved by the producers to the "inner loops" to be even more advantageous for the transition to a circular and sustainable system. This paper details the procedures to be established, and discusses benefits of an inner loop approach. It focusses on trade-in programs, which especially enables producers to source the required materials as well as (spare) parts directly from end-of-use products.
The authors conclude that trade-in activities, when run by producers and manufacturers, can be a substantial contribution to the transition from a linear to a circular economy.

1 Characteristics and Utilization of Trade-in Programs

Originally, trade-in programs used to be marketing instruments to encourage consumers to purchase replacement products. Through such sales promotion techniques, retailers offer a fixed discount on the price of a new model or item in exchange for an older product of the same type being returned by the customer. The buyer is obliged to return the old item and receives a certain reimbursement in return, be it cash or a voucher or a similar benefit. Car dealers use this instrument frequently, but it is also quite common in the consumer electronics and IT industry.

Trade-in works well to push sales of certain products and technologies:

- Items requiring instant replacement once being functionally or technically obsolete. These are primarily products found only once per household (e.g. fridge or washing machine), as there is no need for redundancy.
- Brand products sold at comparatively higher price ranges, while less expensive alternatives are available on the market (especially in the electronics industry with multiple options available).
- Products with short innovation cycles providing new features (upgrades) to the consumer with each new product generation, i.e. smart phones and tablets.
- Products strongly affected by psychological obsolescence, e.g. customizable items with particular features representing latest fashion and/or design trends.
- Personalized products, associated with private memories or emotions, delivering additional value to the owner. The "felt" monetary value of these devices often exceeds the offered price on trading platforms for used devices.

A screening of offers available through the internet delivers evidence for the frequent use of this sales promotion instrument by various well-known players from the electronics industry. On-line offers are readily available, among others, from Samsung [1], Apple [2], Lenovo [3], Amazon [4], Best Buy [5], Nokia [6], HP [7], and Dell [8].

Compared to regular discounts given up-front at the point of sale (POS) by retailers, there are several advantages of such trade-in programs, which make this sales technique attractive for the producers and brand-owners:

- The new product can be advertised and sold at the original (higher) price at the POS, as the benefit may be provided to the customer separately or later. A downward spiral of discounts and price races to the bottom are avoided.
- The sales offer and price is controlled by the producer (brand-owner) – not by the channel partner or retailer.
- Campaigns are run on-line and allow comparable offers in different geographies and markets.
- Such programs allow for “de-marketing” of other brands, i.e. accepting trade-in units of competitors, and hence decreasing their share in particular markets. For products such as printers, this may consequently influence the sales of consumables (printer cartridges). With de-marketing, certain product series may disqualify for continued technical support and services due to declining demand.
- Finally, trade-in programs are an effective tool to identify and target specific used products in the market, e.g. of the own brand. This instrument allows for a selective sourcing of particular used models or equipment types. Trade-in programs provide the possibility to offer specific incentives to encourage consumers to return equipment of a certain kind that might be required to harvest valuable spare parts or to recover particular materials.

2 Steering Material Flows in a Circular Economy

We have seen that in the past, trade-in programs have been mainly used to push sales of new products. The return of the old product merely serves as vehicle to provide a monetary incentive to the buyer. The return product itself was not in the focus. In the light of circular economy principles as such, this provokes the idea of utilizing a trade-in program for targeting certain products to close the loops. The central question arises: Do trade-in programs provide the potential to foster and accelerate measures required in a circular economy such as closing (material) loops?

Any existing economy system (unless those that are completely run virtually) relies on the physical flow of materials and products. In a circular economy, as for example outlined by the Ellen MacArthur Foundation [9], such flows may take several rounds but finally shall be supplied to a production process again.

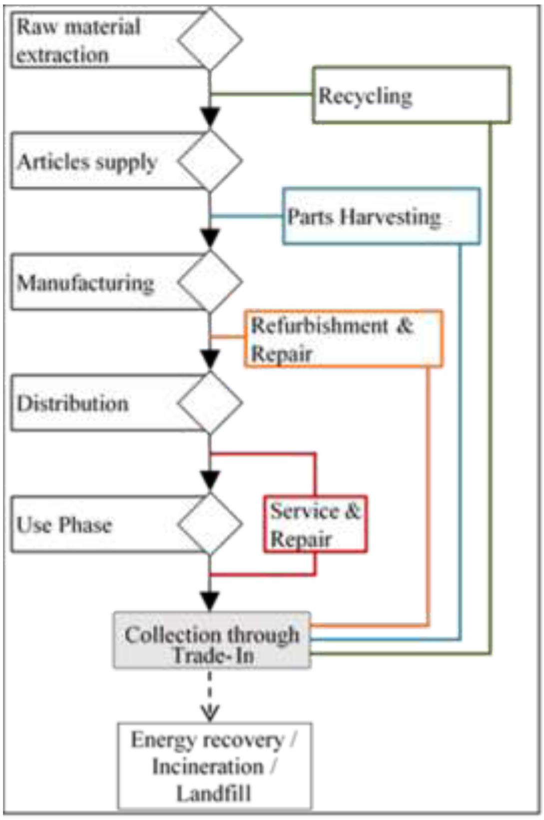

Figure 1: Simplified Circular Economy System Diagram for Flow of Technical Materials

2.1 Today’s Situation of “End-of-Life” Products in the Outer Loop

The concept of the circular economy requires an uninterrupted and controlled flow of (physical) products, parts and materials.

As of today, usually this flow becomes disconnected at the very moment when the final user decides that a particular product has turned into “waste”. The implementation of Extended Producer Responsibility calls for such waste equipment to be collected and recycled responsibly, being financed by the producers. This is mostly positioned in the outer loop “Recycle” (see illustration above): However, usually third party companies – such as take back schemes or compliance systems – conduct these activities.

Producers contract these parties, possibly audit them and their downstream partners on a regular basis, but usually do not (re-)direct the flow of processed materials, nor do they claim their "own" secondary raw materials back. Instead, they would need to purchase recycling material from the market, when they want to – or are required to – use such in manufacturing processes.

2.2 Moving the Technical Materials to the Inner Loops

The inner loops – relating to "refurbish/remanufacture" and to "reuse/redistribute" – often are not steered either by producers or by manufacturers, though controlling such activities and flows in these inner loops would be more advantageous for the transition from the "end-of-life" thinking of a linear economy to a circular and sustainable system.

There are several motivations for the producers to increase their activity in these inner loops, in a regulatory context but also apart from that.

2.2.1 Regulatory Influence in the European Union

Through the recently announced European Green Deal [10], the European Commission have expressed their commitment to continue and accelerate the transition towards a circular economy. The newly adopted "Circular Economy Action Plan" [11], being one of the key actions of the European Green Deal, is an important initiative to increase the circularity of the EU's economy. Among other resource-intensive sectors, it shall focus particularly on electronics:

"The circular economy action plan will include a 'sustainable products' policy to support the circular design of all products based on a common methodology and principles. It will prioritise reducing and reusing materials before recycling them. It will foster new business models and set minimum requirements to prevent environmentally harmful products from being placed on the EU market. Extended producer responsibility will also be strengthened." [10]

Further measures that the sustainable products policy shall address and encourage businesses to implement are:

- Mandatory recycled content
- Re-usability
- Repairability
- Durability vs. pre-mature replacement / obsolescence

Public authorities, including the EU institutions, are encouraged to purchase more sustainable products that match such criteria ("green public procurement", GPP). The proper utilization of trade-in programs can support producers and manufacturers, as well as distributors, to meet such requirements, i.e. by sourcing used equipment through a trade-in offer, refurbish it in-house or through accredited and qualified third parties, and offer the remanufactured devices in a public tender.

An example is Germany's Federal Environmental Protection Agency (Umweltbundesamt), which recently published GPP-guidelines related to the content of recycled plastics [12]. Trade-in mechanisms may support the sourcing of a sufficient volume of specific equipment or particular materials to feed them efficiently into re-use and recycling operations.

2.2.2 Producers' Initiatives and Motives

As long as the "Extended Producer Responsibility" – especially for WEEE – can be covered by joining Producer Responsibility Organisations (PRO, also known as collection, take-back, or compliance schemes), there seems to be not much need for producers to engage in additional return programs or own recycling initiatives – at least from a compliance perspective. From a financial perspective, the cost of joining a PRO are more or less predictable to calculate as they mostly relate to the put-on-market volume. The management of the material (return) flow and treatment, i.e. supplying it back into recycling procedures, is left to the PRO – the producer, manufacturer or distributor usually is not playing an active role in recovery operations.

On the other hand, some manufacturers and producers have realized the benefits of "proprietary" closed loops already many years ago, especially in the case of consumables. In 1990, Canon started a cartridge return program to supply an in-house recycling plant, where parts incl. plastics are dismantled and re-used in the manufacturing of new printing supplies [13]. BRITA is running a recycling program for water filter cartridges since 1992 [14]. From the returned devices, BRITA states that they are able to regenerate 100 % of the ion exchange resin, which is then completely re-introduced for the same purpose in new original cartridges.

Most often, brand owners offer such consumables collections programs without charge to the consumers, but also without benefits – apart from the promise that participation contributes to an environmental friendly and sustainable initiative. However, the lack of appropriate incentives may result in low return rates not being sufficient to supply recycling procedures at an adequate scale. When HP introduced a closed loop initiative for hardware products [15] – with the goal of producing printers with significant recycled plastics content stemming from "own" sources – , buyers were offered a 15 % discount for a new printer when returning an old one.

These examples have in common that the initiating manufacturers receive a pre-selected stock of used equipment with a high share of products of which the composition material quality is known – as they were designed and produced by themselves. Obviously, it is more efficient to run recycling and remanufacturing procedures with input materials of known quality as it reduces the effort for extensive testing and analysis and creates higher material recovery rates in the inner loops.

3 Required Procedures

Closing the material cycles in a circular economy requires moving products and materials physically and it may lead to a change of ownership. As users want to "get rid" of their equipment – from their perspective – at "end of life" of the particular device, it is then by definition turning into waste at that very moment. Therefore, the receiver of such device may become a "waste owner" and subsequent activities are conducted in the régime of "waste treatment".

Trade-in programs support such transfer from the utilization phase to a (waste) treatment phase. Subsequently, they shall implement activities that make waste devices lose their waste characteristics and allow them entering again into a new utilization phase. Such "end-of-waste" approach requires certain procedures, as outlined in the following.

3.1 Specific Communication upon "End-of-Life"

Towards the end of the utilization phase, it is important to have well-informed consumers. They need to be aware of the options where and how to dispose of or return their "end-of-useful-life" equipment, choosing those that are beneficial to the concept of circular economy and closed material loops. Offering trade-in programs provide guidance to consumers to return their old device to particular loops. The granted trade-in incentive reinforces the willingness to participate.

Sufficient communication and interaction with the customers is a precondition for making trade-in programs successful. Naturally, this is of the case for current programs that serve as sales promotion techniques. The needed tools, such as internet presence and web portals, are already available and a daily and omnipresent matter of course. They can be used easily to raise awareness among consumers and enabling their participation.

3.2 Collection Phase

The concept of trade-in programs includes the physical return of out-dated equipment (in contrast to so-called cash-back promotions that provide financial benefits to buyers simply for participating). Hence, the provider needs to implement and run a reverse logistics systems to collect the equipment from the participant. Basically, this can be realized through a sent-in as well as by a pick-up service. Either way, providers have to consider that possibly they are collecting – by definition – actually "waste" and not "goods" anymore.

In the case of "waste", the providers and their sub-contracted transporters are required to follow certain waste-related rules when collecting and shipping the product, i.e. considering the WEEE (waste electrical and electronic equipment) regulations in case of electrical or electronic devices. If the intended place for the next step of "waste treatment" (e.g. a sorting or refurbishment site) is located abroad, the implemented reverse logistics procedures have to comply also with international regulations on transboundary shipments of waste, such as the multi-lateral Basel Convention [16] or the European Regulation No. 1013/20106 on shipment of waste [17].

3.3 Leaving the Waste Régime

Obviously, in a circular economy there needs to be a point of time when "waste equipment" (e.g. WEEE) ceases to be waste and turns (back) into a material or product. For the European Union, the Waste Framework Directive No. 2008/98/EC [18] lays out the applicable procedures, e.g. particular recovery operations (R1 to R13) as listed in Annex II, including recycling operations. If these procedures adhere to end-of-waste criteria (detailed in Article 6), the treated ("recovered") return unit obtains (again) a status of a product or a secondary raw material.

Article 6

End-of-waste status

1. Certain specified waste shall cease to be waste within the meaning of point (1) of Article 3 when it has undergone a recovery, including recycling, operation and complies with specific criteria to be developed in accordance with the following conditions:

(a) the substance or object is commonly used for specific purposes;

(b) a market or demand exists for such a substance or object;

(c) the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and

(d) the use of the substance or object will not lead to overall adverse environmental or human health impacts.

The criteria shall include limit values for pollutants where necessary and shall take into account any possible adverse environmental effects of the substance or object.

(...)

Figure 2: Article 6(1) of EU Waste Framework Directive listing end-of-waste criteria [18]

Hence, a trade-in program that aims to foster a circular economy approach, needs to incorporate an appropriate (pre-)sorting process as well as efficient (material) recovery procedures, to be able to "produce" secondary raw materials and spare parts that can be diverted into new product manufacturing. A well-defined sorting process can even detect equipment that may directly enter into re-use or refurbishment channels for complete products.

4 Specific Advantages of Trade-Ins

Considering the given and expected regulatory circumstances as well as the required procedures, as outlined above, the mechanisms of trade-in programs are beneficial for closing and accelerating the loops (especially the inner ones) in a circular economy.

4.1 Targeted Sourcing

By fine-tuning the incentives and participating conditions (e.g. superior benefits for certain return models), the trade-in program can be amended to a tool for targeted sourcing. It encourages not only higher return rates but also facilitates a pre-selection of preferred return units, as well as prioritization in accordance with the "waste hierarchy":

1. Used products of specific models or product series that notably qualify for upgrade, repair, or refurbishment,
2. Particular end-of-life products that include spare parts being suitable for direct re-use or refurbishment,
3. Certain end-of-life products that contain desired materials, e.g. metallic bonds or recyclable polymers (with known specifications) used in retired product series.

4.2 Quality of Returns

The quality of devices returned through a trade-in (or otherwise incentivized) promotion is usually higher than of those received explicitly for recycling. That is because trade-in devices need to match certain criteria in order to qualify for the (financial) benefit. For example, the program provider may require the participant to wrap and pack it properly when sending it back, and to include essential accessories (e.g. power supplies). This increases the likeliness of the return product being suitable for refurbishment, repair or reuse.

4.3 Targeted Replacement

Besides targeted sourcing, de-marketing has the potential to contribute to the goals of a circular economy, in selected cases. Attractive trade-in offers could improve the collection rate of models with extensive energy consumption and accelerate their replacement with energy-efficient equipment. Whilst leading to net environmental benefits, e.g. the reduction of CO_2 emissions, materials (or potentially complete parts) could be adequately re-purposed. However, the effectiveness of such measures and net impacts on the environment would have to be evaluated on a case-by-case basis.

4.4 Flexibility of Return Flows

The provider of the trade-in program can manage the return flows for products and materials directly (solely considering constraints of waste shipment regulations, if applicable), in accordance with the requirements and locations of involved partners, e.g. for refurbishment or reselling activities. In case such partner network is changing, the return flows can be adapted quickly, e.g. by updating the sent-to information on provided return labels.

4.5 Established (Marketing) Tool

Trade-in programs have a long tradition and are well-known to and broadly accepted by consumers. Many manufacturers and distributor use them regularly as an established tool, having the fundamental mechanisms and communication channels already implemented. It takes comparatively little effort to adapt the existing procedures to the next generation of trade-in programs that – apart from being a sales promotion technique – are capable to support circular economy goals.

5 Summary

Trade-in programs are able to contribute to the goals of the EU sustainable products policy, mainly by supporting product and material return flows in sufficient volumes and adequate qualities. Increasing the availability of (secondary) raw materials is one goal of the European Green Deal, as of today "recycled materials only meet 12% of EU`s demand for materials" [10]. Besides collecting input materials for recycling, trade-in programs facilitate targeting sourcing for re-use, repair, and remanufacturing activities, i.e. the inner loops in terms of a circular economy. To further accelerate and improve the performance of these loops, it will require a modernisation of certain waste laws (e.g. with regard to end-of-waste criteria) and a revision of the waste shipment regulation (which is already addressed in the agenda of the European Green Deal).

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Behind Apple's Ambition to Make Products Without Taking from the Earth

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Abstract

The first three Industrial Revolutions were defined by building things from perceived endless resources. Today, we live in a world of finite resources and we must do more with less. That's why, in 2017, Apple announced its goal to one day use only recycled and renewable material—demonstrating its commitment to conserve the world's resources. To achieve this, Apple studies manufacturing to demand higher process and material efficiency, opened a Material Recovery Lab to enhance recycling technology, invented disassembly robots to liberate materials from devices at end-of-life, and pursues ideas to bring devices back to life in new applications. As a company known to "think different", Apple has taken on this challenge to prove manufacturers can make the best products in the world while leaving the planet better than they found it.

1 Introduction

For centuries, industry has accepted resource extraction as an inevitable requirement of manufacturing. As seen in the example below (figure 1) [1], the extraction of minerals, water and crops have increased exponentially over the 20th century at the expense of increased waste and carbon dioxide emissions. Apple is challenging this paradigm by aiming to make products without taking from the earth.

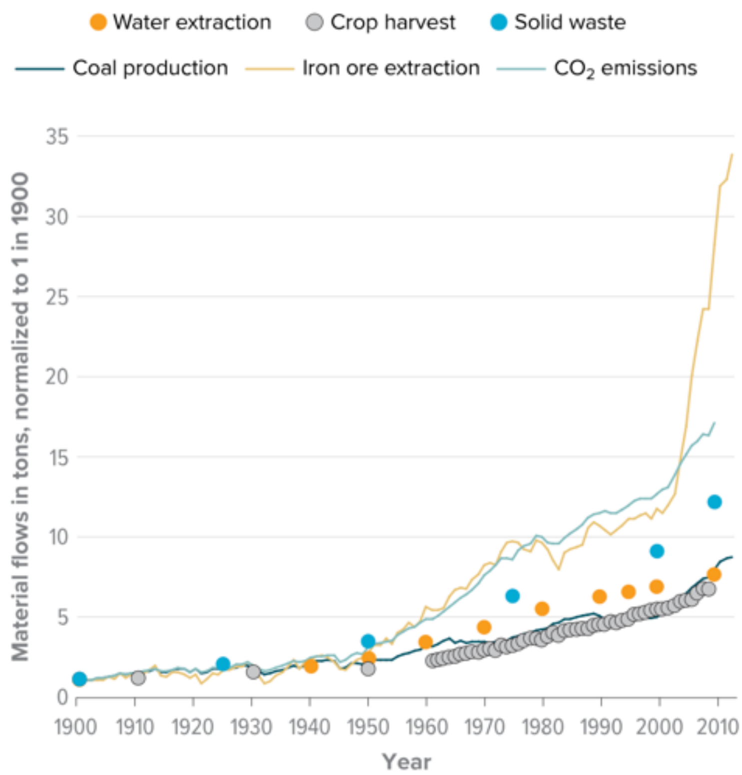

Figure 1: Global Resources Used and Waste produced

2 Apple's approach to resources

When Lisa Jackson, who formerly led the U.S. Environmental Protection Agency, took leadership of Apple's environmental initiatives, the company focused its attention on three pillars: Climate, Resources, and Smarter Chemistry. To better manage resources, Apple prioritizes responsibly sourcing the materials in its products, and minimizing the water its processes rely on and the waste it generates. For example, Apple expanded its corporate Zero Waste to Landfill program to its supply chain, ensuring all the waste created at final assembly sites was reused, recycled, composted, or, when necessary, converted into energy. This effort included the first supplier sites to pursue Zero Waste certifications for Apple's footprint in China.

In 2017, Apple announced one of its most ambitious goals yet: to one day make products using only recycled and renewable materials. To accomplish this, Apple pioneers innovative ways to build its products in order to reduce the amount of material needed. It also designs for durability to make products that last as long as possible, maximize the life of resources used to make the products. Once products reach end-of-life, Apple works with recycling partners to recover the maximum amount of materials. Apple also pursues innovative recycling technologies, like developing a line of robots that are specially designed to efficiently dissemble iPhone devices.

2.1 Building a circular supply chain

Apple envisions a future where its devices are made with materials that follow a circular model eliminating its reliance on mining (figure 1). Rather than continually extracting materials and discarding products at end-of-life, Apple takes the following steps to increase efficiency and have materials flow back into the supply chain:

1. Minimizing material inputs through design efficiency
2. Extending product life by design for durability and product longevity
3. Collecting and recovering the highest quality of materials at end of life
4. Sourcing recycled and renewables materials to create new products

Within this framework, Apple identified a set of materials upon which to focus its efforts. Apple didn't start with materials that were easiest for transitioning to recycled and renewable sources, but those that would result in the most significant impact. Through extensive analysis on the environmental, social, and supply impacts associated with 45 elements and raw materials, Apple created full Material Impact Profiles for each. These profiles informed Apple's prioritization of 14 materials (figure 2), significant not only for their impacts, but also because of how much Apple consumes. Overall, these 14 priority materials represented nearly 90 percent of the total mass shipped by Apple in fiscal year 2019.

With these 14 priority materials identified, Apple set out to create products more efficiently and make them more durable using only recycled or renewable material. For finite materials such as aluminum or steel, this means both sourcing recycled material and recycling scrap and end-of-life products into raw material for Apple or others to use again. For renewable materials such as the wood fiber in packaging, Apple prioritizes sources that continually produce without depleting earth's resources.

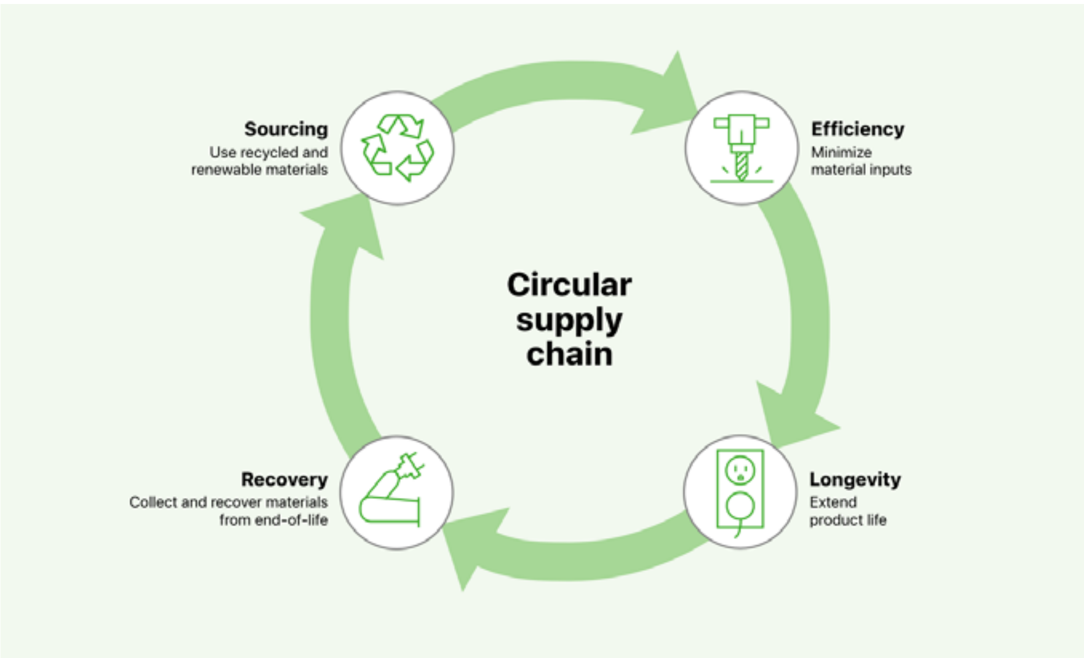

Figure 1: How Apple defines a circular supply chain

Aluminum	Tantalum
Plastics	Gold
Cobalt	Tin
Rare earth elements	Lithium
Copper	Tungsten
Steel	Paper
Glass	Zinc

Figure 2: Apple's priority materials

3 Innovation in Recycling

Critical to the success of Apple's closed loop supply chain is the efficient recovery of materials to the same quality as the original primary source. Technical and economic hurdles can prevent this, and developing new recovery technologies, new materials, and new ways of doing business is required to achieving Apple's goal.

3.1 The Next Generation of Recycling

Building from its learnings of its first disassembly robot, Liam, Apple debuted a new recycling robot named Daisy in 2018 (figure 3). More robust than her predecessor, Daisy is capable of disassembling fifteen different iPhone models, processing up to 200 iPhones per hour (figure 4). Daisy represented a major step forward in Apple's advancement of robotic disassembly in pursuit of material recovery.

Figure 3: Apple's Recycling Robot, Daisy

For every 100,000 iPhone devices, Daisy has the potential to recover:

- Aluminum 1900 kg
- Gold 0.97 kg
- Silver 7.5 kg
- Rare earth elements 11 kg
- Tungsten 93 kg
- Copper 710 kg
- Palladium 0.10 kg
- Tin 42 kg
- Cobalt 770 kg
- Tantalum 1.8 kg

Figure 4: Daisy's material recovery rates

With the output fractions generated by Daisy, Apple sent the high-quality aluminum housing fractions back into its upstream supply chain to contribute raw material for the creation of new MacBook Air housings. Had the Daisy-destined iPhones gone through traditional recycling, the housings would have been shredded alongside other fractions resulting in a mixed alloy unable to meet Apple's specifications for making a new enclosure.

Daisy demonstrated to Apple another key learning — to mobilize a circular economy revolution, participation and innovation from other industry partners and technology producers was a key requirement.

3.2 Material Recovery Lab

To create a model to scale, further discovery and partnership is key. That thinking inspired the launch of Apple's Material Recovery Lab in 2019 with a goal of discovering and proliferating future recycling processes (figure 5).

The 9,000-square-foot facility in Austin, Texas, looks for innovative solutions involving robotics and machine learning to improve on traditional recycling methods like targeted disassembly, sorting and shredding. The Lab works with Apple engineering teams as well as academia to address and propose solutions to today's industry recycling challenges. One of the first launched processes out of the MRL was a semiautomated jig for even more efficient disassembly of AirPods. The new tools were rigorously tested before deployment across Apple's recycling networks. And in a partnership with Carnegie Mellon University, the MRL is also researching applying machine learning to help address part of the recycling challenge. Researchers are developing methods to train automated systems to sort waste in real-time and learn as they go—so the technology can evolve as waste streams do. Any software created from this joint initiative will be open-sourced to help better support e-waste recycling around the world.

Figure 5: Apple's material recovery lab

3.3 Reuse Opportunities

Apple's technical investigations to pursue a closed loop supply chain have highlighted reuse as another key opportunity to reduce material consumption and improve device longevity. Recovered parts that are refurbished and tested to Apple's stringent standards can be used as replacement parts for devices being repaired. This keeps quality parts in use while also reducing the number of spare parts needed. Apple recently piloted a program to collect and ship recovered Apple cables and power adapters to manufacturing sites in Texas and Brazil where they will be used to power production lines. This both extends the life of existing cables and reduces the need for new ones, for cost savings and an environmental win. For other reuse programs, Apple has gotten even more creative. In many Daisy-bound devices, Apple has found integrated circuits that still deliver industry-leading processing, memory, and storage capabilities. Apple realized its developers could use these devices instead of new ones as they design and test apps and software—from developing the latest iOS to enhancing machine learning and artificial intelligence. A pilot program deployed thousands of end-of-life devices—including iPhone, iPad, Mac mini, and Apple Watch—for use by developers at Apple R&D sites and data centers. All these devices continue to perform in the most high-value form possible, before finally being recycled for raw materials.

4 Case Study: Rare Earth Elements

Many of Apple's greatest innovations rely on a small number of earth's elements. This is particularly true of its Taptic Engine, which enables tactile feedback from the user interface on iPhone and Apple Watch devices. The magnets inside these engines account for one of the largest concentrations of rare earth elements within our iPhone devices. However, the processes involved in mining these materials are both labor-intensive and carry environmental impacts. Therefore, in 2018, Apple set out to create a circular supply chain for rare earth elements (figure 6). Success would require innovation in several areas: processes to manufacture magnets made with 100 percent recycled rare earth elements that could perform at the high level our products demand; the ability to recover and recycle rare earth elements; and a pathway to achieve all of this at scale.

Apple started by investigating deep within its supply chain—to businesses operating far beyond the direct visibility of most original equipment manufacturers. It was there that the team made a surprising discovery. Not only was a recycler collecting the scrap generated by rare earth magnet manufacturers, but it had developed a process to recycle this material for reuse. Apple then partnered with a magnet manufacturer willing to try something new: create a magnet with 100 percent recycled rare earth elements. While many magnets contained small percentages of recycled rare earth elements already—often without final manufacturers even knowing—no one had used recycled rare earth elements exclusively. Apple's material scientists analyzed the newly manufactured magnets to better understand their performance and put them through our rigorous performance tests—and they passed.

But building a high-performing magnet was not the only task. Apple also had to create an entirely new supply chain solely for recycled material. This meant connecting each of the players—the recycler, magnet manufacturers, component manufacturers, and final assembly suppliers. And they created a way to trace the material through each node in the supply chain. With the help of all its partners, Apple was able to bring a pilot to scale—and released our iPhone 11, iPhone 11 Pro, and iPhone 11 Pro Max with 100 percent recycled rare earth elements in the Taptic Engine. Since Fall 2019, Apple has expanded the use of 100 percent recycled rare earth magnets to the AirPods Pro Wireless Charging Case and iPhone SE.

Creating a fully circular supply chain also meant recovering rare earth elements from manufacturing scrap and products at end-of-life. Following learnings from Daisy, Apple engineers created a new

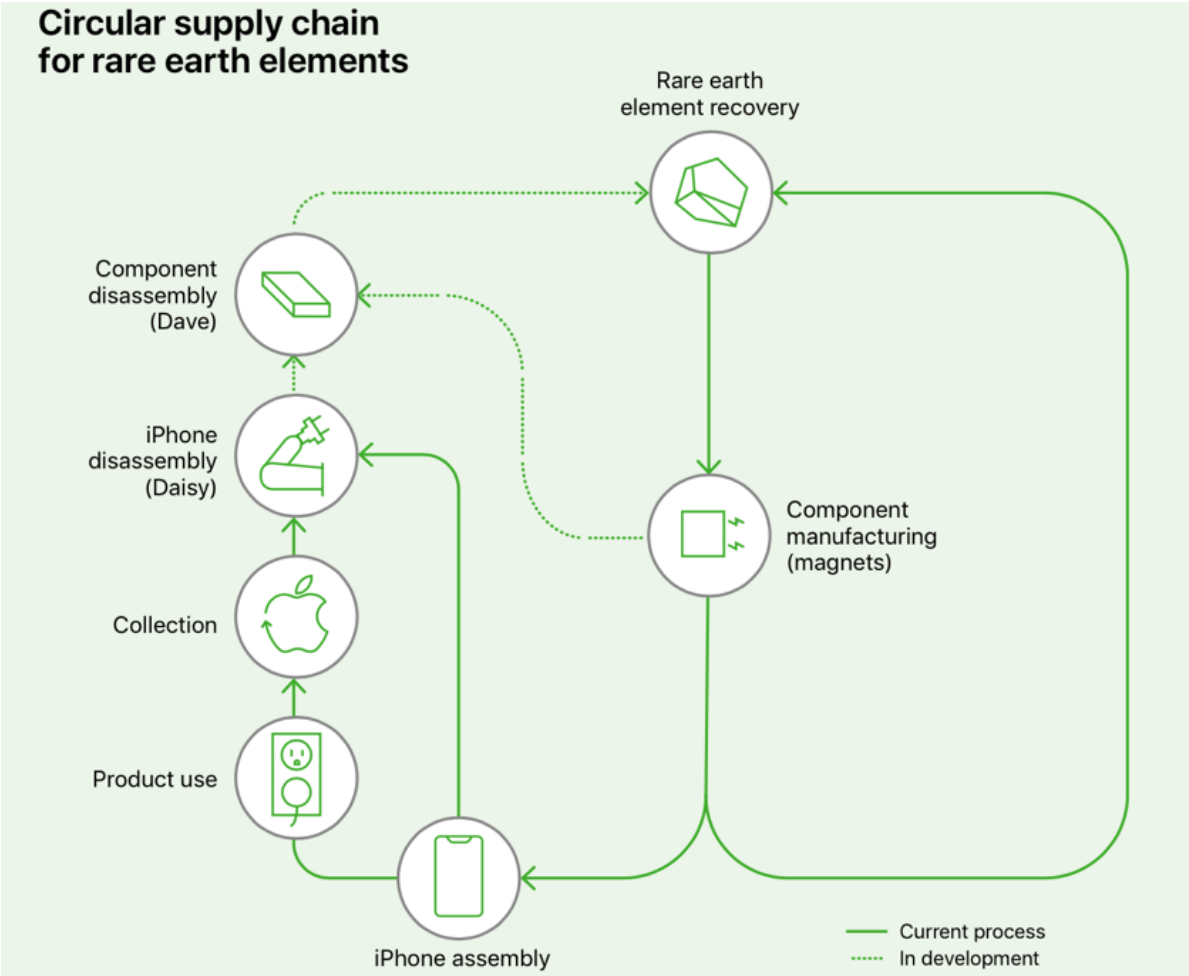

Figure 6: Rare Earth Element Circular Supply Chain

disassembly robot, Dave, to take apart the Taptic Engine and recover the rare earth magnets inside - materials previously lost in traditional recycling. Apple has begun deploying Dave robots at specialty recyclers who can recover recycled rare earth elements and tungsten, while also enabling recovery of steel.

5 Operational Challenges

While technical advancements and case studies like recycled rare earths propel Apple toward a true closed loop supply chain, real operational challenges persist. One set of obstacles are policies that were written to address the negative impacts of waste, but now have the unintended consequence of limiting the movement of materials for recovery and reuse. Waste shipment regulations offer important protections to people and the environment around the world. They were created to respond to the dumping of waste in particularly vulnerable communities. However, it turns out that in many cases, it is easier to move materials newly mined from the earth around global supply chains than it is to move materials for recycling. For example, bauxite rocks—roughly 20 to 25 percent of which will turn into aluminum and which require mining, crushing, chemical processing, and smelting—move more easily than iPhone enclosures separated by Daisy and containing 95 percent already smelted aluminum. Policies treat these materials the same as hazardous waste headed for landfill, even though they are destined for a responsible material recovery operation.

There is an opportunity to strengthen policy to encourage the recovery of material for reuse in manufacturing, and to improve the economics of activities that can reduce the waste burden to begin with. Retooling these regulations can make circular supply chains more competitive with traditional linear supply chains—by responsibly fostering recycled material supply flexibility and competition. Without this policy innovation, circular supply chains will remain niche projects, unable to truly scale in a way that competes with dynamic, global, and linear supply chains.

6 Conclusion

So, how far has Apple come in its journey to create a closed loop supply chain? Based on supplier reports, 10 percent of the total material Apple shipped in products in 2019 came from either recycled or renewable sources, one-third of which has been confirmed through third-party certifications. And because certain materials have a high percentage of recycled content on average in the industry—like steel—the actual amount could be much higher. Four products launched in 2019 were made of 17 percent or more recycled and renewable content, led by MacBook Air with Retina display with more than 40 percent recycled content.

There is no question Apple has many technical and commercial challenges ahead to realizing its ambition to no longer mine materials from the earth. However, it is making real progress and creating a template that proves manufacturers can produce responsibly without extracting precious resources.

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Efficient Use – An interdisciplinary framework towards the cascade use of electronics

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Abstract

Despite the increased awareness on sustainability, product life cycles of electronic products are getting shorter. Consumers today have a traditional linear economy attitude (make, use, dispose) which is inherently unsustainable. This leads to an enormous amount of waste electrical and electronic equipment (WEEE). Furthermore, the production of new electrical and electronic products in low-wage countries is often cheaper than repair, refurbishing, and remanufacturing processes in high-wage countries like Germany. In this paper, we present an interdisciplinary framework for industrial decision-makers with the aim to reduce WEEE by increasing the product lifetime through innovative cascade use. Therefore, sustainable business models for the circular economy will be conceptualized taking into account the retro-production and supply chain as well as the information exchange and connection between stakeholders through a digital ecosystem.

1 Introduction

The fundamental characteristic of the current industrial economy is a linear model, a 'make-use-dispose' pattern, instead of conducting a Circular Economy (CE), and throughout the industrial revolutions, this has not changed [1]. However, despite the increasing awareness about sustainability, the consumption of finite resources and threats such as climate change and scarcity of resources, product life cycles still remain very short and in consequence current industrial economy still mainly relies on this linear pattern [1]. In a very short period of time, electronics and electronic products have become an essential part of our daily life. Even though many people desire to purchase used electronics or repair their products that are out of warranty, repair, or reconditioning is usually not considered. Furthermore, shorter innovation cycles generate new customer needs leading to an increasing demand for product manufacturing of electronics. Thus, the lifetime of these products often depends more on the consumer behaviour and their wishes for new products than on the technical lifetime of the product itself.

The prognosis for the scale of the resulting e-waste problem predicts a new peak in 2021 with 52.2 million tonnes of waste electrical and electronic equipment (WEEE) [2]. This already results in considerable environmental impacts and resource losses, which could be avoided by a closed-loop system based on optimized cascade utilization. Furthermore, the production of new products in low-wage countries is often cheaper than the repair, refurbishment and re-manufacturing in high-wage countries [3]. In contrast to short lifetime, the repair and refurbishment is costly due to a large variety of electronic products available and missing design for disassembly. Therefore, repairers and refurbishes need much more time to repair the products due to missing repair information and spare parts. Consequently, establishing a CE requires just not an elementary change in consumer behaviour towards buying the newest products, but also new business models, optimized processes and methods to keep products and materials as long as possible in use. With the striving for CE, the traditional business models need to be developed into circular business models [4].

There are various approaches for conducting a CE existing such as [5], [6] and [7]. Although the CE is receiving attention, a comprehensive, interdisciplinary approach for optimized cascade utilization and extended utilization of electronics is still missing. Therefore, *this paper presents an interdisciplinary framework for industrial decision-makers with the aim to reduce WEEE by optimized cascade utilization and extended utilization with a vision of keeping the electronic products as long as possible in use.*

The outline of the paper is structured as follows: Section 2 gives a brief overview of the research state and demands. Section 3 describes the proposed interdisciplinary framework in detail. Section 4 shows initial reflections of how the proposed framework can be applied to different cascades and circular business models in practice based on two industrial cases.

2 Theoretical foundations of CE for electronic products

CE describes the idea to transform a linear system into a closed-loop/ circular system [8]. In conventional linear systems, the products are made, used, and finally disposed of. However, resource scarcity and emissions of the production necessitate a different approach since products consolidate resources [9]. Therefore, CE extends the linear approach by reuse, remanufacturing, and recycling of spent products in global reverse networks. To support this, materials, product design, production, and the use of the products need to be modified to enable an efficient CE [4]. Such systems aim to keep products, components, and raw materials as long as possible in the loop [10].

In general, products pass different stages in terms of a cascade use (see Fig. 1). After the *production* (0) of the virgin product, the first cascade is the initial use. Afterward, a variety of different cascades can be realized [11].

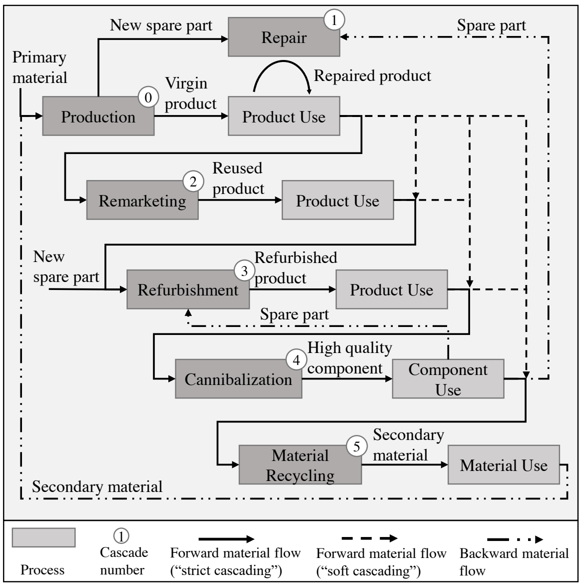

Figure 1: Cascade use of electronics

First, while the product remains with the customer, *repair* (1) can extend the initial cascade. Repair aims to restore the function of a product. Therefore, defect parts are replaced or reconditioned. Hence, only a limited amount of parts needs to be disassembled. However, the achieved quality is lower than "new" [12]. Second, after the initial use by the original customer, the product can be *reused / remarketed* (2) by trade between customers or by trade between customers and companies. In this case, the product structure and quality does not change and only the ownership changes. Third, *refurbishment* (3) aims to achieve a defined quality level, which is lower than the production quality [12]. Therefore, all key components are disassembled and tested. Outdated and defect components are replaced. Afterwards, faultless components and new components are reassembled. The supreme level of *refurbishment* is the *remanufacturing*. Here, the created product should reach production quality. Therefore, all components are disassembled and tested. Only components, which are as good as new, are qualified to be reassembled. Often remanufacturing comes with an advanced technology upgrade. Fourth, the *cannibalization* (4) or reuse of components recovers the functional components of a spent product and uses them as spare parts for the repair, refurbishment, or remanufacturing [12]. Fifth, products, which are not used in one of the first four cascades, can be transferred to the *recycling* (5) together with the defect and outdated components. The recycling aims to recover the materials of the spent products and components to use them in the production as secondary material [12]. Therefore, the composition of the entire product is destroyed to separate different materials.

From the view of CE, the products should be kept as long as possible in the first use since then the utility of materials and components is preserved. However, this rule can be broken in the case of major technological leaps, such as refrigerators. In this case, new products consume so much fewer resources during their lifetime that they compensate for the additional resource consumption caused by new production. But for the focus on consumer electronics, such as laptops and mobile phones, a longer cascade utilization usually is ecologically beneficial. Therefore, this exception is neglected for this contribution.

3 Interdisciplinary framework

Cascade use, e.g. repair or refurbishment, is increasingly challenging since circularity covers a broad range of disciplines and stakeholders. The aim of the framework is to extend the product lifetime by utilizing different cascades through a combination of approaches. According to Umeda et al. [5], three tasks can be identified in the life cycle development. Since manufacturer of electronics show limited interest regarding cascade use, our approach focuses on the life cycle planning and life cycle flow design. As part of the life cycle planning, circular business models are identified and developed under consideration of the technical, economic and ecological feasibility. The technical feasibility of the business models is determined by the retro-production systems. Logistical adjustments in the field of network planning are then made to ensure a suitable spare part strategy for the

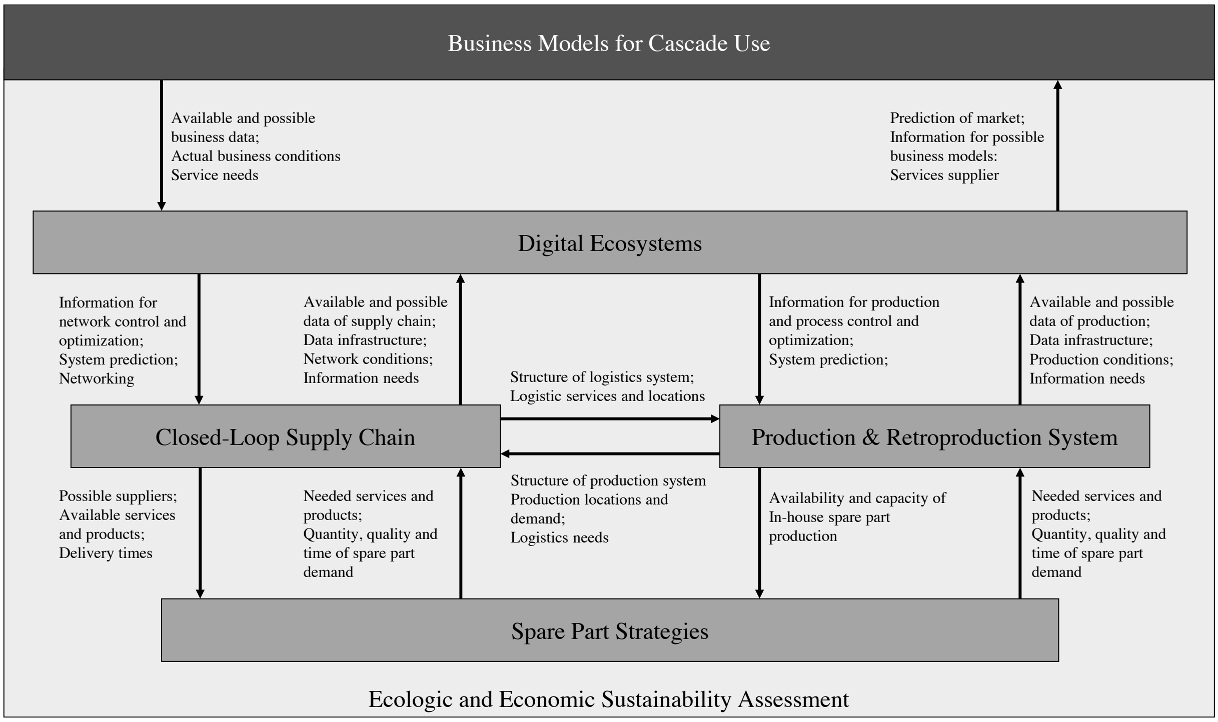

Figure 2: Interdisciplinary research framework to develop circular business models for cascade use of electronics

cascade use of electronics. Due to the complex electronic hardware, the need for software availability and security as well as the connection between relevant stakeholders leads to the development of a digital ecosystem. Consequently, different disciplines are relevant to support cascade use (see Fig. 2).

At the top of the framework are innovative *business models* and product service systems (PSS) (see Fig. 2). PSS are special types of value proposition that need to integrate the customer requirements, servitization strategies and technical solutions for extending the product lifetime. Next, *digital ecosystems* enable a consistent and efficient information flow as the information exchange between relevant stakeholders is likely to increase. At the bottom of the framework, *closed-loop supply chains* and *integrated production and retroproduction systems* focus on the material flows of circular business models. The modified material and informational flow conduct new network structures, e.g. by the utilization of used components as spare parts. Consequently, new approaches for the network and *spare part strategies* are needed to meet the circular business models. Regarding the introduced disciplines, an *environmental and economic sustainability assessment* is implemented in the framework. The economic and ecological optimal depth of repair of used electronics as well as resulting cascading scenarios are analysed.

In order to engineer the elements of the presented framework and to design their complex interactions so that they support CE in an efficient manner, different methods and tools are available to support this process. Furthermore, material and information flows are addressed in the framework in a conceptual manner (see Fig. 2). Here the focus is set on the use as well as end of use/ end of life (EoU/L) phase of electronics. In the following, the elements of the framework and the related engineering methods and tools are presented in more detail.

3.1 Business Models for Cascade Use

A business model is defined as a holistic logic of a company to generate and provide value, including the interaction of resources, stakeholders and relationships between them [13]. Table 1 shows relevant stakeholders associated with extending the lifetime of products. Traditional business models are focused on the selling of a product [14]. Likewise, with the transformation from linear to CE, business models necessitate a shift from ownership to offer also access to functionality and provide benefit- and value-

Table 1: Stakeholders associated with the cascade use of electronics

Material and information flow	Peripheral and regulatory
Components manufacturer	Research & Development
Product manufacturer	Certifier/ test authority
OEM	Software/ service provider
Consumer (new, used devices/ components)	Data protection
Repair service	NGOs
Collection service	Approval/ monitoring authority
Retail and services provider	Policy/ Legislation
Refurbishment service	Border surveillance (customs)
Reseller/ Supplier	
Recycling service	
Logistic	

oriented services [4], [14]. Therefore, manufacturers and service providers need to simultaneously integrate products and services as PSS. PSS as a special type of value proposition is defined as a bundle of interdependent products and services that are capable of fulfilling specific customer needs economically and sustainably [15]–[17].

Based on a life cycle thinking of products and services, PSS have the potential to foster a longer lifetime of products. Thus, this positive impact could evoke uncertainty for the manufacturer as a service provider since the new business models are still not common in economic reality [18]. As the customers decide about extending the use time of their electronic products, they are one of the main decision makers in the CE and the cascading of electronics. Therefore, the customer interests and requirements should be integrated into developing PSS. Moreover, it is necessary to devise incentives by offering PSS for both, the consumer and the manufacturer, to implement the CE. Based on a real life-cycle costs perspective incentives could lead to an optimized energy and consumables consumption and to extend the use time of products and services [15], [16].

To systematically develop new innovative business models, suitable methods and tools are needed to identify the requirements and to organize the complexity of the circular business models. Market conditions, i.e. market structures, customer requirements as well as product and service characteristics need to be analyzed. In addition, existing barriers and their influence on possible market expansions to extend the use time has to be evaluated. As a method, the Business Model Canvas is proposed as it is well recognized and verified in the literature within the context of CE [4], [5], [7], [13]. Given the fact that the development of business models along the aims of CE arises a considerable complexity, an application of modeling notation and simulation can provide suitable frameworks [9]. A systematic analysis of stakeholders and their interdependencies, e.g. by methods and tools of the system of systems engineering (SoSE), need to be conducted. SoSE enables different sub-systems to simultaneously striving for a common goal, i.e. extending the product lifetime [19]. Here, systems modeling approaches (e.g. by using SySML) provide the opportunity to create a model-based understanding of the systems interactions of involved actors. Thereby, the evaluation of these different configurations can be made using environmental or economic evaluation methods, such as life cycle assessment or life cycle costing.

Business models process an extensive amount of information, e.g. actual business conditions and prediction of markets. Therefore, an information system is needed to make complex information and business data available and to visualize it to the stakeholders.

3.2 Digital Ecosystem

One of the main goals of CE is to keep the products as long as possible in use by providing services, such as *maintenance*, *repairing,* and *reusing*. Information and data are central to obtaining the most value of the products. It helps the consumers and manufacturers both to see the true value of the products including the condition and recovery potential [20]. Information and data sharing is often seen as a sensitive topic. But understanding the need for information and developing suitable channels and infrastructure for it can reduce the risk and create more value [20].

An ecosystem in nature is the relation and the balance between organisms and their environment. The environment influences directly or indirectly the life and the development of the organisms [21]. This concept can be transferred to other domains, such as business ecosystems or software ecosystems. Jacobides, Cennamo, and Gawer identified in a literature review three main groups of ecosystems [22]:

- Business ecosystems: centers on a firm and its environment
- Innovation ecosystem: focused on a central innovation and a set of components which support it
- Platform Ecosystems: here, all the actors are organized around a platform.

Missing in this definition was the term software Ecosystem, which is defined as the interaction of a set of actors on top of a common technological platform that results in a number of software solutions or services [23]. In general, all of these ecosystems focus around one central point, a firm, an innovation, a platform or a common software. A digital ecosystem instead is an open community [24].

Within the framework, we define a digital ecosystem as *an open community-driven, loosely coupled union working towards a common goal*. The common goal here is the extension of the product lifetime by supporting the cascade use. The digital ecosystem will act as a center for creating new circular business models and connections for repairers, redistributors, refurbishers, and other companies, which can support their processes. Data and information are at the core of the ecosystem, enabling effective repair, refurbishment, and redistribution. Furthermore, the framework focuses on the consumer. The digital ecosystem will be organized around a platform as a single access point to the ecosystem, but also connect services and stakeholders in the background. Due to the high product variance and the multitude of different manufacturers, the establishment of a complete ecosystem is very challenging. The distribution of information is heterogeneous, but must be transformed into a homogeneous knowledge base. Furthermore, all the relevant stakeholders need to be identified and for all of them there has to be clear incentives to participate in the digital ecosystems.

The method used for the framework for modelling and implementing the ecosystem is based on the phases of the waterfall model, beginning with the requirements analysis, followed by the system design and finally the coding and testing - not inflexible but instead mixed with agile approaches [25]. In the requirements analysis all relevant stakeholders, such as repairers and refurbishers are identified, but also the current state of the art and research. Already existing solutions and platforms e.g. ifixit.com, can be also included here and should be integrated in the overall system. Finally, new data based business models will be derived out of the ecosystem.

3.3 Production and Retroproduction System

The availability and access to market, process, and product information, i.e. demand of refurbished electronics or disassembly manuals, in combination with a collaborative network of stakeholders is a key requirement for an efficient CE. The information which is gained through transparency, i.e. through circular business models which are combined with a digital ecosystem, supports a higher automatization potential of retroproduction systems. Therefore, increases in performance and profitability can result due to the reduction of labor-intensive processes such as the disassembly. In general, retroproduction describes the processes needed to separate a product into components or even materials and includes repair, refurbish, and recycling processes.

Production and retroproduction systems need to be designed regarding the based business model, e.g. which product cascades are focused and how the requirements on product level influence the design of (retro) production system. Therefore, methods for designing (retro) production systems as part of a circular business model of electronics are presented.

To lift the full economic, environmental, and social potential, by reducing required infrastructure and logistics and increasing automatization, a closed-loop production system (CLPS) seems promising. A CLPS is a hybrid production approach that combines structures of the production and retroproduction, i.e. a (dis)assembly process for the manufacturing, refurbishment, and recycling, within one system. A CLPS or in advanced a Circulation Factory is able to create spare parts out of used products that can be implemented directly in the production or refurbishment of new products (see Fig. 1). Furthermore, in-house recycling of low quality returns provides secondary materials for the production [26], [27]. Secondary materials typically create a lower environmental and economic impact compared to primary materials [28]. Hence, a CLPS combines different product cascades within one production system.

The required flexibility and resulting complexity of such a hybrid production system necessitates the understanding and managing of the complex material flows, which is under analysis in different research projects [29]. A simulation approach, i.e. by a combination of an agent-based and discrete-event model, is a promising tool to support the understanding of the interdependences e.g. of product variety and processes flexibility in a retroproduction system. Furthermore, a material flow analysis of the system clarifies the individual material flows. The material flow analysis is a systematic assessment of the state and changes of material flows and stocks within a system under the law of conservation of matter [30]. The results provide valuable information, e.g. about expecting material flows on factory and cascade level and prove the feasibility of the circular business model regarding the production and retroproduction system.

The results are used to optimize the EoU/L options and a related optimal depth of repair for the focused electronics regarding achieving sustainability. Hence, a simulation approach to plan and manage the complex material flows supports the development and validation of business models for the CE, as explained above, and can be the basis for designing Closed-Loop Supply Chains.

3.4 Closed-Loop Supply Chain

Through the innovative business models, new actors are integrated into the CE. Additionally, the interaction and interdependencies between the (old and new) actors in the CE will increase. Furthermore, digital ecosystems will emphasize new opportunities of collaboration between actors and potential for improvements regarding ecologic and economic aspects. CLPS also change the general structure of the production and retroproduction and therefore, the logistical connections of the CE. Hence, a (re)design of the (conventional) supply chains is necessary, which enables an efficient CE.

In the (re)design of supply chains, decisions on the plant locations, resource flows, and supply sources need to be taken [31]. The network planning consolidates these decisions. Furthermore, for spare parts the planning of the supply sources is put before the network planning as selection of the spare part strategy.

The aim of the network planning varies depending on the objective of the decision maker. In the past, economic measures were the dominant objective in such planning processes. However, climate change and the environmental and social awareness of the customers necessitate different measures [32]. Based on information about possible supply sources, demand structures, budgets, plant and transportation capacities, and the existing network structure, new, sustainable network structures can be created. Therefore, a variety of mathematical optimization models exists. Many approaches for forward supply chains exist with a large variety of specialized requirements in the literature [32]. Furthermore, recycling and remanufacturing gain increasing consideration in the network planning. However, only limited contributions take all possible cascades as well as forward and reverse supply chain into account, as necessary in the CE.

3.5 Spare Parts Strategies

For some of the cascades, spare parts need to be sourced. While the spare part supply is non critical before the end of production of the original product and components, the spare part supply gains significant importance after the end of production [33]. Three general strategies can be identified. Often final stocks for spare parts are procured or produced with the existing machinery before the production is finally ended [34]. However, the forecasting of the actual demand is related to high uncertainties and over- and underestimation leads to significant costs. Some parts can also be produced after the end of production [34]. Therefore, often parts of the specialized machinery from the production are used in workshops. This strategy is highly flexible because the supply can easily be adjusted to the demand. Finally, the CE enables the reuse, refurbishment, and remanufacturing of spent components, which serve as spare parts [34]. Combinations of these strategies exist as well. Nevertheless, in case of electronics additional challenges occur because often the original equipment manufacturer only provides spare parts for a short limited time. Hence, remanufacturer and repairer face the challenge of developing their own spare parts strategies. However, most approaches for the design and planning of spare parts strategies focus on the original equipment manufacturer. Therefore, this framework aims to extend the existing approaches by the consideration of innovative spare parts strategies to enable an efficient CE.

3.6 Environmental and Economic Sustainability Assessment

The research framework (see Fig. 2) incorporates the analysis and assessment of the conditions to extend product use and optimized cascade use (including technical, legal, economic, and ecologic). The material flows, i.e. precious metals or toxic materials, can be further evaluated by a life cycle costing and (social) life-cycle assessment to identify key processes and materials regarding cost drivers and their effect on the environment and society over the product lifetime. The results are used for a decision support identifying an optimal EoU/L strategy of electronics under economic, ecological, and social aspects. In addition to the analysis of the ecological impact, an evaluation of possible rebound effects according to economic and ecological criteria can be integrated. This avoids shifting problems and ensures effective and efficient conservation of resources. Furthermore, the analysis of economic and environmental optimal depth of repair of used electronics can be included.

4 Initial reflections on the framework based on two industrial cases

Findings indicate that there is a real need for a more circular way of doing business [28], [35]. Accordingly, the purpose of the presented framework is to apply it with different actors within the CE in the industry.

Circular business models, with a clear focus on the recovery of products and materials and the extending of the product lifetime, need to concentrate on consumers, their needs, and especially on their behavior. Based on this, a circular business model can shift from traditional to CE by allowing access instead of ownership to meet result-oriented models that are focused on the desired outcome. From a customer perspective, circular business models propose a more efficient use of resources [4].

For the application of the framework, a spare parts strategy for electronic products as a circular business model will be developed in the following. The strategy will be implemented in two case studies ((1) repair; (2) remarketing and remanufacturing). Spare parts are necessary to operate a repair service as well as a remarketing business model. By focussing on the efficient use of resources, spare parts can act as an enabler of a circular business model.

(1) The first case study is about the *repair of electronics as a service*. Thus, a sustainable business model for the manufacturer-neutral repair of high-quality electrical and electronic multimedia products (e.g. HiFi, electronic toys, televisions, etc.) is developed.

(2) The second case study deals with *remanufacturing and new ways of distribution of used electronic products as Product Service Systems*. Accordingly, circular business models for the take-back and, if necessary, refurbishment of electronics for remarketing within the framework of PSS are developed. For this purpose, innovative approaches are analyzed, e.g. to refurbish high-end laptops after their original use in the business sector and to market these laptops in the consumer sector.

Both case studies are based on an exchange of information, i.e. demand for components and spare parts, quantity of damaged electronics to be processed or market based information. Therefore, a digital ecosystem is needed. The information platform is not only necessary for the exchange of data, but also for connecting the stakeholders of both case studies.

Based on the recovery of products, components and materials a reverse supply chain and retroproduction comes into place. (Retro-) production planning and (closed-loop) supply chain design need to be developed based on modelling approaches to apply necessary spare parts within an efficient transportation, disassembly, processing and reassembly system.

5 Conclusions and outlook

The transition towards a CE to keeping the products as long as possible in use presents clear opportunities and environmental benefits. Driven by the need for more sustainable and circular business models, research on approaches for supporting cascade use reveals high potential of an interdisciplinary framework, especially in the field of consumer electronics. In this paper an interdisciplinary framework is presented for reducing WEEE by optimized cascade utilization and extended utilization.

Circular business models need to integrate customers with their requirements as they are the essential decision makers for the cascading of their electronics. The digital ecosystem enables channels and infrastructure for information exchange as well as acts as a hub for creating new circular business models and connections for repairers, redistributors, refurbishers and other service providers. The inefficient retroproduction is due to high labour cost, one obstacle for the CE. A simulation based approach can quantify material flows and thus provide planning reliability. A comprehensive optimization model for the network planning enables an optimal design of the new supply chains under consideration of the changed conditions. Furthermore, innovative spare parts strategies are part of the circular business models and enable cascades after the end of production, such as repair and remanufacturing.

Furthermore, two case studies are presented which give an overview of how the proposed framework can be applied in practice. There is a need to inform stakeholders (i.e. customers) about the potentials and cascades of CE as they decide about the lifetime of their electronic products. That needs to be communicated by the digital ecosystem and are content of the business models.

The exemplary case studies demonstrate already at this early stage how the presented framework makes an initial attempt to indicate a real opportunity in the transformation towards a CE. The future work will present the results of these case studies when the framework is adapted in practice. Additionally, the combined methodologies and the generic approach need to be validated in the economic reality

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6 Literature

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A Method for Identifying Cross-Functional Teams and Processes for Managing Uncertainty in Remanufacturing of Electronics Products

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Abstract

Compared to new manufacturing, the distinctive nature of remanufacturing is found to have high variability, high uncertainty and, thereby, complexity. Therefore, remanufacturers need to enhance their ability to adjust their systems flexibly. Especially, the ability to reconfigure the production planning and control is crucial for reacting to the high variability and uncertainty. However, few practical methods to do that are available so far. Therefore, to solve this problem, this study aims to propose a method for production planning and control in remanufacturing based on the concept of loosely coupled systems. In the proposed method, Design Structure Matrix (DSM) is applied to identify loosely coupled subsystems that enable to localize impacts of changes within themselves. Through the application to a real case of remanufacturing of information technology (IT) equipment, the proposed method was found to be effective for reconfiguring teams and processes for performing production planning and control activities efficiently depending on given uncertainties.

1 Introduction

Remanufacturing, as reviewed by [1] and [2], is crucially important for our societies to move toward a circular economy (CE), "which is restorative by design, and which aims to keep products, components and materials at their highest utility and value, at all times" [3]. The potential economic gains from remanufacturing are also substantial, while an EU funded project on remanufacturing [4] recently reported that the ratio of remanufacturing compared to new manufacturing in Europe was only 1.9% in terms of total production value. Although a large number of studies have proposed methods for quantitative optimization of remanufacturing processes with a variety of aspects in focus, these quantitative optimization methods can be very useful for companies facing a particular challenge and with access to sufficient data, but this is often not the case with many remanufacturers. Considerations of how to begin or sufficiently improve remanufacturing as a viable way of doing business are largely absent from the literature and complex mathematical methods for optimizing decision making in particular circumstances are not always called for in practical contexts [5]. This lack of practical support for companies hinders remanufacturing businesses from growing which concomitantly risks missing out on the environmental and social benefits associated with remanufacturing.

Compared to new manufacturing, remanufacturing is distinctive because it is characterized by high variability, high uncertainty and, thereby, complexity [5]. For instance, the number of returning cores per unit time and the quality of cores are uncertain, and product models are variable. In addition, the fluctuating number of in-coming cores creates a huge challenge vis-à-vis hiring and allocating appropriate human resources to different subsystems. Further, each of the uncertainties and variabilities have differential impacts on other aspects of remanufacturing operations. This represents a key barrier to achieving sound economic functioning in remanufacturing [6]. Despite the importance of uncertainty and variability in remanufacturing, practical support for how to address these issues pursuant of attainting viable business models is lacking.

Therefore, this paper proposes a practical method to identify leverage points to efficiently manage uncertainty in remanufacturing operations i.e., places where a shift produces a bigger change in a whole system. Especially, a method for designing processes of production planning and control in remanufacturing is proposed based on the concept of loosely coupled systems. To this end, the paper builds upon the notion of a design structure matrix (DSM) following [7]. The authors extend DSM to address uncertainty and apply it to a real remanufacturing case. Results of the application are discussed with a focus on deriving insights for improving the management of remanufacturing processes.

2 Literature review and research motivation

2.1 Industrial needs for dealing with uncertainties in remanufacturing

Due to high variability and uncertainty, remanufacturers need to enhance their ability to adjust their systems flexibly, i.e., changeability. Variability is "something that varies in fact": for instance, a core model has variability. Uncertainty is "something not definitely known or knowable" [8]: e.g., timing of cores returning has uncertainty. In general, changeability of manufacturing systems can be achieved through reconfigurations both in logical and physical terms [9]. At the physical level, manufacturing and assembly systems have to be reconfigurable; at the logical level it is necessary to reconfigure production planning and control to react to changes in production volume and so on. Production planning and control is the mechanism that matches the company's output and logistic performance with customer demands [9]. Typical production planning and control activities in remanufacturing include forecasting [10], logistics [11], scheduling [12], inventory control and management [13]. These activities are more complex for remanufacturing firms due to uncertainties [14]. However, few practical methods are currently available to accommodate this [14]. Therefore, further investigation is required to develop a general method for production planning and control activities, aiming to enhance the changeability of remanufacturing systems against uncertainties.

2.2 Loosely coupled systems for managing uncertainty

In the field of system science, the concept of loosely coupled systems for dealing with uncertainty has been popular. Glassman defines loose coupling as a situation where two systems either have few variables in common or have more than a few such variables, but they are weak compared to other variables which influence the system [15]. Features of loosely coupled systems can be described by comparison to tightly coupled systems [16]. Tightly coupled systems are portrayed as having responsive components that do not act independently, whereas loosely coupled systems are portrayed as having independent components that do not act responsively [16]. It has been suggested that loose coupling is effective under uncertain environments, since it enables to neutralize, assimilate, and accommodate the impact of changes in the environment by localizing it within specific subsystems.

2.3 Design Structure Matrix

The design structure matrix (DSM) (e.g., [17]) is a popular representation and analysis tool for system modelling. A DSM displays the relationships between elements of a system by a square matrix with identical row and column labels. An off-diagonal mark represents an element's dependence on another element. Reading across a row reveals what other elements are provided by the element in that row. Scanning down a column reveals what other elements the element in that column depends on. Several type of DSMs have been developed and applied to many industrial practices. Especially, a component-based DSM is used for modeling system architectures based on components and/or subsystems and their relationships. Component-based DSMs are usually analyzed with clustering algorithms that generally cluster along the diagonal marks by reordering the rows and columns of the DSM. While clustering requires several considerations, the foremost objective is to maximize interactions between elements within clusters while minimizing interactions between clusters.

2.4 Research gap and opportunity

As per the foregoing, practical methods are needed, but lacking, to manage uncertainty for the purposes of optimizing production planning and control in remanufacturing. This issue will hinder companies from initiating, or efficiently improving, remanufacturing. Systems thinking has been shown to be useful for managing complexity in manufacturing (e.g. [18][19]). Concepts, theories, and methods such as loosely coupled systems and DSM based on systems thinking have the potential to be advantageously leveraged in remanufacturing contexts. This provides the rationale for the research reported herein.

3 A design method for loosely coupled systems in remanufacturing

3.1 Overview

The concept of loosely coupled systems is applied to remanufacturing for enhancing changeability pursuant of navigating uncertainties. The proposed method focuses on changeability at the production planning and control level, which adjusts system elements in remanufacturing, such as the planning of remanufacturing processes, and the management of logistics and inventory. The method aims to design processes to determine the logical sequence of planning and control activities [20].

3.2 Procedure for designing loosely coupled systems in remanufacturing

3.2.1 Step 1: decomposition of a remanufacturing system

The first step is to decompose the remanufacturing system into elements and analyze their dependencies based on axiomatic design, which is a methodology focused on how to use fundamental principles during the mapping process among domains of the design world [21]. Design parameters (DPs) of system elements are identified, thereby their dependencies are analyzed based on the the design matrix, which represent the relationship between functional requirements (FRs) and DPs as shown in Equation 1.

$$\{FRs\} = [DM]\,\{DPs\} \qquad (1)$$

where
A vector {FRs} represents the set of FRs
A vector {DPs} represents the set of DPs
[DM] is the design matrix.

As shown in Figure 1, the dependencies among DPs are determined based on the design matrix. When the matrix is diagonal, such a design is called an "uncoupled design [21]." Since these DPs can be determined independently to satisfy relevant FRs, there is no relationship among DPs in an uncoupled design. When the matrix is triangular, such a design is called a "decoupled design [21]." For DPs in a decoupled design, the relationship is determined in a given sequence indicated by the design matrix. For example, in Figure 1, DP1 is planned and controlled first and then DP2 is determined next. Therefore, the dependency is determined in a single direction from DP1 to DP2. All other designs are called "coupled designs [21]." With regard to DPs in a coupled design, the dependency is determined bi-directionally, since it requires feedback and mutual coordination.

Relationship between FRs and DPs in design matrix	Dependency among DPs in design structure matrix		
		DP1	DP2
$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{vmatrix} X & 0 \\ 0 & X \end{vmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$ Uncoupled design	DP1	0	0
	DP2	0	0
		DP1	DP2
$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{vmatrix} X & 0 \\ X & X \end{vmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$ Decoupled design	DP1	0	X
	DP2	0	0
		DP1	DP2
$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{vmatrix} X & X \\ X & X \end{vmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$ Coupled design	DP1	0	X
	DP2	X	0

Figure 1: Dependency among DPs in design structure matrix

3.2.2 Step 2: analysis of uncertainty propagation on design parameters

The next step is to quantify the dependencies of DPs. Since the proposed method aims to identify loosely coupled subsystems capable to localize impacts on uncertainties, the dependency among DPs is quantified based on risks of change propagation due to uncertainties. In the previous step, the dependency of DPs is identified as a directional relationship from a source DP to a target one. Therefore, in the same manner as existing studies on change propagation, such as [22], the risk is calculated by the multiplication of the probability of the change in the source DP due to uncertainties and its severity to the target DP as shown in Equation 2.

$$DSM(i,j) = \begin{cases} P(DPi) \times S(DPi, DPj) & \text{(if dependency from } DP_i \text{ to } DP_j \text{ exists)} \\ 0 & \text{(if there is no dependency)} \end{cases} \qquad (2)$$

where
$DSM(i, j)$ is the risk of propagation from DP_i to DP_j
Note that when $i = j$, $DSM(i, j) = 0$, $DSM(j, i) = 0$
$P(DP_i)$ is the probability of changes in DP_i
$S(DP_i, DP_j)$ is the severity of changes in DP_i against DP_j

To calculate the probability of changes in DP_i ($P(DP_i)$), uncertain factors (UF_k) are extracted by analysis of the system environment, and then, the uncertainty of each factor is measured as the coefficient of variation before its magnitude ($M(UF_k)$) is given as an algebra from a five-point Likert scale ranging from "1: very low" to "5: very high." Next, the probability of changes in DPs is evaluated as shown in Table 1.

Table 1: Procedure for calculating the probability of changes in DPs

Uncertain factors (UF_k)	Magnitude of uncertainty ($M(UF_k)$)	Influence of uncertain factors on DPs ($I_{DPi}(UF_k)$)			
		DP_1	DP_2	…	DP_m
UF_1	$M(UF_1)$	$I_{DP1}(UF_1)$	$I_{DP2}(UF_1)$	…	$I_{DPm}(UF_1)$
UF_2	$M(UF_2)$	$I_{DP1}(UF_2)$	$I_{DP2}(UF_2)$	…	$I_{DPm}(UF_2)$
…	…	…	…	…	…
UF_n	$M(UF_n)$	$I_{DP1}(UF_n)$	$I_{DP2}(UF_n)$	…	$I_{DPm}(UF_n)$
Probability of changes in DPs ($P(DP_i)$)		$\Sigma\, I_{DP1}(UF_k) * M(UF_k)$	$\Sigma\, I_{DP2}(UF_k) * M(UF_k)$	…	$\Sigma\, I_{DPm}(UF_k) * M(UF_k)$

UF_k Uncertain factor ($k = 1, \dots, n$)
$M(UF_k)$ Magnitude of uncertainty of each factor (UF_k)
$I_{DPi}(UF_k)$ Influence of an uncertain factor (UF_k) on DP_i

In the same manner as Quality Function Deployment (QFD) [23], a table is prepared to determine the influence of the uncertain factors on each DP ($I_{DPi}(UF_k)$) by using a five-point scale ranging from "1:

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very low" to "5: very high. Finally, the probability of changes in each DP is calculated by the summation of the multiplication of the magnitude of uncertainty of each factor and its influence on the DP. On the other hand, the severity of changes in a DP against the other DPs ($S(DP_i, DP_j)$) is evaluated by using a five-point scale ranging from "1: very low" to "5: very high," based on the dependency among DPs determined in the previous step. Finally, the risks of propagation among DPs are calculated via the multiplication of their probability and severity.

3.2.3 Step 3: determination of loosely coupled subsystems

According to the risk of propagation among the DPs, DSM is applied to identify loosely coupled subsystems that enable localize impacts on uncertainties. To obtain a high-quality result with a limited calculation cost, this study adopts the clustering algorithm proposed by [24] that enables identifying clusters that maximize the risk of change propagation among DPs within clusters while minimizing the risk between clusters. Based on these clusters, loosely coupled subsystems are identified as a set of clusters, and DPs that affect other subsystems are specified as interfaces among the subsystems.

3.2.4 Step 4: formalization of teams and processes for production planning and control

For dealing with uncertainties in the remanufacturing system, finally, teams and processes for production planning and control are determined. First, for each subsystem, a cross-functional team that consists of the persons responsible for DPs in the subsystem are organized. Based on the teams, subsequently, processes for production planning and control are formalized from two perspectives: system- and subsystem-level. System-level processes are formalized to share changes in the interface DPs among the teams. At the subsystem level, on the other hand, each team needs to define processes that adjust the planning and control of DPs within the subsystem for dealing with uncertainties. Since loosely coupled subsystems enable localization of the risk of change propagation within each subsystem, each team can perform these planning and control activities autonomously and concurrently as long as the interface DPs remain the same.

4 Application of the method

4.1 Case overview

The design method proposed was applied to a particular case-study company. This paper refers to the case company as "RemanCo." RemanCo is a remanufacturer of information technology (IT) equipment (predominantly laptops, tablets, and mobile phones) based in Sweden.

RemanCo handles the entire process of retrieving, remanufacturing, and redistributing IT products that have reached the end of their first life. As the laptops arrive at RemanCo's facilities, they first undergo a visual check. Thereafter, in-depth functional checks are performed and all data potentially remaining on the devices is permanently erased. If a customer of RemanCo has already procured the devices and stipulated a set of requirements then the relevant upgrades and changes (e.g., regarding memory, operating system, or software) will be carried out according to this specification. If, however, the laptops are sold individually, e.g., on RemanCo's own web shop, updates and parts exchanges are carried out as needed in reference to current market requirements. Finally, the laptops are packaged in RemanCo's proprietary packaging and delivered to the customer or stored until they are sold.

From this case description, a number of challenges RemanCo is experiencing in the context of uncertainty in remanufacturing become apparent. There is great variation in the number of cores RemanCo is able to procure. Great variation is also observed in terms of the condition of the cores. A further challenge is the nature of the cores, which tends to be directly related to fluctuating demand for RemanCo's remanufactured units. Fluctuation in core supply, condition, quality, and demand have put a strain on the continuous development of the business. These fluctuations are tackled by the proposed method. The main opportunity to improve the efficiency of the remanufacturing process lies in analyzing the existing processes and their inherent uncertainty and variance and ensuring a more efficient allocation of internal resources.

4.2 Results of the application

4.2.1 Step 1: decomposition of a remanufacturing system

For decomposition of the system, first, the FRs (functional requirements) of the remanufacturing system were determined as shown in Figure 2. FRs were extracted from the viewpoints of quality, cost, and delivery of the remanufactured products, thereby corresponding DPs (design parameters) were developed by conceiving system elements. For example, DPs - "users of acquired cores (DP1)" and "types of acquired cores (DP2)" were identified so as to fulfill an FR - "quality of acquired cores (FR1)." Subsequently, the design matrix was developed as shown in Figure 2, where X denotes an influencing relationship between FPs and DPs. Based on the relationship, the dependencies among the DPs were derived. For DPs in a decoupled design, such as "lot size of core acquisition (DP13)" and "reverse logistics (DP14)", the unidirectional dependency was determined in a given sequence indicated by the design matrix. In this example, DP13 should be planned and controlled first and then DP14 is determined next. For DPs in a coupled design, such as "users of acquired cores (DP1)" and "types of acquired cores (DP2)," the dependency was determined bi-directionally, since it requires feedback and mutual coordination between the DPs.

Functional requirements (FRs) \ Design parameters (DPs)		Users of acquired cores DP1	Types of acquired cores DP2	…	Lot size of core acquisition DP13	Reverse logistics DP14	…
FR1	Quality of acquired cores	X	X		0	0	
FR2	Cost of disassembly	X	X		0	0	
⋮	⋮						
FR16	Quality of purchasing parts	0	X		X	0	
FR17	Lead time of core acquisition	X	X		X	X	
⋮	⋮						

Figure 2: Design matrix of the remanufacturing system

4.2.2 Step 2: analysis of uncertainty propagation on design parameters

The propagation of changes in DPs was analyzed in consideration of uncertainties. First, four types of uncertain factors in remanufacturing were extracted based on [5]: uncertain product quality, uncertain time of supply, uncertain rate of technical development, and uncertain and immature market. To calculate probabilities, the magnitude of each uncertainty was evaluated using a five-point scale, as described above, ranging from "1: very low" to "5: very high." This was performed in consultation with the practitioners of the case company. Next, the probability of changes in DPs was calculated as shown in Table 2. The influence of uncertainty on each DP was ascribed as "1: low", "2: medium", or "5: high". The probability of changes in DPs was calculated by summation of the multiplication of the uncertainty of each factor and its influence on DPs as shown in Table 2. In this application, the probability values were normalized, with the maximum value corresponding to 5. As a result, DPs with high probabilities included "types of acquired cores (DP2)" and "lot size of purchasing parts (DP4)." Moving on, severity was calculated based on the dependency among DPs determined in the previous step. For each dependency, severity was evaluated using a five-point scale ranging from "1: very low" to "5: very high." For example, the influence of "types of acquired cores (DP2)" on "lot size of remanufacturing (DP3)" is very high (5), while the influence on "reverse logistics (DP14)" is very low (1). Finally, the risks of propagation among DPs were calculated via multiplication of probability and severity. As shown in Figure 3, for example, the risk of change propagation from "types of acquired cores (DP2)" to "lot size of remanufacturing (DP3)" is relatively high, since the probability of changing types of acquired cores is very high and its influence on the lot size of remanufacturing is also very high.

Table 2: Degree of uncertainty influence on changes in design parameters (DPs)

Uncertainty and its score \ Design parameters		Users of acquired cores DP1	Types of acquired cores DP2	Lot size of remanufacturing DP3	Lot size of purchasing parts DP4	Process of disassembly DP5	…
Uncertain product quality	5	5	5	2	5	2	…
Uncertain time of supply	5	5	5	5	5	5	…
Uncertain rate of technical development	2	1	2	5	2	2	…
Uncertain and immature market	2	1	1	1	1	1	…
Probability of changes in DPs		4.8	5.0	4.2	5.0	3.7	

Note: 1, 2, and 5 denote low, medium, and high influence, respectively.

4.2.3 Step 3: determination of loosely coupled subsystems

According to the dependencies among DPs, a matrix was developed as shown in Figure 3. Each number in the matrix shows the risk of propagation from the DP in the row to the DP in the column. Subsequently, clusters were identified that maximize the risk of change propagation within clusters while minimizing the risk between clusters. As a result, seven DP clusters were specified (demarcated in Figure 3 via emboldened black-lined boxes). In this application, each cluster was defined as a loosely coupled subsystem. For example, subsystem 4 contains DPs – "location of core acquisition (DP15)," "lot size of core acquisition (DP13)," and "reverse logistics (DP14)." This subsystem depends on subsystem 3, where the interface DPs correspond to "types of acquired cores (DP2)" and "users of acquired cores (DP1)." On the other hand, this subsystem does not influence other subsystems.

Sub*	Clus*	Dept*	Design parameters (DPs)	DP12	DP11	DP4	DP2	DP1	DP6	DP5	DP3	DP16	DP20	DP18	DP15	DP13	DP14	…
1	1	Proline	DP12 Equipment for test/data erase	■														
		Proline	DP11 Process of test/data erase	7	■													
2	2	Proc	DP4 Lot size of purchasing parts			■												
3	3	Proc	DP2 Types of acquired cores	5		10	■	10	10	10	25		10	10	5	10	5	
		Proc	DP1 Users of acquired cores	5		10	10	■	10	5	5		5	5	10		10	
		Proline	DP6 Disassembly yield rate						■	7								
		Proline	DP5 Process of disassembly						7	■								
		Proline	DP3 Lot size of remanufacturing	8					4	8	■	21		21				
		Invent	DP16 Warehouse size									■		12				
		Sales	DP20 Other remanufacturers										■					
		Sales	DP18 Lot size of distribution										13	■				
4	4	Proc	DP15 Location of core acquisition												■		24	
		Proc	DP13 Lot size of core acquisition												9	■	9	
		Proc	DP14 Reverse logistics												17		■	
:	:	:	: :															■

Sub*: Subsystems, Clus*: Clusters of DPs
Dept*: current departments that assume DPs (Proline: production line, Proc: procurement of cores, Invent: inventory management, Sales: sales of remanufactured products)
Note. Each number shows the risk of propagation from the DP in the row to the DP in the column.

Figure 3: Loosely coupled subsystems in the remanufacturing system

4.2.4 Step 4: formalization of teams and processes for production planning and control

Finally, processes for planning and controlling system elements were formalized for dealing with the uncertainties. At the system-level, first, each subsystem was assigned to a cross-functional team. For example, the team that assumes responsibility for subsystem 3 included the procurement and production line departments. In that case, the production line department takes responsibility for planning and controlling DPs such as "lot size of remanufacturing (DP3)" and "process of disassembly (DP5)" whilst the procurement department manages DPs such as "types of acquired cores (DP2)" and "users of acquired cores (DP1)." Subsequently, as shown in Figure 4, a system-level process was formalized to share changes in the interface DPs among the teams. With regard to subsystem 3, since "users of acquired cores (DP1)" and "types of acquired cores (DP2)" influence subsystems 1, 2, and 4 (see Figure 3), it is required to adjust these subsystems if DP1 or DP2 is changed. On the other hand, if "lot size of remanufacturing (DP3)" is changed, subsystem 1 needs to be adjusted.

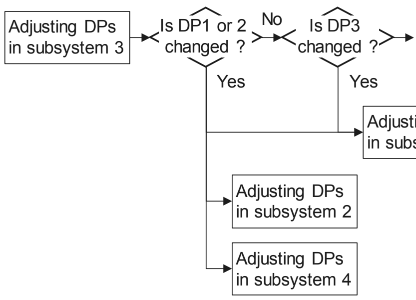

Figure 4: A system-level process for adjusting design parameters in each subsystem

On the other hand, subsystem level processes were analyzed so that each team could adjust the planning and control of DPs so as to address the uncertainties. For example, in the subsystem 3 team, "users of acquired cores (DP1)" and "types of acquired cores (DP2)" are highly influenced by uncertain factors, thus it is necessary to formalize a process that adjusts the planning and control of the other DPs which are under responsibility of the subsystem 3 team: "process of disassembly (DP5)" and "disassembly yield rate (DP6)" need to be adjusted when "users of acquired cores (DP1)" and "types of acquired cores (DP2)" are changed. DP1 and DP2 belong to the procurement department, while DP5 and DP6 belong to the production line department; therefore, coordination among these two departments is required for better adjustment. In this case, the process of disassembly could be adapted to the given types of cores or the types of acquired cores could be adapted to the existing process of disassembly.

5 Discussion

Through application to a real remanufacturing case-study, the proposed method was found to be effective for production planning and control. First, the proposed method is useful for reconfiguring teams and processes for production planning and control depending on given uncertainties. The major theoretical contribution of this research lies in the capability to identify cross-functional teams and necessary processes within and between those teams to better manage given uncertainties. Suggesting that cross-functional teams are relevant in remanufacturing is not a new idea [25] but the research presented herein contributes to the literature by quantifying this relevance using a systematic methodology. These cross-functional teams and processes would enable remanufacturers to clarify decision making boundaries [26], as well as enhancing sensitive sensing mechanisms that are able to navigate uncertain environments [16]. For example, the team which takes responsibility for subsystem 4 focuses on DP planning and controlling within the subsystem, such as "lot size of core acquisition (DP13)" and "reverse logistics (DP14)," based on the monitoring of relevant uncertainties.

Second, the proposed method enables efficient execution of production planning and control activities. By localizing the risk of change propagation within each subsystem, the planning and control of DPs can be adjusted autonomously and concurrently within each subsystem. Third, the method enables identification of those DPs associated with high change probabilities due to uncertainties, such as "types of acquired cores (DP2)," as well as DPs most likely to be affected by these changes. These results could be useful for planning human resource allocation based on the uncertainties and variability of DPs. For example, monitoring "uncertain time of supply" and changes in "types of acquired cores (DP2)" could enable rapid adjustment with respect to "process of disassembly (DP5)" with requisite human resources reallocated in a more systematic way. Finally, the proposed method is not contingent upon onerous amounts of quantitative data and as such could be more accessible and appealing to remanufacturers.

6 Conclusions

This paper proposed a method for appropriately determining leverage points in remanufacturing based on the concept of loosely coupled systems. Through application to a real remanufacturing case-study, the method was found to be effective and efficient for reconfiguring teams and processes to better manage production planning and control in contexts characterized by uncertainties. This effectiveness can be conceptualized as enabling remanufacturers to enhance the sensitivity of sensing mechanisms against uncertainties, allowing clarification of relevant decision making boundaries in terms of, for example, human resource allocation. Furthermore, the proposed method can be utilized without organizations needing to have prior access to quantitative data related to the problem at hand and as such this is expected to stimulate uptake of this method in actual practical contexts.

7 Acknowledgements

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Bridging the Gap – The Role of Service Experience as a Major Driver for Circularity in the Home Appliance Industry

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Abstract

Circularity can bridge half of the gap towards the 1.5°C climate target and makes a € 1.8 trillion opportunity alone in Europe. With global electronic waste being expected to double by 2050, this is an urgent field of action. Today, regulations, consumer needs and technologies provide new opportunities – so for start-ups like us. Taking the large home appliance industry as a starting point, we realized that poor after-sales service is a major barrier for circularity. This is supported by looking at recent press coverages and experiences, e.g. consumers will always prefer new appliances if repair services are too expensive, take forever or are not even available – which already defines key parts of the problem space. FixFirst aims to overcome those and other challenges by building an online platform and AI-first software that enables the current ecosystem. Finally, our solution is impact-driven and further accounts to the ambitions of the European Commission regarding circular economy and contributes to the UN Sustainable Development Goals. As outlined, we believe looking at the service aspects including customer experience and processes will be crucial to bridge the gap for a more circular economy beyond the home appliance industry and provides opportunity for future research and collaboration.

1 Introduction

Circularity (Circular Economy) can bridge half of the gap towards the 1.5°C climate target [1] and makes a € 1.8 trillion opportunity alone in Europe [2]. With global electronic waste being expected to double by 2050 [3], this is an urgent field of action.

However, taking a consumer standpoint and making this tangible, it can become fuzzy. For now, we're focusing on large home appliances such as washing machines, dryers, dish washers, freezers, ovens and the like since they can't be sent or carried somewhere easily, e.g. to a repair shop or an expert to get support.

After looking at the market and having a personal link to craft businesses in that industry, we picked this niche to start with because for large home appliances - poor after-sales service is a major barrier for circularity. This is supported by looking at recent press coverages and regulations (see Figure1).

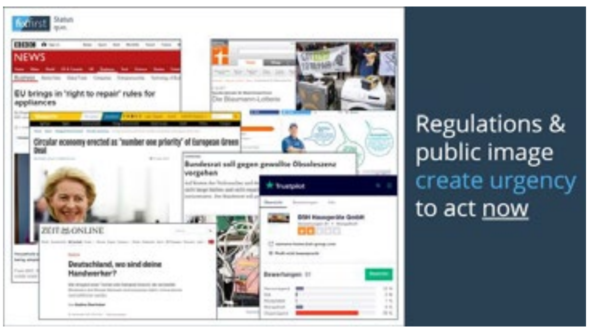

Figure 1: Public perception and media coverage

As a Berlin-based tech start-up, our role and approach are slightly different compared ot that of researchers which is why I will start with a short introduction to provide more context as follows.

FixFirst is an online platform for keeping large home appliances healthy. Our AI-first software enables the ecosystem of local repair services providers, manufacturers, retailers and insurances by providing an instant error analysis and remote video consultations combined with a seamless booking experience for inspections and repairs as well as recommendations for sustainable appliances. Our mission is to accelerate the transition to a circular future by creating a world where fixing comes first.

Our solution not only helps local craftsmen companies tackling skill shortage but also accounts to the ambitions of the European Commission regarding Circular Economy and further contributes to the UN Sustainable Development Goals [4].

Our start-up was founded last year, currently being in the go-to-market phase where we won first partners already. We are also collaborating with research institutes to either contribute or support them with our offering and expertise.

We see ourselves as a partner and enabler of the current ecosystem that consists of various stakeholders ranging from repair and maintenance service providers to manufacturers, researchers, recyclers and others that aim to close the circular gap in our and other industries.

2 Context

Let's look at the facts. Anyone who thought that the throwaway society and electronic waste were a problem until now should be warned: it's more likely to get worse. The United Nations estimates that e-waste will actually double worldwide by 2050 [3]. In addition, Earth Overshoot Day - the day of the year when we have exhausted the earth's resources - is always earlier. If one were to take the lifestyle of industrialized countries like the United States as a benchmark, we would currently need five earths to maintain our lifestyle... [5].

It's a bit like getting your salary for the whole month on Monday at the beginning of the month and then realizing on Saturday of the same week that it's all gone. Too bad there are still 24 days left. What we're doing right now is that we get a loan, but at the expense of the environment and future generations. Can this go on for long? Of course, no - the question is: What can we do now?

The answer is circular economy. It is based on the idea that in a world with limited resources, these are kept in use and returned to the material cycle and the impact on the external environment is minimized. A core pillar of this is that products are used for longer - which in turn is made possible by proper handling, repairs and maintenance.

This results in direct and indirect effects. The European Commission assumes that the new regulations for household appliances in Europe will save up to €150 per household per year and approximately 64 million tonnes of CO2 equivalents and 700 million cubic metres of water by 2030 [6]. All in all, it is even assumed that the circular economy can contribute up to 50% to achieving the 1.5°C climate target [1]. The European Commission is even supporting this with € 1 trillion under the new Green Deal [6]. So, in this respect it is a great influence with a lot of potential.

Apart from influence, it is also a question of what kind of world we want to live in. Back to Earth Overshoot Day: In 1970 we only needed one earth, even then there was the first European Year of Nature Conservation, and many things were repaired or at least tried out by people themselves - including my grandfather. Today all age groups are on the streets again in the context of Fridays for Future and even demand a Right to Repair.

So, with FixFirst we want to further establish the mindset that products can continue to be used and repairs can be considered - of course in the same way that people are used to digital services: simple, transparent and at the touch of a button. In fact, all generations book our service, even via messengers such as WhatsApp.

Recent trends and developments support our hypothesis why now might be a good time for doing this (see Figure 2).

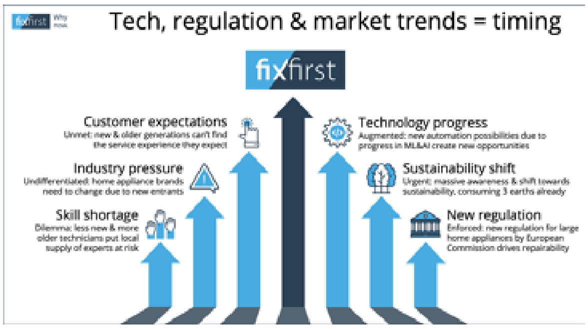

Figure 2: Why now is the right timing

3 Problem Space

If you want to make sustainability in large household appliances tangible, you have to start with the first occurrence of problems or oddities, e.g. when the washing machine makes strange noises. This can have various causes, which can be quite harmless, but also serious if ignored for a long time, leading to greater damage. In general, the first thing you want to know is: 1. what is the problem? and 2. how bad is it? The next step is to ask: What can I do? Where can I get help? How long does it take? What does it cost approximately? How could it be avoided in the future?

Today, you can click through forums or watch YouTube videos in addition to looking at the user manual - but often this is very tedious and only helps to a limited extent. In some cases, a technical defect is more quickly assumed there, e.g. to sell spare parts. One must be careful with free rides and inspections - the money is then usually recovered elsewhere. Conclusion: finding the right information quickly, purposefully and without reservations is therefore difficult.

The next point is the costs. Even if you decide to have a technician do the inspection, it is often not clear what the final costs will be. In addition, sometimes horrendous prices are charged for an inspection - sometimes you pay up to 150.- € to find out that a repair costs 240.- € or you can do it yourself [7]. Furthermore, spare parts are often too expensive or not available. This opens a gap - do I take the risk and am willing to pay the money or do I buy a new device directly? Conclusion: High costs with no transparency with prices and unclear performance promises are challenges at the moment.

Added to this is the duration. Nobody who has a family and owns a defective dishwasher or washing machine has two weeks to wait. Even one day's waiting time is critical for refrigerators. But unfortunately, this is regularly the case. Often, service providers are busy and can only be reached by phone or with difficulty. It takes time until everything is sorted out - and new appliances are available online in less than 24 hours. Conclusion: This needs to be addressed, and the process must be much faster, otherwise repairs remain unattractive.

Last but not least, structural challenges of the industry itself in Germany are an obstacle, such as a shortage of skilled service technicians and the dependence on local service partners in terms of the availability of different partners. We regularly hear from companies who can choose which brand they want to repair for. So, if you live in a rural area, you may find that there is almost no repair service available for your brand. Often the rides there are also longer, and the total costs are correspondingly higher. Nevertheless, the order books of many service providers are full, as there are hardly any alternatives – most don't even advertise. For a long time, there was little incentive for digitization... that is changing now - and FixFirst offers a simple and effective solution.

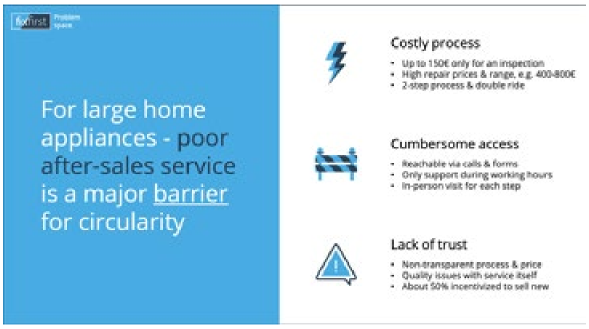

Figure 4: Summary of problem space

4 Solution Offering

Our vision is a world where fixing products comes first. So, the idea of FixFirst is rather to further establish the mindset of using products longer and considering repairs. To do this, we are mapping everything in a digital platform that offers solutions around this mindset - and we do so throughout the entire customer journey, from the first problem to the solution. That's why we have created FixFirst.

Our mission is to accelerate the global change towards a circular economy. We want to achieve this in turn through our four core pillars and goals: 1. best and fair experience for customers, 2. sustainable use of resources, 3. strong craftsmanship and digital services, and 4. shaping the future in partnership.

This is all about making parts of our technology available to different participants in the repair ecosystem, which in turn benefits our mission. Similar to Tesla and patent disclosure - so if a company wants to offer our solution under its own brand, that is possible.

In particular, we offer smaller repair providers as partners a kind of "digitalization at the touch of a button". Here we also provide support in the change process, if necessary, and thus address existing challenges, including the shortage of skilled workers.

We will solve the challenges with the status quo in various ways. First of all, we will provide the right information in a targeted manner and within seconds. This way, customers know directly and at all times what the most likely problem is, what they can solve themselves and what the best next steps are, including consideration of potential costs and energy efficiency gains.

In the next step, services such as inspections including cost estimates can be booked directly in digital form. Processing is possible through all channels, including messengers. Payment can be made by any means; the inspection is even tax-deductible in Germany as a household-related service. In this way we aim to exceed modern customer expectations - other well-known platforms are good examples of this.

We also offer a neutral assessment. The background is that according to customer opinions, depending on the inquiry, there is a smack with a tendency to recommend a new purchase. Other providers sometimes earn their money with hours or the cost of spare parts - in the worst case, they may even install something that is not necessary...

That's why we only work with qualified partners and offer an exact analysis in advance as possible. It is also important for the on-site inspection that all possible causes are tested correctly step by step, otherwise errors cannot be found correctly, the assessment often remains inaccurate and no improvement is made.

To this end, we offer flexible options with our CHECK and VIDEO services, which additionally enable the inspection to be carried out without contact, which will help both technicians and customers in the course of the Corona pandemic.

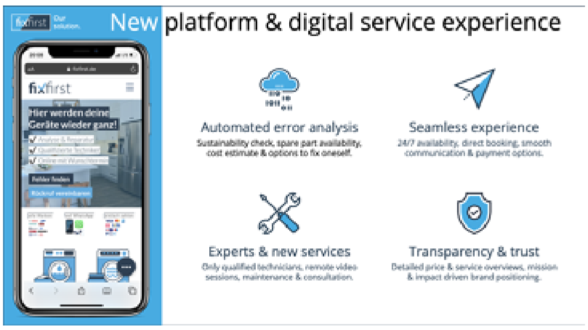

Figure 3: Summary of solution offering

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5 Sustainability & Impact

FixFirst plants a tree for each successful repair as part of the "Trillion Tree Campaign". This has not only a symbolic effect but can significantly help to bind up to 25% of the global CO2 emissions we cause and contribute to achieving our climate goals [8].

In the case of the new appliance we offer you the option to offset the resource consumption. To do this, we determine how long your appliance is used on average and set the resources of it per month. If the life span of the old one is below the average, the purchase of a new appliance and thus the disposal of the old one has a negative impact on sustainability goals and increases the amount of electronic waste which we aim to avoid.

Therefore, we calculate an amount that can neutralize this negative influence, similar to offsetting CO2 emissions, e.g. from flights. We use the money as an opportunity to support other initiatives and projects which, like us, pursue the mission to accelerate the global transition towards a more circular future.

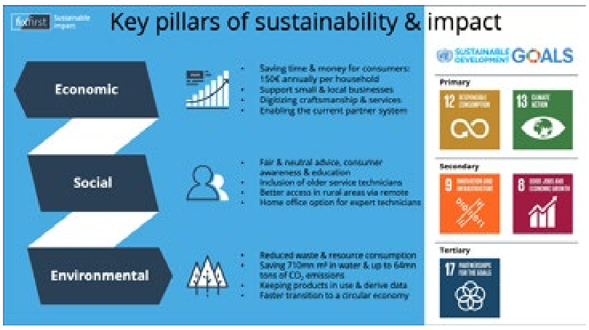

Figure 6: Impact overview

6 Next Steps

As quickly outline in this paper, we believe looking at the service aspects including customer experience and processes will be crucial to bridge the gap for a more circular economy in the home appliance industry.

Thus, we are looking forward to further collaborate with more partners – from industry experts to repairers, researchers or cities that want to initiate circular platforms. We hope to bring in expertise and solutions next to a platform that can help in gathering data and insights to accelerate that progress – even beyond Germany and Europe.

Feel free to reach out to us anytime. Thank you!

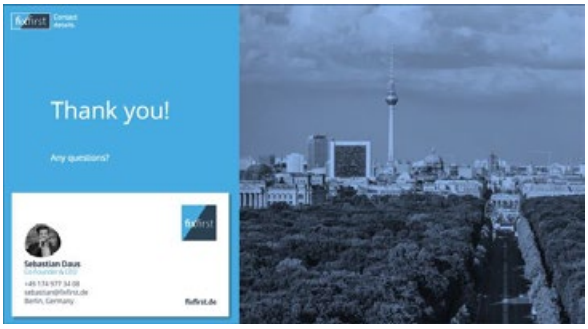

Figure 5: Contact details for future collaboration

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Developing a Standard Operation Procedure for the remote maintenance of smart heating pumps

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Abstract

State of the art heating pumps are tailored towards high energy efficiency in operation. The research project "ResmaP" aims at increasing the products' resource efficiency over their entire lifespan. This paper presents the development of a standard operation procedure (SOP) incorporating repair and maintenance operations that utilise the increased ICT potential presented by new pumps in order to prolong their lifespan. Approaches are developed to streamline the repair and maintenance process by making spare parts logistics more efficient and fitting for a certain malfunction. Additionally, the potentials of remote maintenance operations such as remote software updates are explored. Subsequently, adjustments to the recycling process are explored with focus on reusing reclaimed electronics parts. The SOP development and implementation for the pumps is accompanied by an LCA study.

1 Introduction

State of the art heating pumps come with built-in hardware and software features aiming at increasing their overall energy efficiency throughout the lifecycle. The introduction of an energy label by leading pump manufacturers in 2005 helped to promote energy efficiency in pumps through a variety of measures [1]. Additional features aim to make these pumps "smart", enabling them to communicate with both building management systems as well as external service providers such as maintenance companies or the producer. These features come at the expense of higher material intensity and resource consumption for the production of the necessary additional electronic components. Current research suggests that long-lasting goods such as pumps have a high potential for improvement in terms of circularity especially in the fields of manufacturing and end of life-management [2]. Utilising the potentials of digitisation has been identified as a key enabler for the circular economy [3]. This paper addresses end of life-management as well as activities to extend the products' lifecycles explored within the research project "ResmaP" [4]. To this end, a standard operation procedure (SOP) was developed to explore pathways towards lifecycle extension via software updates and extended repairs within standardised repair and maintenance processes.

The project aims at increasing the resource efficiency of smart pumps through repairing and updating. Resource savings can be achieved at different points in the pump's lifecycle. Where repair and maintenance work has to be carried out, the project explores means to perform it remotely as pumps of the newest generation offer the potential to be updated and thus eliminate malfunctions caused by software. Software updates require no additional manufacturing of spare parts as well as no travel of service technicians. Furthermore, resource saving potentials are explored through reducing the amount of spare parts to be used because of better knowledge about the error. Additionally, potentials of reusing reclaimed parts form returned pumps will be explored with focus on the control electronic as it allows for recombination of parts and contains rare materials and a high amount of labour value that is lost in the recycling process.

To this end, two main processes are analysed, modified and discussed with regard to their potential contribution to increased overall resource efficiency: Physical repair and maintenance activities on the one hand and reuse and recycling on the other hand. The existing and new processes will be compared in terms of resource efficiency, process performance and life cycle assessment (LCA).

2 Method

The SOP development aims at exploring the resource efficiency potential of smart pumps via a case study of using digital and remote technologies to perform maintenance work for product lifetime extension. To this end, involved actors have been interviewed in process mapping workshops and the subsequently specified process maps have been validated by the interview partners. Figure 1 below shows the processes covered

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by the interviews. Based on these process maps, a SOP was developed and data requirements for the SOP implementation and accompanying LCA study were identified.

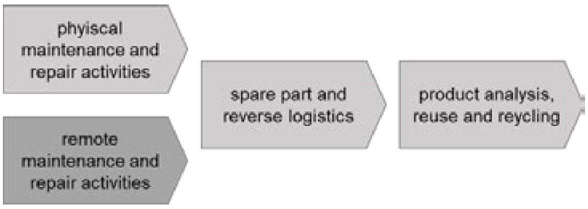

Figure 1: Scope of activities covered by ResmaP

The SOP is developed for in house technicians as they are closer to the pump design and development and can provide direct feedback within the company. Additionally, they are tightly integrated with the company's ICT infrastructure and can thus easily provide data for the processes' and products' evaluation.

Workshops with experts from different groups within the company were undertaken aiming at understanding the different processes as well as aspects of the products themselves and data and information either used during existing processes or required to implement the SOP and perform the LCA study.

3 SOP development process

The development of the SOP contains five aspects that have been taken into consideration to identify relevant changes to existing processes in order to carry out the research project's objectives as shown in figure 2. Firstly, the selection of pumps for a) the SOP and b) the comparison with older pumps for which a comparative LCA is performed (section 3.1). Secondly, processes and data requirements for both the evaluation of the SOP from an organisational point of view as well as for the LCA are being mapped (sections 3.2 and 3.3).

Based on this information new SOPs are being developed and implemented (section 3.4). Alongside, a LCA model is developed and fed with data collected during the SOP execution (section 3.5).

3.1 Selection of pumps

To carry out the project's objectives, the pumps relevant for the SOP have to be equipped with a control electronic module that allows for connection to external devices either directly or via a gateway. Thus, only pumps of the newest generation are being considered as only these generations allow for remote data readout and remote updating and maintenance measures.

The older pumps for the comparative LCA study are selected based on data from a previous research project. With about 80% of pumps being used as replacements for existing pumps and only 20% of pumps being used for applications in new buildings, identifying older generation pumps as a comparison appears to be the more relevant path form both an economic and ecological perspective. Based on the analysis of data from 2,703 individual pumps for which information on the year of construction was available, the average age of a replaced pump was calculated to be 15.65 years. Based on this, the commonly used pump generations at that time were identified for comparison. To ensure comparability of the results of the LCA, pump models with similar applications and performance profiles are selected. This mirrors the common approach to replace a defective pump with a new model. Many manufacturers offer specialised web services to help specialised craftsmen to identify matching replacements [5, 6].

3.2 Process mapping

During several workshops with different actors from hard- and software development and service departments at WILO, relevant processes were identified and

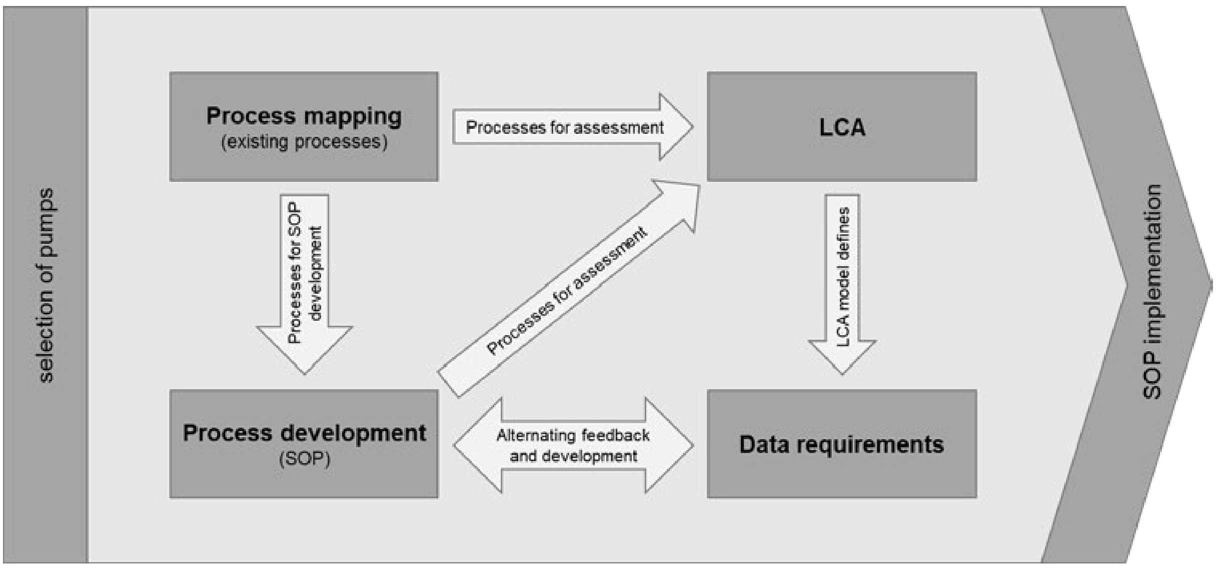

Figure 2: SOP development process

subsequently mapped using process chain management according to Kuhn, a method for process mapping developed at Fraunhofer IML. The benefit of using this method is its versatility and accessibility for people not familiar with process mapping so it can be used to explore processes with experienced experts as well as untrained staff. [7]

As hinted at in section 1 of this paper, two main processes are to be detailed for the analysis and SOP implementation. The maintenance process' major focus is lifetime extension through repair and service work whereas the recycling process' focus lies on quality analysis and material recovery from returned pumps through disassembly.

Both processes are characterised by interactions of various actors from within and outside of the company. Thus, only parts of the process can be influenced directly during the SOP implementation. While no focus of the SOP definition and implementation, aspects such as incentivising external actors to participate in a more resource efficient process will be explored at a later stage of the project. The presence of both internal and external actors causes an inconsistent information flow as cross-accessibility of IT systems is often not possible or desired by the actors involved. As a result, information have to be collected from different sources and actors with a high share of semi-automated or manual processes for data acquisition.

3.2.1 Service/maintenance process

The service process starts with notifying the service centre about a defective pump by an external actor (often times a mechanic or facility manager), either via a website, e-mail or telephone. Service jobs are collected and scheduled centrally regardless of the contact channel. Service technicians are organised by geographies so that service jobs will usually be allocated based on their location. From this step onward, the service technician becomes the customer's contact person.

There are three main processes steps relevant for understanding the service process: (1) information acquisition, (2) spare part order and delivery and (3) service execution.

During step (1) the service technician acquires additional information regarding the occurring error and the specific pump model. Since circumstantial conditions can also be of relevance, these are also discussed. The extent to which information has to be acquired depends on several factors, such as communications channel, skill level of the person first discovering and describing the error, the pump's age and model. The last part is particularly relevant as newer models with LCD screens allow the pumps to display not only an error code but even a written description of the error. Additionally, the installation in which the pump is used, is relevant.

Based on the information acquired, the technician will order spare parts in step (2) that are shipped overnight to the technician's storage in order to ensure a timely service operation. The spare parts necessary for the repair procedure can be derived from the previous process. Alternatively, an exchange motor (a new pump without the pump housing which can usually remain inside the heating installation) can be ordered. While various spare parts are available, technicians currently often fall back to ordering an exchange motor to compensate remaining uncertainty regarding the nature of the error.

For the service execution in step (3) the technician will travel to the pump's location and perform service as required to repair the error. With newer pumps, this includes establishing a wired or wireless connection with the pump's module housing the control electronic in order to read out a detailed error log or perform software updates if a software error is the cause of the pump's malfunction. After the service execution, the exchanged parts are sent back to the company's recycling centre for analysis and recycling.

Characteristic for the current service process is the diversity of used communication channels and ICT systems involved in the process execution. While not much information regarding the pumps themselves is collected automatically, the systems and processes are highly standardised and as such prepared to process standardised information.

3.2.2 Recycling process

The recycling process connects to the service process in the cases in which pumps are returned to the company. The pumps are disassembled and their parts subsequently recycled.

The last option even for entirely defective pumps is always to recover the material value of the pumps, thus disassembling them to the point of having as pure as possible metal and other fractions. However, depending on the model and condition of the pump as well as the circumstances under which it was reclaimed, a breakdown and analysis of the pump and its parts is a reasonable approach. Upon arrival, the pumps are selected for either direct disassembly or analysis and subsequent disassembly. An analysis will be performed if it is relevant for warranty cases, required by the user of the pump, or for product development purposes, especially with relatively new pumps that show malfunctions early in their lifetime. The degree to which pumps are disassembled depends on the model and considerations balancing the material value that can be recovered with the labour cost involved in disassembling the pump. Due to the diversity of pump models and relatively low return volumes disassembling relies heavily on manual labour. Disassembled parts are collected in separate containers and sent to specialised recycling companies for material recovery.

3.3 Data requirements

To properly assess process quality and resource efficiency of the SOP, data are collected and processed during and after the implementation phase. Generally, data can be classified via its purpose and its source. For the SOP, a lot of data that is already collected during business operations or existing in databases can be utilised in order to assess the processes and products. However, certain data, especially regarding the material composition of the pumps, has to be gathered by analysing products. To this end, X-ray fluorescence spectroscopy (XRF) will be performed on electronics components in order to determine the exact content of electronics parts.

To properly assess the SOP's success and performance, quantitative and qualitative data has to be collected on performed maintenance jobs. The aim is to limit qualitative data such as descriptions of the pump installation situation or photographs thereof to the necessary minimum since its screening comes with a high workload and an objective interpretation is difficult to achieve. Since the processes in their existing form already rely on standardised documentation, i.a. for quality analysis and billing purposes, this data is assessed with its repurposing potential for the process analysis in mind. The high degree of standardisation enables easy and robust statistical analysis within a quantitative approach. Additional data not already existing within the information collected during service operations is collected in addition to the existing documentation and evaluated together.

For the LCA, all material and energy flows over the chosen life cycle within the defined system boundaries must be recorded. The recorded processes are recorded as input and output variables. [8, 9] Relevant data for the LCA were primary data mainly related to raw materials (i.e. metals, electronic and plastic parts), manufacturing processes (i.e. grey cast iron (pump housing), die-cast aluminium (motor housing, modules), copper (motor windings), permanent magnets (FeBNd), electronic components (copper, gold, platinum group metals), chrome steel (rotor shaft) and iron (rotor package)) and transport distances as well as operating data (i.e. maintenance and repair operations) were acquired by means of direct questions to the manufacturer. Secondary data, mainly related to the lack of data of the whole life-cycle of the pump and the end-of-life (Eol) processes, were acquired by the study of the specific literature and the consultation of reference databases.

3.4 Process development

The SOP development was characterised by a high reliance on the pumps' ability to share information remotely and to be remotely accessed and potentially maintained by updates. Key to the process implementation, especially in the service process, is a consistent flow of information from the pump to the company and back. Previous pumps already allowed for manual readout of information. While a technician is present, pumps of the most recent generation are able to exchange information directly through a gateway now. Processes have been adapted in three ways: The service process can be modified based on the higher amount of information on the malfunction available through remote data acquisition for a more efficient physical repair (section 3.4.1) or to enable a remote service process (section 3.4.2). Adjustments to the recycling process are less extensive, partly due to its being performed under standardised conditions in a production plant (section 3.4.3).

3.4.1 Physical repair and maintenance activities

Process adjustments have to be made mostly in steps where data acquisition is necessary. For the service process focused on physical repair and maintenance activities, this includes all three previously described steps.

In step (1) of the service process, a substantial part of the data acquisition is undertaken remotely. Assuming the control electronic and communication interface of the pump are unaffected by a malfunction, a pump connected to a gateway can transfer its current status to the producer, thus allowing for the integration of these information with the service job. Additional steps for information gathering performed by the scheduling team and/or the service technician can be reduced to the acquisition of relevant environmental conditions such as the installation point and any information exchange that is needed to arrange repairs (e.g. access to the installation point, time frames). Any relevant information regarding the nature of the pump's malfunction can be accessed via the gateway and the potential of misunderstandings and omissions is vastly reduced.

The exact information about the pump's malfunction enables the company to supply the exact spare part to the technician in step (2), potentially reducing the total amount of spare parts produced as well as shipping efforts because falling back to exchange motors is less likely. Additionally, this reduces the risk of fully working parts to be broken down and recycled as they cannot be reclaimed and reused in any case and reusing them in products is a difficult undertaking from a legal perspective.

In step (3), potentially necessary data acquisition activities can be skipped as the data has already been collected. The available information enables the technician to repair the pump without performing additional investigations at the installation point, thus saving time and effort.

3.4.2 Remote service process

The remote service process differs from the service process with physical presence of a technician in steps (2) and (3) whereas step (1) remains unchanged except for the way an appointment to repair is scheduled in the remote process as a remote repair can be performed at any given time and needs little preparation and no travel time. Since there is no travel involved, an allocation of service jobs based on geographical location is no longer required.

Step (2) is omitted in the remote service process as no exchange of parts is necessary.

The main difference in step (3) is that neither travel nor physical presence of the technician are required to perform the repair. If needed, additional analysis of the pump malfunction can be performed remotely before undertaking a repair. The physical presence of a person in proximity of the pump is generally not required, but could be advisable during early stages of the SOP implementation to assure that no unexpected effects occur after a remote service operation.

3.4.3 Recycling process

Changes in the recycling process are aiming at information gathering in order to better understand potentials for circulating parts of taken back pumps based on their properties. Therefore, an analysis is undertaken regardless of the warranty status of the pump. The control electronic and its log are read out at the recycling centre and disassembled parts are not sent to recycling but further analysed.

The electronics module of the pump will be put through tests similar to the quality assurance process after original manufacturing. In conjunction with the data collected from the pump's log file the aim is to identify the amount of wearing of the electronics parts after a given period or amount of operating time. Additionally, data about environmental conditions as well as implicit information about the heating system in which the pump operated, are gathered and analysed.

Since its software can be updated to the most current version, a module's fitness as a spare part is only determined by the hardware's condition. While mechanical parts of the pump wear down during operation and are often the cause of defects, there is not as much knowledge about the effects of operating time and environmental conditions on the electronics module.

3.5 LCA

The LCA is a tool that calculates and compares the environmental impact of different products and services. The result of a LCAusually serves as a decision-making aid for the development and improvement of products and services as well as for strategic planning. According to DIN EN ISO 14040 ff., the procedure of a life cycle assessment is subdivided into the four following steps: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase and the interpretation phase. [9]

In the first step of a LCA, its goal and scope of investigation are defined in detail. The "functional unit" quantifies the function and benefit of the products to be compared, in the case of the research project the selected heating pumps (see section 3.1). It is essential that the objects to be compared provide the same benefits, such as several variants of the heating pump with similar applications and performance profiles. [8] The system boundaries define the processes of the life cycle of a product or service considered in the LCA. As mentioned above, these include the extraction of raw materials, procurement, production and distribution of goods, the service and maintenance process in the use phase, the recycling process and the disposal of waste for the selected heating pumps. In addition, environmental credit, upstream and downstream processes are included. [8]

The inventory analysis phase includes data collection, data validation, reference of the data to a module or functional unit (modelling), data combination (balancing) and, if necessary, improvement of the system boundaries. [8] The data categories cover energy, raw materials, supplies and other physical substances, products, emissions to air, water and soil and other environmentally relevant aspects (see chapter 3.3). Data quality requirements for LCA are set with regard to a current time reference, a geographical reference and a technical reference. The investigation area refers to the selected heating pumps in the defined period that are manufactured and distributed in Germany. In addition, confidential data are used for this investigation. These are checked for plausibility and completeness. The additional requirements for data quality (precision, completeness, representativeness, consistency, reproducability) specified in the standard DIN EN ISO 14040 ff. [8, 9] depend on the information related to the data. In particular, data quality testing is only possible to a limited extent if aggregated data is available or data is provided for information purposes without original data (e.g. measurement reports) being stored.

The impact assessment phase is used to select impact categories, impact indicators and characterization models, to assign life cycle inventory results to the impact categories (classification) and to calculate the impact indicator results (characterization).

The interpretation phase will include the identification of the significant parameters on the basis of the inventory analysis phase and impact assessment phase, the evaluation, conclusions and recommendations. Optional components are described in accordance with DIN EN ISO 14040 ff. completeness, sensitivity and consistency checks.

The ReCiPe method, which is currently the international standard, is used for the impact assessment phase as described in the LCA standard. [10] This method is impact-oriented, defines impact categories to be considered and determines the contribution of the corresponding environmental impacts (e.g. pollutant emissions) for each of these impact categories. The Dutch Institute for Health and Environment (RIVM), Radboud University, CML and Pré Consultans have developed the ReCiPe method. This method combines the CML 2001 and Eco-Indicator 99 methods to develop a consistent framework for the classification of midpoint and endpoint indicators. This allows for both impact and damage-based impact assessment, i.e. equivalence factors are provided for both midpoint and endpoint to increase the transparency of the analysis and still provide a clear decision support. The environmental influences are first classified into impact categories according to the CML method and then summarized in the damage categories. The impact categories include climate change, ozone depletion, terrestrial acidification, eutrophication of freshwater and seawater, human toxicity, photochemical oxidation, particulate matter formation, terrestrial, marine and freshwater eco toxicity, ionizing radiation, land use broken down into urban and agricultural, natural land conversion, water consumption and consumption of minerals and fossil fuels. The ReCiPe method uses 17 of these midpoint indicators and, on this basis, models potential damage to the three protected goods human health, ecosystems and resources. [10, 11]

In practice, the use of life cycle assessments - especially with regard to the procurement of life cycle inventory data - involves a great deal of effort. The Life Cycle Inventory data must take account of company- and industry-specific features as well as regional and national differences in order to provide meaningful results. It is planned to realize the LCA with the software systems Umberto (supplier: ifu Hamburg). This software systems can access "internal" databases with reference processes and information on usable materials or substances. However, external databases such as ecoinvent (provider: ecoinvent Zentrum), Probas (provider: Umweltbundesamt) and Gemis (provider: Gemis: IINAS GmbH - International Institute for Sustainability Analysis and Strategies) will be used. HBEFA (provider: Infras) and TREMOD (provider: ifeu) will be used for logistical questions regarding transport (emission factors for common vehicle types in different driving situations).

4 Discussion

The SOP outlined in this paper is streamlined significantly in terms of information management when compared to the original process. Utilising the pumps' ICT potential, the process of information acquisition is automated and thus less susceptible to human error or misinterpretation, both of which lead to inefficiencies and potential procurement of unnecessary spare parts or exchange motors. Specifically, the following aspects are worth noting:

- The amount of *travel can be reduced* when remote maintenance processes are performed, leading towards more available technician capacity for maintenance work. While the positive ecological impact of reduced travel is obvious, the impact of a higher ICT utilisation remains to be assessed.
- The amount of *spare parts* needed can be reduced as well, either through the use of better fitting parts for a specific malfunction or because of the remote process. Both lead to resource efficiency gains through less original manufacturing of spare parts and subsequently reduced logistics costs.
- In terms of *data acquisition*, it is notable that a lot of the required information is already collected in some form during the original process. This might be an indicator for a high transferability of the project's findings to other companies and industries.

Furthermore, several aspects remain to be examined further during the project's run-time:

- *Quality and wearing of electronics parts* from returned pumps and their potential to be reassembled e.g. for new control electronics in order to save resources have to be examined.
- The *remote repair and maintenance operations* have to be statistically analysed. The frequency of cases falsely identified as fitting for remote maintenance is particularly interesting as these will cause not only a high amount of additional effort but are also linked to the customer's perception of the product quality.

5 Conclusion

This paper contributes to understanding ways to increase overall resource efficiency of products throughout their lifecycle by addressing resource efficiency outside of the use phase. The approaches outlined in the SOP have the potential to utilise state of the art control electronics and ICT in heating pumps to advance overall efficiency and extend the energy efficiency of modern pumps into the area of resource efficiency through lifetime extension. However, increasing resource efficiency through the approaches discussed in this paper encompasses only a fraction of the potential approaches to the topic and should inspire further research in this area.

Such research could focus on modifying the processes even more by integrating repair and maintenance into the recycling process and carrying out these activities in a controlled environment. This would enable trained servicemen from outside the company to participate by exchanging entire pumps at the installation point and open an opportunity for parts harvesting before recycling.

The impacts of modular construction and software will have to be addressed in further research as they offer great potential to extend the approaches to part reclamation and reuse outlined in this paper. Especially the introduction of cross and downward compatibility between different pump generations has the potential to improve overall resource efficiency while also simplifying spare part production and storage for the producer.

Another potential research area is the exploration of approaches to retrofit repair and maintenance processes for older pump generations based on some of the insight gained from the SOP. In cases where malfunctions can be explicitly characterised, these characterisations could be integrated with data acquisition to enable a lean process involving only the necessary spare parts and not an entire exchange motor.

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Condition monitoring of power electronic modules for predictive maintenance

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Abstract

Ensuring safe and reliable functionality of the electronic components, especially the power electronic assemblies, during the life of automotive and energy supply applications will become more and more of a challenge. This makes condition monitoring and failure forecasts of power electronic devices for a condition-based and predictive maintenance almost necessary. Predictive maintenance ensures functional reliability as well as an increased efficiency by exploiting the entire service life adapted to the actual load. This approach of predictive maintenance supported by early degradation or damage detection allows an increase in resource efficiency by dispensing with redundant system components. The costs for service and maintenance can also be reduced if the remaining service life can be reliably estimated. Under the assumption that more and more wind turbines are installed and operated off shore, such operation also involves costs and energy for maintenance. Due to this reason, suitable condition monitoring, which leads to more predictable maintenance, can have a positive influence on costs and energy demand.

1 Introduction

Wind power plants represent a targeted alternative to conventional fossil power plants for the generation of electrical energy. In order to achieve the set climate goals in the future, the installed wind energy capacity is also being expanded continuously. 325 new onshore wind turbines with a capacity of 1,078 MW were installed in 2019. This brought the total number of turbines to 29,456, with total installed capacity from onshore wind energy amounting to 53,912 MW [1]. In the future, the number of offshore plants will continue to increase worldwide, as further expansion possibilities onshore are limited. These systems are highly effective but at the same time much more expensive to maintain and service. At the end of 2017, offshore wind farms with a total capacity of around 18,800 MW were installed around the world [2]. In order to be able to carry out more predictable maintenance and thus enable more cost-effective operation, effective condition monitoring is a goal-oriented approach.

Current studies [3] show that defects in converters or power electronic components are often the reason for downtimes. In [3] the failure data from the years 2015-2016 of 1045 offshore wind turbines were evaluated. Here it was shown that frequency converters are ranked fourth as the cause of failure. In Figure 1, the main causes of failure are shown as monthly repair rates.

Condition monitoring of the power electronic components, which makes it possible to derive a remaining service life from the measured parameters and thus to plan a repair as required, would significantly reduce downtimes and support cost-efficient operation.

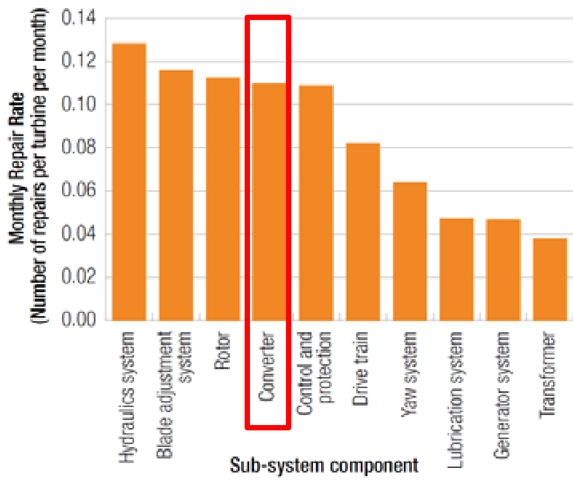

Figure 1: Comparison of Sub-System monthly repair rate [3]

2 Condition Monitoring

2.1 Concepts of condition monitoring

There are three concepts of condition monitoring (Fig. 1). The first concept is parameter monitoring, where a parameter inherent to the system that is sensitive to the aging process is constantly monitored (Fig. 1a). The second concept is known as the canary device (Fig.-1b). This refers to a component unnecessary to the devices functionality that is loaded just as the regular components but has a weaker structure. Therefore it will fail prematurely. Different structural layouts can be used to implement different warning stages so that a prediction becomes quite accurate. The third concept, the so-called life cycle unit (Fig. 1c), constantly monitors the load upon a device and predicts the remaining life-time via an underlying life-time model [4].

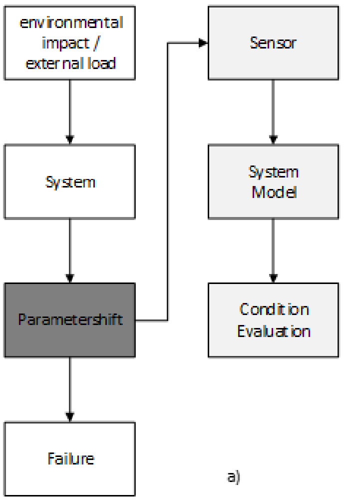

Figure 2a: Concepts of condition monitoring: a) parameter monitoring [4]

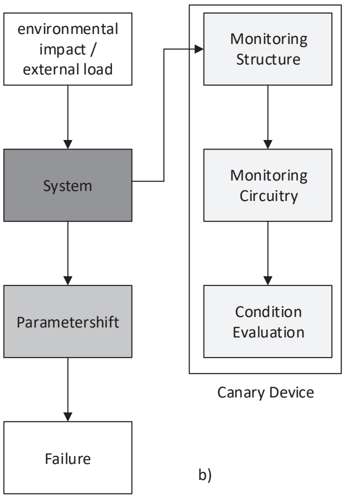

Figure 2b: Concepts of condition monitoring: b) canary device [4]

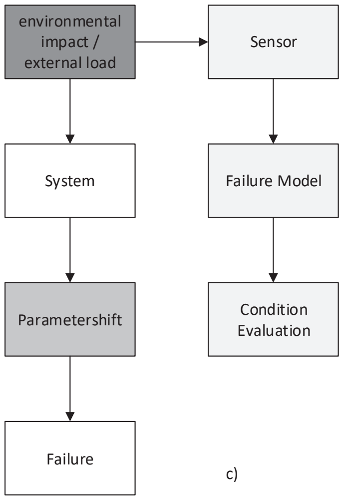

Figure 2c: Concepts of condition monitoring: c) life cycle unit [4]

As the IGBT's die temperature is dependent on both load and state of damage, a combination of the first and the third concept is feasible for usage in this research. Temperature swings, being one of the most critical aspects regarding lifetime.

These fast temperature changes should be counted as well as a continuously increasing die temperature under similar working conditions might be observed and related to a progressed damage.

2.2 Failure mechanism

The thermomechanical stress during operation usually leads to damage of power electronic modules and in the long run to their failure. The failure of the module can be caused by different error mechanisms in different areas of the module.

The following Failure mechanism dominates the degradation of power electronic modules. [5]

- Bond wire fatigue
- surface reconstruction
- solder fatigue

The dominant driving force for these error mechanisms is temperature or temperature changes. It follows that a local measurement of the temperature at the alleged defect location would give a very good evaluation of the condition of the component.

2.3 Temperature-sensitive electrical parameter (TSEP)

Since direct temperature measurement is not suitable for determining the chip temperature during operation, it must be carried out indirectly. This is usually done by

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measuring a temperature-sensitive electrical parameter (TSEP) and then converting it into temperature. The TSEPs suitable for this purpose show a dependence on the junction temperature Tj, which corresponds to the temperature inside the chip.

- threshold voltage
- Maximum gate current
- trans conductance
- Duration of the Miller Plateau
- collector-emitter forward voltage

TSEP	sensitivity	time resolution	influencing variables
threshold voltage	high	ns	Tj
Maximum gate current	high	ns	Tj
trans conductance	high	ns	Tj, Vge
Duration of the Miller Plateau	high	ns	Tj, dVce/dt, Ic
collector-emitter forward voltage	very high	µs	Tj, Ic

Table 1: Summary of the TSEP boundary conditions

As the NTC thermistors installed on most power electronic modules only gives a slow measured value of the total temperature. This is due to the distances to the active components. The temperature distribution and the small temperature spread lead to a reduction of the measured value of several Kelvin temperature difference and to a very slow behavior of the measured value at fast temperature changes. However, these are absolutely necessary for the assessment of the module's condition.

3 Measurement of TSEP

In [6, 7] 2 concepts for the in sito measurement of TSEP were presented. Both concepts measure the TSEP by an additional circuit during operation. These circuits can be integrated on the module.

3.1 Measurement of Vce

This concept is based on the interpretation of the temperature dependent behavior of the Miller Plateaus. The gate driver takes care of supplying sufficient energy to the IGBT's gate. Three high speed comparators monitor the gate voltage. These define the start and two stop events, of which only one is evaluated at the moment. The time to digital converter (TDC), an Acam GP 22, measures the time between start and stop with a sampling accuracy of up to 22 ps. The resulting time is communicated via SPI over an isolation barrier to the evaluation unit. In addition, current and collector-emitter voltage are measured by analog digital-converters (ADC) and communicated to the evaluation unit. To ensure that the measurements taken by the digital acquisition unit (DAQ) are within reasonable limits, the temperatures on the heatsink and the module will also be measured using thermocouples. The selected IGBT is an IXGN 200N60A2 in a SOT-227B package with a current rating of 200 A and a maximum blocking voltage of 600 V. Its field of application is motion control, DC choppers and uninterruptible power supplies. The IGBT is turned on for a pulse duration of 30 ms and turned off afterwards. This allows for a test with relatively low self-heating. This setup allows testing the measurement method with close to real life application blocking voltages and high currents.

3.2 Measurement of Vce_on

In a second concept study the collector-emitter forward voltage is used as a standard indicator to determine the junction temperature of IGBTs. Due to the required sensitivity of the measuring system of a few mV, the large difference between forward and reverse voltage and the short duty cycle of the IGBT in the µs range, measurement in power converters during operation is complex, but offers the possibility of measuring the temperature more accurately than with commonly used temperature sensors. A major challenge with this concept is that the measurement is on the high-voltage side and the measuring system must be designed to be voltage safe.

By an inductance L connected in series to the IGBT and a resistor R connected in parallel to the IGBT, voltage pulses with a current-dependent peak voltage of several 100V are generated at the collector of the IGBT at the moment the IGBT is switched off and the course of Vce during operation of the IGBT with high voltages is simulated.

The required nominal voltage of 1200V can only be checked up to 488V during the application test. Since the MOSFET used for the measuring system has a rated voltage of 1700V and the resistance of the MOSFET to parasitic switching increases with increasing voltage, it can be assumed that the measuring system is also safe with reverse voltages > 1200V.

The resolution of the measuring system is for Vce,on < 2V less than 3mV, for Vce,on < 2.5V less than 8mV. Thus, for IGBTs operated at nominal current with Vce,on < 2V a reliable temperature determination down to below 1K is possible, for IGBTs with Vce,on < 2.5V accurate to 2K to 3K. Since IGBTs of the voltage class < 1700V usually have forward voltages of less than 2V, this does not represent a limitation for the majority of possible application scenarios.

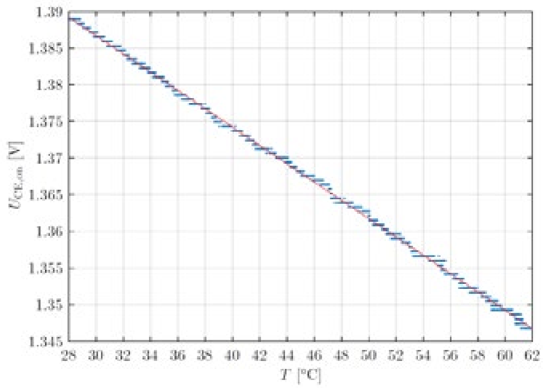

Figure 3: Exemplary measured temperature-voltage characteristic for Ic = 75A and compensation line [6]

Fig. 3 shows the measured temperature-voltage characteristic for the load case Ic = 75 A.

The measuring system fulfills approximately the specified requirements and shows that the determination of the junction temperature of IGBTs can be carried out by measuring the collector-emitter forward voltage while a power converter is in operation and that it is fundamentally superior to measurement by temperature sensors. The temperature resolution achievable with the measuring system is in the range of the limit deviation of common temperature sensors such as thermocouples or NTC thermistors or even below, but the time resolution achievable with the measuring system in the µs range is far below the time resolution of the temperature sensors, which is typically in the ms range or above. At the same time, temperature sensors can only be used to measure the temperature at a spatial distance from the chip, which means that the high temperature strokes occurring on the chip can only be detected to a limited extent, while the Vce,on measurement can be used to determine the temperature inside the chip. Therefore, rapid temperature changes occurring during peak loads of the IGBT can be detected much better with large temperature strokes of the chip than with temperature sensors.

4 Conclusion

Based on the results of [3], which show that the converters of wind turbines in 4th place with a monthly repair rate of about 0.11 are the cause of turbine downtimes, condition monitoring concepts that enable health monitoring offer a target-oriented approach to increasing runtimes and thus cost efficiency.

In the EEG 2012, a feed-in tariff of 14.5 ct/kWh was still defined in Germany. However, this value will probably fall in the future. From a cost perspective, reliable operation of the plants will therefore become all the more important in future. Assuming that converter failure or malfunction results in an average of 11% downtime per month with an average installed capacity in Europe of 4.6 MW per wind turbine, there is significant potential for cost optimisation through appropriate health management by monitoring the condition of the power electronic modules.

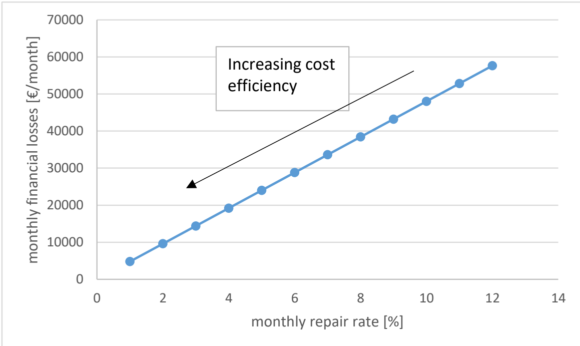

Figure 4: Exemplary increase of the cost efficiency per month of a 4.6 MW plant while reducing the repair rate of the converters

The diagram in Figure 4 shows the monthly cost saving potential based on the feed-in tariff alone. The further savings potential through a reduced input through labour and material costs is not yet considered here.

With the works shown here it could be shown that a significant potential can be achieved just by considering the feed-in tariff alone by installing a suitable additional measuring circuit that enables health management.

5 Acknowledgements

As part of the AMWind project, the Federal Ministry of Economics and Technology funded the research leading to the results, which are described as in concept measurement of Vce.

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A Deep Learning Product Label Identification Pipeline for Recycling and Repair

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Abstract

When electric or electronic products fail, it is often challenging and time-consuming to identify the product model and retrieve the related information to support repair and recycling. These difficulties are a severe barrier to document information for future repairs, and the challenge of information retrieval often prohibits product-specific recycling strategies to be adopted, resulting in the recycling of raw materials by bulk processing instead. Therefore, a deep learning Object Character Recognition (OCR) pipeline is proposed to automatically identify the device by extracting text from an image of the label on the device, which can be used for matching the text with a product database. The presented results on a dataset of 200 images for repair with an open-source pipeline demonstrated that 87,5% of the device model numbers were recognized with a Levenshtein distance of over 60%. With a commercially available OCR platform, 92,5% of the device model numbers were recognized with a Levenshtein distance of over 80%.

1 Introduction

The Circular Economy Action Plan [1], adopted by European Union (EU), identifies Electronics and ICT to be one of the key product value chains that needs to be focused on to achieve a circular economy. Up to €600 billion in additional savings for EU businesses, corresponding to 8% of their annual turnover and 450 million tonne reduction of EU carbon emissions by 2030 are envisaged [2]. According to the action plan, approximately two in three European citizens would like to keep using their current device longer, if the performance of the device is not significantly affected. However, many devices are today discarded when failure occurs, because of the cost of repair. For example, because the design of the device does not allow for the it to be fixed, or because of the high cost of repairing the device. To handle these challenges, many community repair organisations have been founded throughout Europe. These communities organise repair events, where volunteers assist consumers in repairing their broken device, and often actively campaign towards creating an active repair culture. For example, the repair community Maakbaar Leuven organises courses on how to repair certain types of electric and electronic devices for the general public [3] and strives towards organising repair events periodically in every borough of the city of Leuven.

The action plan also highlights that it is fundamental to improve the existing recycling strategies of Waste Electrical and Electronic Equipment (WEEE) to accomplish a closed loop of materials. The current recycling strategies often focus on treating collection groups of products the same with automated procedures in order to recycle common raw materials in an economically viable manner. With this methodology, many raw materials are lost and the potential reusability or value of certain components and devices is often not considered. The exploration of new methodologies to incorporate reuse into recycling processes is also mentioned as a planned action in the Circular Economy Action Plan of the EU.

When an electric or electronic device fails, the owner of the device has four general options to choose from in Belgium: Attempt to repair the device himself, visit a local community repair event, relay on professional repair, donate the device to be repaired and resold by a non-profit second-hard store, or discard the device and bring it to a collection point or a retailer for WEEE recycling. For all these options, information to support the treatment of the device generally needs to be found. This procedure is today often performed manually, which poses unique challenges for every option.

1.1 Self- and community repair

When the owner attempts to fix the device by himself or visits a local repair initiative, the specific product model will often be new for the person repairing the device. In order to find repair guides, the device will need to be examined to find the label and to search for the model number. Then, this information will need to be entered into an online search engine, along with the cause of the failure or the observed malfunction. However, when trying to identify the device, other information on the label, such as the series number or the serial number might be confused with the device model number. Therefore, multiple trials of combinations of numbers found on the label in combination with multiple paraphrases of the failure are generally required before a suitable guide, or any other information is found. As a result, a lot of time is lost, and in some cases, the device is not identified because of confusion. The time constraints are especially relevant during community repair events, because volunteers want to assist as many people as possible. Community databases of in-depth repair guides, such as iFixit [4] have been developed as an alternative, but guides on devices which are less popular, for example kitchen appliances or large household devices, are often not available.

On the online Fixometer platform [5], repair communities log encountered devices and note whether the device was irreparable because of the inability to open the device, the lack of spare parts, a lack of equipment, or because there was no repair information available. The collected statistics are then used to raise awareness on improving the reparability of EEE. However, the device category, or model number is often logged differently or wrong by volunteers. Therefore, it is challenging to determine which devices or device categories are often reparable and which are not.

1.2 Professional repair

The owner can also decide to relay on professional repair. When the device is still under warranty, the same issues will arise to register the device online or to communicate the model to a call centre. If the device is not under warranty and the owner decides to visit a professional repair store, this store will also have to identify the device in order to determine an estimated cost of repair and check whether spare parts to handle the repair are available. Because the complexity of electronic devices is increasing, professional repair stores generally only provide services for specific brands and product types. As a result, it is becoming more of a challenge to find repair services for a broad range of products and even for specialised repairers, the retrieval of information, e.g. on spare part availability, can be time consuming.

1.3 Repair by second-hand stores

If the owner is no longer interested in owning the device, or does not consider the cost of repair proposed by professional repair services to be worth it, in Belgium, there is the option to donate the failed device to a second-hand store. In Flanders the network of repair centres and second-hand stores “De Kringwinkel” [6], repair electronic devices themselves in order to resell them. Employees of these repair shops often also become experts in repairing specific types of devices. Asides from issues they face that are similar to professional repairer stores, it is crucial to also provide correct and detailed information on electronic devices when they are resold. Examples of this information are the brand and model number, the weight, the device dimensions, a link to a device manual and, for some large household appliances, the energy label. It is also not always evident to determine a reasonable selling price for second hand goods. As a result, information often needs to be searched for online when a device is repaired, which is time-consuming.

1.4 Recycling

When the device can no longer be repaired and has reached end-of-life, the owner will bring it to a collection point for recycling. Today, the device will most likely be treated in the same manner as all other products of the same collection group. Generally, no differentiation is made between these products. Even when specific product groups of devices are manually disassembled, only a small number of components are separated for reuse or dedicated recycling routes before the remainder of the device is shredded. The main reason being the time and the manual labour required to find information on the device itself.

1.5 Object Character Recognition to improve repair and recycling

Hence, it can be concluded that for all end-of-life options, the time required to identify the device challenges the economic viability of various treatment options or improvements that are preferred from a circular economy perspective. However, the text on the label could also be identified by capturing an image of the label and recognizing the text automatically with Object Character Recognition (OCR). By comparing the information extracted by OCR with a dedicated database of known device properties (model number, brand, category, battery type, barcode…), the model and model information could be identified without the need for manual labour. OCR model identification would result in the following advantages:

1. It takes less time to capture an image of the device and apply OCR in comparison with manually entering the label information.
2. No manual labour is required to identify the device. Thus, devices can automatically be identified continuously, for example, by a conveyor belt camera setup.
3. The series number, the commercial model name and model number, which are all often mentioned on the label, can all be read out simultaneously

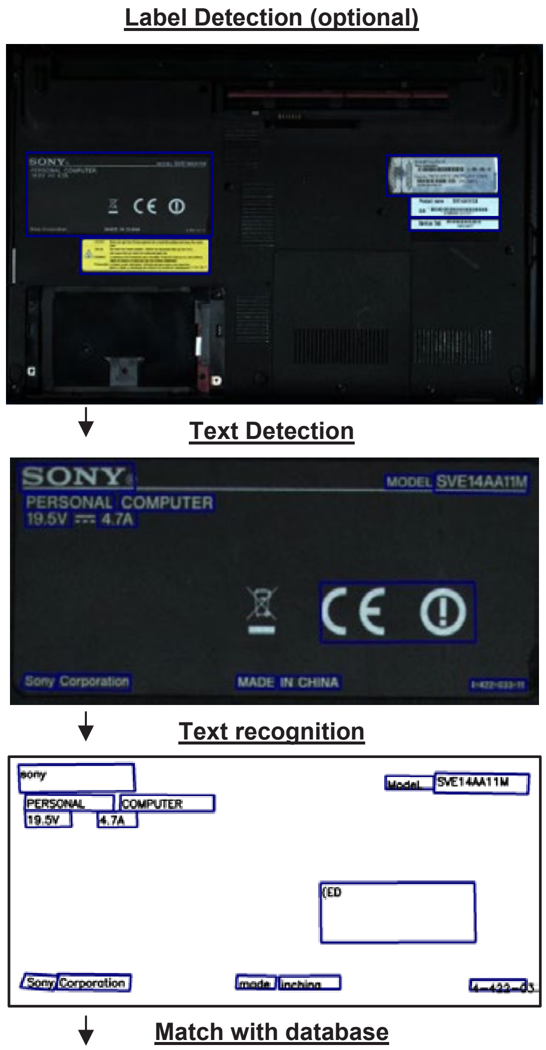
and be used in combination to retrieve product information in a database. In contrast, when a device is logged manually, only one description is often used to describe the model, making it sometimes impossible to retrieve devices from a database.

4. Product-specific information can automatically be retrieved when the device is identified. Hence, useful information can be retrieved or updated without human interaction, reducing the barrier of time constrains.

2 State-of-the-art computer vision techniques for retrieving information

In order to identify the device with OCR, the steps displayed on Figure 1 are required. If an image of the entire device is captured, the label, or multiple labels on the device, first need to be detected and cropped in order to be able to perform OCR on the label. After the label has been cropped, or if an image of the label was directly captured, the locations of all the text strings can be detected. Then, text recognition can be performed on the detected text regions to define all characters present. Both the optional label detection, text detection, and text recognition algorithm need to be able to handle the variation and challenges of scene images. For example, special fonts, damaged text, poor lighting and text portrayed on a rotated image or at an angle.

The classification, detection and recognition of text on scene images has been a deeply researched topic and a popular benchmark to evaluate the performance of newly developed scene detection and recognition algorithms. Whereas in the past, engineered pattern matching techniques were often used to identify characters with the most resemblance, deep learning architectures are today primarily used. These architectures consist of a number of layers that are trained to identify features that are increasingly distinctive as one layer passes information to the next. To train these deep learning architectures, large datasets of accurately annotated images such as the COCO-text dataset [7] are generally used.



Brand	Model	Category	...
Whirlpool	WTW5000	Washing machine	...
Sony	SVE14AA11M	Laptop	...
MSI	GS66	Laptop	...
Sony	SVP132A1CW	Laptop	...
Kitchenaid	K45 SS	Stand mixer	...

Figure 1: Overview of the envisaged OCR pipeline to identify information on labels of EEE

The approaches of state-of-the-art deep learning architectures to detect text differ widely. The Textboxes++ architecture [8] detects quadrilateral bounding boxes (a polygon with four edges and four vertices), and performs non-max suppression to select overlapping box proposals. This approach is commonly used for many general applications. Another approach is adopted by the Seglink architecture [9], which decomposes the task into detection *segments* and *links*, where segments are rotated textboxes, and links are vertices between neighbouring textboxes. This methodology makes the architecture especially robust for detecting rotated and warped text on scene images

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These are two distinct methods to improve the evaluation of the proposed detections. However, the design of architectures has also been improved over time. For specific applications, a standard model structure, trained on a large set of images to detect general objects is often used as a backbone and is then optimised. For example, the Single Shot Multibox Detector (SSD) [10] relies on the VGG-16 network [11], which can for example have been trained on ImageNet [12] dataset. Because of the size of the resulting model, a relatively large amount of time and computation is required to perform text detection. Therefore, the Deeply Supervised Object Detectors (DSOD) [13] architecture makes use of *deep supervision* as alternative by implementing *dense blocks*. Dense blocks are connected with all of the previous layers, whereas traditionally, only the previous layer is fed to the next. As a result, the intermediate layers are forced to learn discriminative features. This methodology was first implemented in the DenseNet [14] architecture. Another recent improvement is the use of *separable convolutional layers*, that split the convolution into a channel-wise and depth-wise operation. Both of these improvements greatly reduce the amount of parameters required, which results in a reduced size of the architecture, making them more suited for mobile applications, with MobileNets [15] as an example.

Because text recognition only needs to be performed on the detected regions with text strings, text recognition models are often smaller in size. For example, the Convolutional Recurrent Neural Network (CRNN) [16] architecture consist of a small number of convolutional layers followed by, for example, a Gated Recurrent Unit (GRU) [17] or Long Short-Term Memory (LSTM) [18] to extract the nature of text on images of labels, account for the variation in the representation of text, and learn patterns over time.

Finally, the extracted text needs to be compared with a database of device information in order to identify the device. In most cases, the recognized text will not be identical to database records because there are only small differences between certain characters, especially for model numbers, where letters, numbers, and other symbols are used interchangeably. Therefore, a technique to search for the most similar match in a database is required. During matching, multiple properties can also be considered for a proper evaluation, such as the brand, the model number and the category of the device.

The presented research focused on evaluating whether state-of-the-art text detection and recognition algorithms can robustly detect and recognize text on images captured of the label of the device. In future work, multiple state-of-the-art matching techniques will also be extensively researched.

3 Materials and methods

3.1 Materials: Case study datasets

Two case studies are evaluated. The first dataset consists of a sample of 200 images of labels from washing machines, randomly selected from a larger dataset of images. This dataset was made available by the company Servilux [19], which provides repair services. These images were captured by customers, often with a mobile phone, during an online service request procedure [20]. Therefore, the quality, size and resolution of the image can drastically differ from image to image. Even though the costumers can be given instructions on how to capture an image of the label, the quality of the image is often poor because customers are commonly first time users. Examples of this dataset are shown in Figure 2.

(a)

(b)

Figure 2: Examples from the dataset of images captured by unexperienced users. The model number is highlighted in yellow.

The label on Figure 2a, is fully displayed, not rotated, and well lit. On the contrary, the label on Figure 2b is not fully displayed and rotated. Therefore, it is more challenging to identify the device.

Within the Life Cycle Engineering research group of the University of KU Leuven, a conveyor belt setup with a high resolution Dalsa LineaTM 2K GigE VisionTM camera was constructed. With this setup, a total of 5000 images of laptops, which were collected to be recycled, were captured at a recycling company. A randomly selected sample of 100 images is selected as the second case study for this research. An image of the entire device is captured. Thus, label detection is performed to first detect and crop the labels. The text can still on the cropped label was anticipated to still be recognisable because a high resolution camera is used to captured the images in a controlled, well lit environment. An overview of the different challenges for both datasets is shown in Table 1.

	Case study datasets	
	Washing machine labels	**Laptops**
Purpose of images	Assist device repair	Assist in recycling
Device category	Washing machines	Laptops
Displayed on image	Labels only	Entire device
Image capturing	Smart phone or tablet camera	Dedicated high resolution camera
Environment	Uncontrolled scene by unexperienced operator	Controlled conveyor belt setup
Computing	Server	Dedicated hardware
Dataset size	200	100

Table 1: Overview of the properties of both datasets

Every image is manually evaluated to determine the quality of the image and the text. First, the presence or absence of a label, the model number and the brand is manually verified and annotated. Second, the properties of all images are evaluated by checking whether (1) the text is skewed because the image is captured from an angle larger than 45 degrees, (2) the text is blurry because the images are captured out of focus, (3) the text is damaged, (4) the label is partially cropped from the image or occluded because of an obstacle, such as the wire on Figure 2b, (5) reflection is visible on the image because of the flash of the camera or because of too much lighting, resulting in the occlusion of a number of characters, (6) the image is poorly lit, resulting in the occlusion of certain characters, or because (7) a very small text font is used or only for the repair dataset, only 20% of the label is displayed on the image. Finally, when one of these properties challenges the ability to visually recognise the text, the image is annotated as difficult.

3.2 Method for training and evaluating deep learning architectures for OCR

To first detect the labels on whole-device images of the Laptop dataset, the YOLOv2 object detection architecture [21] was used because of the fast detection speeds, relatively small network size in combination with good performance. A set of 135 different images was arbitrarily selected from the laptop dataset and all labels in these images were manually annotated and used for training. Weights pre-trained on the ImageNet dataset were used as a starting point.

Multiple state-of-the-art deep learning architectures are tested to evaluate the ability to perform OCR on images of the labels. To perform text detection, both the SegLink and Textboxes++ architectures, that both use the DSOD architecture as a backbone, were tested. To perform text recognition, both the CRNN architecture with GRU as the final layers, and CRNN with LSTM as the final layers are tested. Both text detection and text recognition are combined to identify the best performing pipeline. For both detection and recognition, weights trained on 80000 images from the SynthText dataset [22] were used. This is a dataset of scene images containing syntactically generated text.

These four pipelines were compared with two off-the-shelf text scanning modules: Tesseract, which is an open-source module, and Google Vision, which is a commercial platform which offers multiple image scanning solutions. An overview of the tested pipelines is shown in Table 2.

	Label detection (only on laptop dataset)	Text detection	Text recognition
1	YOLOv2	SegLink	CRNN (LSTM)
2	YOLOv2	SegLink	CRNN (GRU)
3	YOLOv2	TextBoxes++	CRNN (LSTM)
4	YOLOv2	TextBoxes++	CRNN (GRU)
5	YOLOv2	Google Vision	
6	YOLOv2	Tesseract	

Table 2: Overview of the tested text detection and recognition pipelines

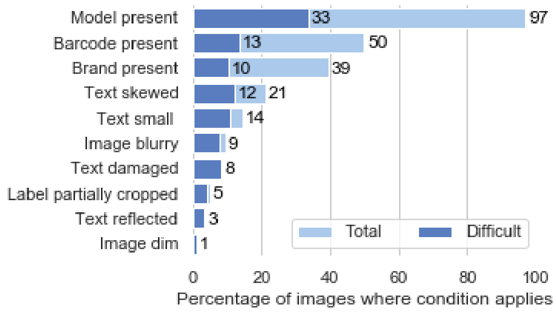
For this research, the evaluations were performed on a Nvidia Quadro P1000 GPU. However, to assist in the repair of devices, a smartphone or tablet application would be preferred as a platform. Therefore, the image captured by the user would be sent to a server. The OCR label identification pipeline would then be run on the online server. In comparison with a dedicated setup, the computing power and memory of servers is limited. The amount of parameters and memory use of the used deep learning model is therefore also limited. On the contrary, to assist in the recycling of WEEE, a dedicated setup is realistic to be used to run the OCR device identification pipeline. More computing power and memory is then available in and larger deep learning models could be used.

To evaluate and compare the ability of the pipelines to identify the device. The extracted text was compared with the ground truth model number by calculating the Levenshtein distance between every recognized string and the known model number. The string with the highest Levenshtein distance was then selected as the model number prediction by the OCR pipeline. The Levenshtein distance acts as a metric to quantify the difference between two text strings. The output of the calculation is a value between 0 and 100. The closer the matched text string is the 100, the higher the chance of being able to match the result with a database. A pass-fail criteria would not allow for this evaluation to be made. When a string is matched with a Levenshtein distance of 100, there is no difference between the extracted text and the ground truth model number. At a Levenshtein distance above 80% only a small number of characters is incorrectly recognized and the characters are generally very similar in shape to the ground truth. At a distance above 60% multiple characters are misinterpreted, possibly due to the challenging condition of the image. However, there is oftentimes still a significant relation between the interpretation of the model number and the ground truth. Every pipeline was tested on both datasets and the Levenshtein distances were calculated. This method was also used to evaluate whether, on average, a lower Levenshtein score was obtained for images that were manually annotated as difficult, which would indicate that the OCR text extraction pipelines would struggle with extracting text from difficult images.

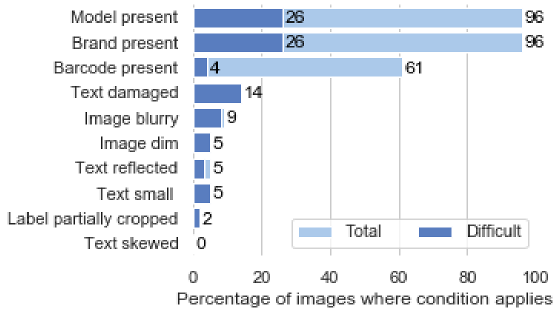
4 Results & Discussion

4.1 Dataset image characteristics

By manually annotating the characteristics of both datasets, the challenges of evaluating both datasets with OCR could be determined. The resulting bar plots are displayed in Figure 3.



(a)



(b)

Figure 3: Overview of the characteristics of the washing machine dataset of images to assist repair (a) and the laptop dataset of images for recycling (b).

The model number was identified on 97% and 96% of the images of the washing machine and laptop datasets respectively. This indicates that a large share of the arbitrarily selected images contain a model number on the label, which is positive for the proposed OCR identification pipeline.

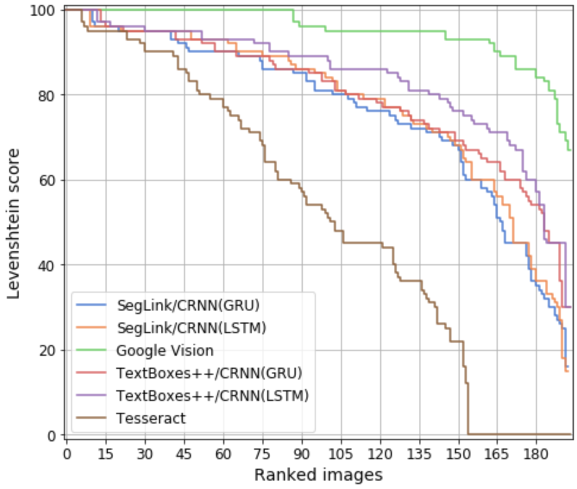
Furthermore, the most frequent negative characteristic for the washing machine dataset is skewed text with a share of 21%. This is because unexperienced users often capture the image at an angle when the label is hard to reach, for example, when the label is at the back of the washing machine. Only 39% of the time, the brand can also be identified on the labels of the washing machines. This can primarily be explained because washing machines often contain a label of solely the model number on the front of the washing machine. In total, 32% of the images were annotated as difficult due to a variety of issues, especially skewed text, text with a small font, a blurry image, and a damaged label.

On the laptop dataset, a total of 25% of the images were annotated as difficult. Mainly due to damaged text, which can be explained as these products have often been discarded and collected with limited care. Thus, for these products it will be important to handle the challenge of damaged and dirty text.

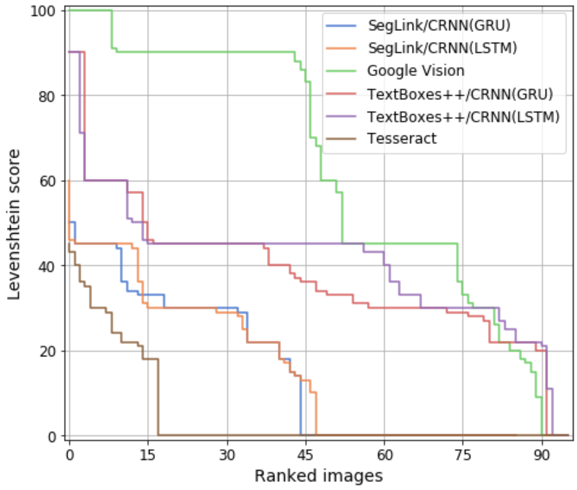
4.2 Dataset image characteristics

As shown in Figure 4a, the overall performance on the washing machine dataset of images for repair is promising. Especially on the Google Vision pipeline, were a Levenshtein distance of over 80% was calculated for 95% of the images. After Google vision, the Textboxes++ text detection model in combination with the CRNN text recognition model with LSTM performed best with an over 80% Levenshtein distance for 70% of the devices. This is a significant difference with the Google Vision pipeline, but the results still indicate the applicability for the envisaged applications and show the opportunities for further improvements. No trend of low Levenshtein scores were also examined on the images annotated as difficult. Instead, the scores of difficult images were found to be spread in a similar manner as the other images. This indicates that, images are not matched with a low score because of the difficulty of the image, but rather that further specialised training and optimisation is required for the network to be able to handle the detection and recognition of text on labels.

On the dataset of images for recycling from laptops, shown in Figure 4b, the current calculated Levenshtein distances are poor, especially for the open-source pipelines. However, a Levenshtein distance above 90% is still calculated for 40% of the images with the Google Vision pipeline. This result suggests that the YOLOv2 label detection module does often succeed to detect the labels. Hence, it are the text detection and recognition algorithms which are expected to fail to find text on the cropped labels. Again, it was found that not only the difficult images receive a low Levenshtein distance score. Hence, opportunities are still expected in improving the training for the task at hand.



(a)



(b)

Figure 4. Overview the Levenshtein matching distance on multiple OCR text detection pipelines on the dataset of images to assist repair (a) and the dataset of images to assist recycling (b).

5 Conclusion & Future Work

The labour intensity and barriers of manual product identification challenge the economic viability of implementing end-of-life treatment options and improvements for EEE which are preferred from a circular economy perspective. These difficulties are extensively reviewed for four end-of-life treatment options for EEE: self- and community repair, professional repair, repair by second-hand stores, and recycling WEEE. As an alternative, a method is proposed in which an image is captured of the device or the label depending on the application, the label is optionally detected and cropped if an image of the entire device was captured, the text on the label is detected, text recognition is performed on the regions of detected text, and finally, the extracted text is matched with a database of devices. The proposed pipeline poses major advantages and possibilities for end-of-life treatment improvement, such as the ability to perform an automated product-specific recycling procedure, and the ability to easily retrieve and update notes and links to useful repair guides.

To evaluate this methodology, two datasets were used. A dataset of 200 images of the labels on washing machines, captured by consumers with the goal of identifying the device to receive repair assistance, and a dataset of 100 whole-device images of laptops captured on a conveyor belt setup with a high-resolution camera, with the goal of identifying the device to improve the recycling procedure. The different state-of-the-art deep learning combinations of a label detection architecture for the dataset of whole-device images, two text detection architectures, and two text recognition architectures are compared with the performance of two text scanning modules: Tesseract, which is an open-source module, and Google Vision, which is a commercial platform.

The results of the performed experiments with the washing machine dataset are promising. With a Seglink text detection and CRNN text recognition pipeline, 87,5% of the device model numbers were recognized with a Levenshtein distance of over 60%, and with the Google Vision commercially available OCR platform, 92,5% of the device model numbers were recognized with a Levenshtein distance of over 80%. The results obtained with the dataset of laptops for recycling are currently poor for all evaluated methods. However, different opportunities for retraining the adopted networks have been identified, which are expected to significantly improve the detection and recognition results.

In future research, state-of-the-art matching algorithms will be investigated, to match the extracted text from the in this research presented best performing OCR pipelines with a database. The text detection and recognition architectures will also be retrained and optimised for this application. In addition, the current optional label detection architecture will be integrated into the currently used text detection architectures to form one model to perform both tasks. Furthermore, additional modules, such as barcode scanning will be investigated to provide more information to identify the device.

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C.2

ASSESSMENT: LIFETIME, ROBUSTNESS AND CIRCULARITY METRICS

Projected Obsolescence in Electric and Electronic Consumer Equipment? – What are the Limiters of Lifetime, Service Life and Reparability of Modern Consumer Electr(on)ics?

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Abstract

In the recent years, projected obsolescence became a political issue, understanding that manufacturers of electronic/ electric equipment limit the service life of their equipment in order to secure a continuous market demand for renewal purchases or consumables. While only few cases were proven, the public discussion of projected obsolescence derailed by assuming projected obsolescence in a wide variety of electronic appliances. This paper tries to get back to the facts by highlighting today's real limitations in service time, in which cases projected obsolescence really has been observed and why, and where and by which measures the service lifetime of electronic and electric equipment can be extended.

1 Introduction

In general, if someone buys an electronic device, his expectation is that it will serve reliably for a long time. At the same time, a cheap price is expected for modern consumer electronic equipment. Between 1980 and 2000, a nearly ruinous competition with Far East manufacturers bankrupted most of European consumer electronic companies. Former famous names like Grundig, Graetz, Philips etc. sold or closed their consumer device factories – today, they are no more than labels of their ancient Far East competitors. The worldwide hard competition forced sub-suppliers to lower their production cost, so that derating, redundancy, failure tolerance etc became a privilege of industrial and professional electronics – at appropriate prices. Consumer electronics manufacturers started to think about what are limiting factors of service times of their appliances – and found that a continuous flipover of new standards, the force towards miniaturization and even fashion/ design aspects became by far more service-time-limiting factors than the lifetime of the components on the printed circuit boards. This brought questions up, whether it is useful (and copes with competition aspects) to use expensive high-reliability components with an expected lifetime of, say, 20 years, to build a consumer electronic apparatus with an expected average service-time of, say, a maximum of 5 years. Indeed, in the recent years, it became obvious that some equipment just failed short time after the warranty expired, and, in consequence, a discussion about projected obsolescence came up. This paper introduces in more depth into the topic with respect to different aspects as lifetime, service time limitations, production cost aspects and customer expectations.

2 Projected Obsolescence: a definition trial

Obsolescence describes an approach to limit the usability-time of a product by a dedicated selection of materials, components, production methodologies, design issues, adaption to (expiring) standards, etc. Projected obsolescence means to plan the period of usability (that what we call in following service-time) towards a dedicated time frame in order to ensure a continuous marked demand on replacement products or at least to ensure a continuous sales flow of consumables for this product.

Here we have to distinguish between two kinds of projected obsolescence:

The first one, ensuring a continuous market demand of the product itself, would mean that the construction of the product itself would limit the service time. An easily comprehensive example would be the use of a control processor IC that is compatible with the actual software at the time of sale. If, however, already the next version of this product would use a later software version, which cannot run on the processor used in the old hardware but would need a newer one, this would already limit the service lifetime, since no upward compatibility is given anymore and the support of the old soft- and hardware would be terminated.

The second type of projected obsolescence doesn't target onto the product itself but on its consumables. In such cases, sometimes, the product price is at a very low level, while the consumables are expensive and business plans are based on the sales of consumables. Here we meet the projected obsolescence in a short service time of these consumables. In addition, the manufacturer tries to protect his equipment against the use of third party consumables, which usually are compatible with the original consumables. Typical examples are printer cartridges or ink cartridges of printers, where already at an early time (when still enough ink resp. colour powder would be available) a replacement is recommended and indicated. Another example are electric toothbrushes, where only original replacement toothbrushes may work, if an RFID device verifies the use of the original or approved consumable. The same may (but must not) apply for ink cartridges or other consumables in order to avoid the use of cheap third party consumables or those sold directly from OEMs.

When discussing about projected obsolescence, it is mandatory to evaluate the limitations of service times of various consumer electronic equipment. This evaluation will show, where and whether obsolescence is the limiting factor respectively what are real limiting factors in service time.

3 Limiting factors in lifetime and service time of electronic equipment

3.1. The bathtub curve and the equipment lifetime

Many of the readers might already know the bathtub curve, describing the failure rate versus the time of use. This curve (fig. 1) is generally valid for any kind of technical systems (and not only for them) and has three sections, forming it to a kind of "bathtub cross-section": at the beginning of the lifetime, the failure rate is

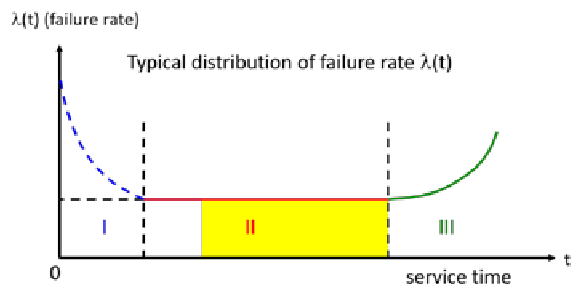

Fig. 1 bathtub curve of failure rates

rather high and described as "childhood" or "early-life"-failures. Typical examples are bad solder joints, missing contacts etc., causing failures at an early time after the initial operation. When these bugs are fixed, a long period with a continuously low level of failures follows, describing the service time. The failures in this period are frequently root-caused from outside; for instance, accidents, voltage transients, misuse or operation under harsh, non-specified environmental conditions are in this category. In the third section - at the end of the service time, the failure rate increases again, but now, the failures are caused by real wearout effects of components. At that time, repair costs increase and, in most cases, they reach a level where further repairs are no more justified due to economic reasons. Today, only few consumer electronic devices reach the third section of this curve, describing their real lifetime limitation.

3.2. Early life failures – are they obsolescence?

The abovementioned competition forces generated two phenomena: On the side of the construction departments of consumer electronic equipment, derating became a luxury term. This means that the components used in the circuitry are exactly specified for the voltage and current load applied there. There is no guardband between specification and real use load. Using components, which could suffer short-term current overload or voltage transients, would create additional cost and sometimes would need even more space – both are no-goes in nowadays economic pressure.

Since the same issue applies to the component manufacturers, it ends up in components, which must not suffer loads beyond their specification without suffering fast damage. This superimposition concludes in the fact that today many early life failures are the result of a combination of missing derating in circuit design and a "sportive" specification of the components used in this circuitry – ending up in a discussion between what experts call "electrical overstress" (EOS) and robustness, see fig. 2. In fig. 3, we can see that the category

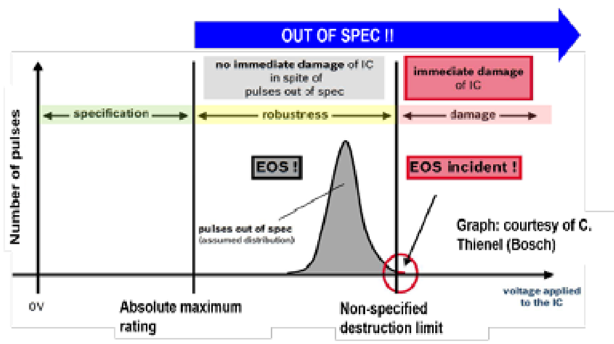

Fig. 2 Electrical Overstress (EOS) may result if devices are operated b their specification within a non-specified area called "robustness". Missing derating, cost saving and sportive device specifications are often superimposed in consumer electronics

"overload and missing derating" is a big part of the total of EOS failures. Another big part are missing protection circuitries against transient voltage spikes, which may kill semiconductor devices, relay contacts and capacitors. Both categories cause early life failures and,

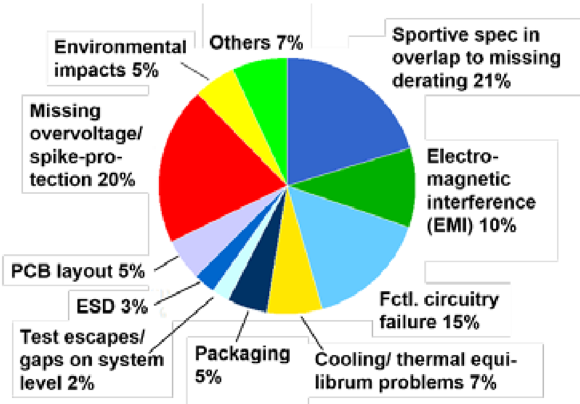

Fig. 3 Electrical Overstress (EOS) root causes

thus, are hardly projected obsolescence: if a consumer electronic apparatus fails within the guarantee time, it is by far more expensive for the manufacturer than providing some derating and it might even cause expensive public callbacks.

3.3. Development of repair strategies and its consequence for obsolescence

Up to the early nineties, consumer electronic manufacturers mainly used standard components, which could be bought in any repair shop or service center for comparably small money. With the ongoing integration of semiconductors, the triumphal procession of so-called ASICs (Application-Specific Integrated Circuit) began. ASICs are non-standard ICs, designed for a specific application in one dedicated type of apparatus. Of course, their manufacturing lasts only for a short period-of-time, hardly longer than the application equipment is on sale. In large-volume productions, ASICs can save a lot of cost and space compared to a construction based on standard components. However, considering billions of different consumer apparatus, no service shop can hold a reasonable stock of ASIC spare parts. While repairs of apparatus up to the nineties could be conducted easily in the dealer's service workshop, todays repair coffee shops are limited to the repair of very simple failures as for instance broken power cables, burned filter capacitors, defective switches, exchange of flat screens or power supplies. A repair in depth, based on standard components and a detailed knowledge and understanding of the functional circuitry is no more possible in most cases of modern consumer electronic equipment. Furthermore, the repair cost would be immense, if a highly paid expert would need for instance some hours to repair a TV-set. Therefore, repair paradigms of complex consumer electronics have changed towards refurbishment. This means that defective equipment is sent to a specific refurbishing factory of the manufacturer, where the equipment is disassembled into 5-6 key components. These component blocks are automatically tested on their functionality. Good components are used to rebuilt a "new" setup for sale or warranty exchanges while the malfunction components are directly material-recycled – or forwarded to a deeper failure analysis in order to highlight systematic production- or construction-weakness items. It is self-understanding, that a refurbishment strategy is only useful to repair early life failures (which are the most expensive ones, since many of them appear within the warranty period); thus a projected obsolescence would generate more cost than generate payback-effects.

3.4. Nowadays limitations of service-time of consumer electronics

At first, let us have a look at the historical development of service times and the main reasons which limited the service times of typical consumer electr(on)ic products, which is summarized in table 1. This table shows two main trends: in general, the service time becomes shorter, especially considering electronic products

equipment	Service time which can be reached within a household-typical use	Achievable service time by technical improvements	Really reached average service time	This service time was limited due to…
TV-set	10 years	15 years	7 years	New standards and channels, improved image resolution
Hair dryer	10 years	25 years	7 years	Defective cables or switches, motor blocked by hairs, hygiene
Toaster	7-8 years	10 years	5-8 years	Heating wire open, hygiene
Laptop	10 years	20 years	3-5 years	Software, slow processors, memory limitation
Smartphone	15 years	20 years	2-3 years	Software incompatibilities, new features, trendy designs
Washing machine	10-15 years	15-20 years	10 years	Switching unit, water exit, drive belt, too high energy- and water consumption
refrigerator	20 years	25 years	15 years	Exit of cooling liquid, missing isolation, energy efficiency
Laser printer	5-10 years	15 years	5 years	shmeering due to internal dirt, mechanical defects, toner availability and -cost
LED lamp with E27-socket	2-6 years	10 years	2-6 years	Capacitor failures, SMD-resistor failures in the electronics, LED chain opens
Electric toothbrush	6 years	10 years	6 years	Humidity ingress into electronics, hygiene

Table 1 Service time limitations of consumer electronic and electric equipment

(while for electric products (e.g. refrigerators, vacuumizers…), the decrease is slower). The second trend changes with the implementation of highly integrated electronics. Before this time, (electronics made by using discrete and standardized components), typical end-of-life failures as broken capacitors, failed electronic tubes show that the equipment has been used as long as possible and even at the end, repair trials were made before taking a decision to replace the equipment. With the upcoming high-integration of electronics, more feature-related reasons ended the service time. Improved features in smartphones, the implementation of HDTV in TV-sets, lower energy consumption dominate from this time on, so that many consumer electronics were wasted or recycled before they failed in their specified functions. A further significant contribution in limiting the service time is shown in table 2: The rapid development in new technologies in general brought many cross-sectional technologies onto the market, which just dispensed the equipment based on previous technologies. In the 21st century, this

equipment	Approx. Average service time	Replaced by
typewriter	>20 years	Personal Computer/ printer
Photo camera with film	20 years	Smartphone, digital camera
Telephone: mechanical operation centers	40 years	Computer systems/ VoIP/ smartphones
Vinyl disc player	15 years	Compact Disc/ CD-Player
CD-player/ DVD player	10-15 years	Internet streaming/ downloads/ MemStick
Vacuum cleaner	10-20 years	Roboters, building-embedded airflow cleaning systems
Telefax	10-15 years	E-Mail-attachments
Light bulb	2 years (household-typical use)	Fluorescent lamp
Fluorescent lamp	5 years (household-typical use)	LED lamp
Computer-hard disc (magnetic)	3-4 years	SSD memory (semiconductor-based)
FM Radio	10 Jahre	DAB/ DAB+ radio, FM termination

Table 2: Limitation of consumer electric and electronic equipment due to cross sectional technologies

happens sometimes even within few years, so that today, the service time of any technical equipment nearly never reaches the end-of-life period of the bathtub curve. From this point-of-view, it becomes comprehensive to design new products not as durable as possible by using highest quality components (as former-generation engineers did) but to consider the expected real lifetime, the market demand and the economic frame conditions of a new product. Also in this case, we should not talk about projected obsolescence.

3.5. Economic and environment aspects of repairs

Considering this topic, also a historical review is useful to understand actual developments and limitations. I took two examples of consumer electronic: a TV set (fig. 4) and a cellphone (fig. 5) and compared their de-

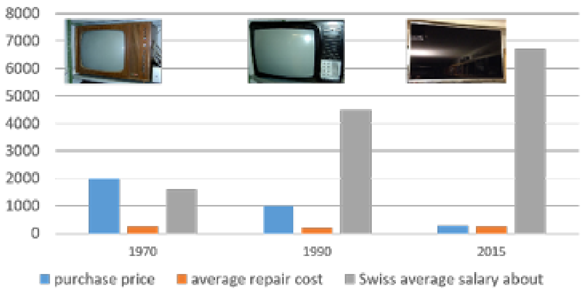

Fig. 4 Purchase- and average repair cost (CHF) in Switzerland versus income: example TV set

velopment in the categories "purchase price", "average repair cost" and "average salary of men in Switzerland); each for three years (1970, 1990 and 2015). Where I could not find proven statistical data, I replaced it by "best engineering assumptions", based on my own experience in my private technical museum, in which I personally collect and repair such equipment since I was a 14-years-old pupil. First, these charts show that the development of purchase price and salaries show opposing trends. The repair costs, however,

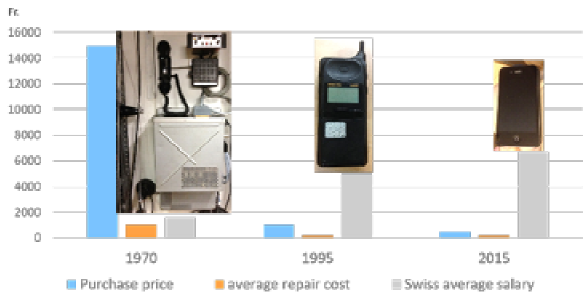

Fig. 5 Purchase- and average repair cost (CHF) in Switzerland versus income: example mobile phone

remain more or less stable with the consequence that today, in many cases repair (if actually possible) costs are at a higher level than a replacement.

A special role is that of the repair coffee shops. Their activity is limited to repairs where still standard spare parts can be used as cables, switches, capacitors etc. In addition, some of these locations also use replacement parts from scrapped electronics (which however, needs significant storage space). Repair coffee shops usually are operated by voluntary technical retirees and low-cost workers and are not linked to specific brands so that may use non-specified workarounds for their repair activities and their fix costs are comparably rather low. Anyhow, their repair success rate is between 40 and 60%, which underlines that, even today, many trivial defects and not complicate hard- and software failures cause a high amount of equipment defaults.

Considering environment aspects, three contributors need to be observed: the energy and material consumption needed for producing a replacement equipment and, second, the energy consumption during operation within the service time and, third, the energy cost and material losses during the recycling process.

4 Projected Obsolescence: a ghost discussion?

A frequently cited early example of projected obsolescence is the filament lamp syndicate (also known as Phoebus syndicate) of 1925, where the leading filament lamp manufacturers met in Geneva. In the public conscience, it was spread that this syndicate met there to agree on a maximum operation time of filament lamps of 1000 hours and to share the world market. However, the real purpose has been a standardization meeting, since at that time, filament lamps were produced for a variety of applications with rather different requirements as for instance:

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- Lamps to illuminate rooms
- Lamps for cinema projection
- Lamps for advertising and ornamentation
- Lamps for signals

In a filament lamp, three main parameters are dependent from each other:

- Brightness
- Current consumption
- Lifetime

The same lamp is useful as a very bright lamp, but then it needs more current to shine bright and it will suffer a reduction in lifetime. In contradiction, in a signal, long-term lifetime is more important than brightness. And a household lamp requires both a minimum brightness and reasonable current consumption. Based on these different requirements, general agreements have been fixed there. The discussion, whether this ancient lifetime agreement of 1000 hours for household applications, should be regarded as a useful compromise between brightness, current consumption and service time, or as a first famous case of projected obsolescence, is still ongoing and controversial.

Since projected obsolescence in electronic equipment would target on early life failures, it would be a high-risk approach to promote the market demand. First, in many countries, the legal warranty periods are so long that related failures would create returns or repair activities, becoming severe factors in both avoidable cost and loss of reputation to the manufacturers. Therefore, real obsolescence of today targets more on consumables and software issues. Considering consumables, already printer cartridges and electric toothbrushes have been mentioned as examples. All electric and electronic equipment needing consumables for its regular operation purpose is a potential subject of this kind of projected obsolescence.

Another approach targets on software compatibility and extended features, performing a benefit to the end user. The trick here is to make the previous generation of the same equipment incompatible to the new features and to make upgrades of previous-generation-equipment impossible or at least difficult. If software is not an issue, indirect projected obsolescence can also be achieved by incompatibilities in the hardware. Here, favored approaches are interface incompatibilities, deviating connector standards, the implementation of non-upgradeable user features, non- or difficult-exchangeable accumulators, buffer batteries with short-limited lifetime and frequent changes in standards.

A third category, often used with very cheap electronics is to make access to warranty or repair services as difficult as possible. If the equipment has been distributed at low cost, many users tend to replace it by new items, even if the problem appeared within the warranty period. High shipping cost or difficult return- or service procedures may make the customer preferring another lost-cost replacement instead of making use of repair/refurbishment or even guarantee claims.

In few cases, failures may be looked at as projected obsolescence, where, in reality, technical limitations are still at the border of serial production. For instance, lifetimes up to 20'000 hours were solicited for 230V-E27socket LED bulbs with in-socket drivers. In reality, many died already after short time by small electrolytic capacitor explosion. The sockets were just too small to offer enough space for capacitors which could withstand the operational voltage for long time (fig. 6). Even facing such risks, capacitor- and LED-lamp manufacturers were worldwide under competition pressure to offer these lamps nearly at the same time.

Fig. 6 LED lamp with E27 socket (left); disassembled socket with a replaced bigger electrolytic capacitor for demo purpose (right)

5 Approaches against projected obsolescence

In order to both minimize projected obsolescence and to promote the idea of "Electronics Goes Green", several legal and accreditation (e.g. CE sign) initiatives would help increasing service times and slow down the cycle of purchase – use – recycling of consumer electronics. Projected obsolescence and reparability are natural enemies and, thus, all measures promoting reparability are measures are at the same time a precaution against projected obsolescence. Here the most important suggestions are listed:

Restrictions of defeat devices, which just avoid the use of equipment-compatible consumables of third-party manufacturers and OEMs.

Standardization of Li-ion batteries, operation voltages and battery charging units (partially, some progress in the last point has been made already by implementing USB standards for this purpose)

Legal entitlement of free-of-charge and on-site-service in case of enforced technology changes regarding standards, router exchanges e.g. due to glass fiber implementation, program sequence changes (TV cable providers) etc. Today, many elder persons are excluded from latest technologies, since they are overstrained in self-implementing/ installing new equipment every year.

Standardization of many frequent interfaces (e.g. earphones, chargers, signal in-/outputs)

Prescriptions considering easy access for battery exchanges and housing disassembly for repair purpose (e.g. ban of one-way- or special-screws, self- destroying plastic clips etc.)

Upwards compatibility prescriptions for new soft- and hardware to avoid total losses in functionality

Prescription of galvanic decoupling switches to limit a blow-up of numbers of standby equipment with the upcoming artificial intelligence trends

Consideration of long-term standby operation power needs in energy classifications

Prescription of an open-source policy by sharing technical documents as circuitry, assembly diagrams, part number lists etc. of consumer equipment for repair purpose (free-of-charge downloads)

Implementation of a European-based, manufacturer-independent technical commission, dealing with mandatory standardizations in consumer electronics, its user-friendliness (manuals!), also acting as a European ombuds-office and complaint point for consumer electronics

6 Conclusion

At the beginning of the conclusion, let me state a personal remark: this paper is neither to be understood as a literature review nor as a classical research work. I am collecting and repairing electric and electronic equipment since my pupil age of 14. Today, I operate a private technical museum including various fields of electronics and within my 40-years professional career, I've been working on the reliability of professional and industrial electronics from device-to-system level. From this point-of-view, this paper should be understood as an experience report and a critical view onto the discussion of projected obsolescence including all its technical and economic aspects around.

Comparing the reliability of an electronic tube function and a transistor function within a modern integrated circuit, we know, that modern electronics are orders-of-magnitude more reliable and lower in energy consumption than they were in former times. Of course, this matter-of-fact encouraged the hard competition to exhaust (frequently unneeded) functions and features and to approach to the actual technical limits of miniaturization – frequently on the account of derating, overload-tolerant specification ("robustness") and reparability. In parallel, the production cycles were accelerated, meaning, that modern electronic consumer equipment are produced for a maximum of 2-4 years before their replacement by the next generation with more features, smaller dimensions and often even new standards. Today, these factors are responsible that the service time of electronic equipment became shorter. Nowadays scrapped or recycled equipment is in most cases still fully functional, but the user doesn't regard it as state-of-the-art anymore. This is by far the most limiting factor in service time, while in comparison, projected obsolescence is by far a minor issue. Indeed projected obsolescence exists but many aspects of this problem could be handled and effectively limited by legal initiatives on an international basis.

7 Literature recommendations (not-text-related, but for further reading)

[1] Rivera, Julio L. "Environmental implications of planned obsolescence and product lifetime: a literature review", International Journal of Sustainable Engineering, Vol. 9 2016, Issue 2, p.119-129

[2] Walker, Stuart, "Longer Lasting Products: Alternatives to the Throwaway Society", Book Review, edited by Tim Cooper, The Design Journal, Vol. 14, 2011, Issue 3, p. 375-380, DOI

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Current State of Durability Assessment for Four Consumer Product Groups

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Abstract

Four consumer product groups (Vacuum cleaners, washing machines, mobile phones and television sets) have been analysed in regard to the current state of durability assessment. The dominant failures have been determined and compared to the current test programs. Gaps in current tests as well as requirements for tests to close these gaps have been identified.

1 Introduction

Postponing obsolescence for end-user products is a task that involves different aspects. The EU project PROMPT is dedicated towards developing a test program, enabling consumer organizations and public authorities. This paper focuses on one aspect of the project, which is the measurement and assessment of durability measures with respect to product reliability and lifetime. This is a challenge because lifetime and durability measurements can be costly and time consuming. In order to specify the specific needs and gaps in the given context, four product groups have been systematically analysed. On the one hand, washing machines and vacuum cleaners represent white goods. On the other hand, smartphones and televisions represent consumer IT-products.

In a first step, the analysis is based on different input data sources. On the one hand, data from consumer reports with respect to product failures have been analysed, on the other hand, data has been gathered from expert interviews within the PROMPT consortium. From this data dominant "failure modes" are identified and the top 3 are chosen for further investigation. In the next step current existing test programs have been analysed with respect to their relevance to the given "failure modes". Gaps in testing are identified as well as areas where tests can be improved with the goal of developing new tests for better reliability assessment for consumer organizations and public authorities.

2 Dominant Failures in the product groups

To identify relevant gaps in current testing approaches the dominant failures in each product group (vacuum cleaners, washing machines, mobile phones, television sets) have to be determined. Based on various resources as well as customer surveys within the PROMPT project, the most relevant failures have been identified [1], [2], [3], [4], [5], [6]. Most of the available data is in agreement with the findings in the PROMPT project. The most notable difference is that batteries are the most critical part of cordless vacuum cleaners. This will have to be accounted for with the increasing number of cordless vacuum cleaners in the market. Table 1 shows the most relevant failed parts that are investigated. It should be noted that data aggregated in the project for mobile phones and television sets also show a large impact of software in regards to obsolescence. Software is not part of the investigation.

Vacuum cleaners	**Washing machines**	**Mobile phones**	**Television sets**
Battery	Electronics	Battery	Screen
Motor	Shock absorbers/ bearing	Screen	Power Supply
Cable and return mechanism	Motor	Connector	Connectors
		Speaker	

Table 1: Most relevant parts in the product groups

3 Breakdown of failure causes

To determine if there are gaps in the current testing programs, it is necessary to understand what can cause these parts to fail in more detail. Each of the identified parts can fail due to one or more failure mechanisms. These failure mechanisms are activated by various loads. It is important to know what causes these failures to determine if the current test can excite theses mechanisms to test the products. While scientific literature

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on failure modes and mechanisms of domestic appliances is scarce, guides and manuals by repair initiatives offer some insight into possible failure causes and derivable mechanisms.

3.1 Vacuum cleaners

Concerning battery-powered vacuum cleaners, the battery appears to be a major failure cause. In case of lithium-ion batteries, failures of the battery can be expected to be caused by common failure mechanisms for these batteries, i. e. cell-ageing and subsequent loss of capacity and increase of internal impedance [7].

For mains-powered vacuum cleaners, the motor and the cable are major failure causes. Failure of the motor can be caused by overheating, possibly due to clogging or by water damage due to wet filters or bags. Universal AC/DC motors which use carbon brushes may fail due to various problems associated with the brushes, e. g. wear-out of the brushes or connection problems. As vacuum cleaners are subjected to dust or dirt, accumulated debris on the brushes can cause a loss of contact between brush and commutator. Problems with carbon brushes may cause intermittent or permanent motor failure or sparking [8]. Also, coil insulation may degrade over time due to temperature and humidity causing electrical shorts.

As vacuum cleaners employ switching devices like TRIACs for motor power control, motor failures can actually be failures of the motor control. The TRIACs inside a vacuum cleaner are particularly vulnerable to operating conditions that occur when the nozzle or tube is blocked as this causes increased motor current and cuts off airflow required for cooling of the electronics. This, in turn, leads to greatly increased thermal impedance of the heatsink and high junction temperatures of the TRIACs and subsequently decreased lifetime of the TRIACs [9].

Deterioration of the cable can be accelerated by poor design of the housing, as sharp edges, or too much bending of the cable during use. Other causes include insufficient robustness of (cable, spring and break) for repeated use. Failure of the cable, return mechanism or the return brake can be further accelerated by misuse such as bending of the cable.

3.2 Mobile phones

The most reported failed hardware parts for mobile phones are the battery and screen followed by the connector and speakers. The last two having a much smaller impact in most surveys. As mentioned in the vacuum cleaners section, failure of lithium-ion batteries occurs primarily via loss of capacity and increase of internal impedance over lifetime due to cell ageing. Cell ageing and subsequent loss of capacitance may be accelerated by various factors such as state of charge/depth of discharge, the quality of the charger and battery management system and extreme ambient temperatures [3]. Besides the loss of capacitance, ageing of the battery can also lead to swelling, especially if overcharging or high ambient temperatures occur. Swelling of the battery can lead to deformation or damaging of the mobile phone or damaging of battery pack enclosures [7].

Most common failure causes for the screen are scratches and cracks or splinters which are overwhelmingly induced by drops of the phone from the hand or back pocket. In most cases, this leads to broken glass without further damage to the screen [10]. Thermal cycling can also lead to failures in packaging technologies and interconnects which can cause screen scrambling or intermittent failures of the screen [11]. The used OLEDs or LEDs can age leading to less brightness or loss of contrast. Typical ageing-related degradation mechanisms for OLEDs or LEDs used in screens are mostly driven by elevated temperatures. OLED screens are also susceptible to screen burn-in, caused by the display of static images or screen elements for long periods. To mitigate the risk of burn-in and to increase lifetime, modern screen technologies implement software-controlled methods, e.g. by local dimming or shifting the position of always-on display elements like clocks.

Apart from the major failures as shown in Table 1, the connector and speaker are less often a concern. For both parts the failure causes are mechanical loads due to drops and repeated use as well as water damage or particle intake if protective mechanisms are insufficient. Current water protection mechanisms can degrade during use and thus increases the susceptibility of the phone to water damage over time. Ingress of water can also damage other electronic components due to electrochemical migration, corrosion or conductive anodic filaments [12].

3.3 Washing machines

Defective shock absorbers are caused by too high loads, imbalanced loads or low-quality materials. Defective bearings are commonly caused by wear and tear of the bearing and accelerated by undersized bearings or poor quality materials, e. g. plastic housing.

In June 2013, a web survey was conducted by *RREUSE* (Reuse and Recycling Social Enterprises in the European Union) among members working in the field of reuse and repair to gather information about failure causes and mechanisms, repairability and product design of washing machines. Respondents pointed out several possible causes for washing machine failures. Examples are shock absorbers and bearings not designed for spinning speeds of current washing machines, leading to accelerated degradation. Often, rubber seals degrade, possibly blocking pumps or causing water or dirt ingress into bearings. Degradation of pressure switch membranes can lead to failure of the switches, causing the washing machine to take in too much water [13].

As washing machine electronics are normally subjected to moisture as well as heat, failure mechanisms for electronics can be both heat- and moisture-induced. Mechanisms induced by moisture can be expected to be similar to those of mobile phone electronics, discussed in section **Fehler! Verweisquelle konnte nicht gefunden werden.**. The formation of CAF in washing machine electronics can be expected to be less likely since washing machine PCBs and components are generally less miniaturized than mobile phone electronics. Heat-induced failure mechanisms are discussed in section 3.4 as these are the main failure causes for television sets.

Failures of washing machine power supply units (PSUs) caused by failure of non-isolated DC/DC-converters within the PSU are frequently reported [15]. As this usually leads to subsequent failure of the external input resistor, a likely failure mechanism is dielectric breakdown of the gate oxide caused by voltage peaks or gradual degradation. Failures of the PSU due to degradation of electrolytic capacitors are also possible and are discussed in section 3.4.

3.4 Television sets

Failures or defects of the screen may occur in the form of dead pixels, screen burn-in, controller defects, failures of LED backlight units (BLUs) or mechanical defects. Dead pixels are caused by malfunction of transistors in the screen which result from manufacturing defects and may be present on new devices or develop over time. Screen burn-in concerns mainly OLED displays and is discussed in section 3.2 of mobile phones.

Possible failure mechanisms of LED BLUs can be divided into failures of the LED strips and failures of the driver boards. Failure of LED strips can be caused by thermal cycling or exposure to moisture leading to interface delamination, solder fatigue or chemical degradation of the lens. Failure of driver boards can be caused by degradation of the components, e. g. MOSFET degradation due to hot carrier injection and charge trapping. In addition, failure of the driver boards can be caused by PCB assembly degradation through various failure mechanisms, e. g. solder fatigue caused by thermal cycling and the coefficient of thermal expansion (CTE) mismatch. Failure of the LED backlight can result in intermittent or persistent failure of the screen or reduction of luminous flux [16].

Failure of the PSU can be caused both by failure of the PCB assembly and degradation of electrolytic capacitors as the PSU contains most of the televisions electrolytic capacitors. Failures of assembled PCBs due to thermally induced stresses are common and well researched. Thermally induced stresses can be caused by temperature cycling or constant high temperature, both can be expected in televisions. Thermal cycling causes mechanical stresses due to repeated expansion and contraction of the assembly and CTE mismatch of the materials involved, resulting in strain and eventual fatigue of solder joints [17]. The CTE mismatch between the circuit board substrate and copper interconnections can also lead to ruptures in traces or plated through holes due to thermal cycling, resulting in open circuits or intermittent failures [18].

Ageing of electrolytic capacitors occurs via several degradation mechanisms mainly driven by heat or the electrical stress of the capacitor during use due to low voltage safety margins [19]. Therefore, mounting of electrolytic capacitors near heat-emitting components can considerably accelerate degradation [14]. However, depending on the functionality of the circuit, it may be necessary to place capacitors close to heat-emitting components as longer traces can act as both parasitic inductances and antennas and can therefore impair the function of the circuit or cause problems with electromagnetic compatibility (EMC), especially if high currents or switching frequencies are involved [5].

The operating temperature of components is also dependent on the available installation space within the appliance which is limited in compact devices like televisions. This can impede circulation and heat dissipation within the device and thereby cause increased temperatures, even more so as circulation can further decrease over lifetime, e. g. through dust deposits blocking air vents. In contrast to computers, television sets usually do not use fans for active cooling [5].

Failure of external connectors accessible by the user, e. g. HDMI, can be caused by mechanical overload or fatigue, possibly due to misuse. As internal connectors are inaccessible by the user, failures are likely the result of failure mechanisms associated with thermal stress, e. g. through thermal cycling leading to surface corrosion and fretting corrosion [20].

4 Current test program and gap analysis

4.1 Vacuum Cleaners

Test procedures for vacuum cleaners are harmonized in the EU directive 666/2013 and standards EN 60312-1 and EN 60335-2-2 among others. In 2016, a study on durability tests was prepared for the European Commission in which the suitability of existing test procedures was reviewed [1].

4.1.1 Battery

For batteries in vacuum cleaners no standardized test is yet available. In a “Review study on Vacuum cleaners” for the European commission [21] a recommendation was made to require a charge cycle lifetime of 600 cycles with a remaining capacity of 70% based on EN 61960:2011. Consumer organizations are implementing such a durability test for batteries, which discharges and charges the battery in a defined manner. These durability tests require the whole system for the test. This has the definite advantage of being a test relatively close to the real application (e. g. including battery management systems) as well as combining the battery test with the motor test but have the disadvantage of requiring relatively long test times.

The currently used system tests are a viable way for testing but have disadvantages in regard to duration. Currently, the battery is completely charged and discharged during the cyclic tests. This does not necessarily conform to the use case. Different battery capacities in combination with real use cases might lead to differing lifetimes compared to the current tests.

4.1.2 Motor

There are currently standardized tests (EN 60312-1:2017) for motor reliability of mains-powered vacuum cleaners. Battery-powered vacuum cleaners are not scope of these motor tests. Mains-powered vacuum cleaners are tested via cyclic operation under normal environmental conditions. For battery-powered vacuum cleaners, consumer organizations adopted a similar approach. The battery-powered vacuum cleaners are subjected to cyclic combined motor/battery reliability tests. Damages occurring during testing are assessed and photographed. Motor durability tests are currently performed with half-full dust bags/receptacles according to EU directive 666/2013. However there is an ongoing discussion about test conditions concerning the filling degree of bags/receptacles, corresponding test durations and the implications on motor durability for different types of motors [1], [21].

As discussions in the past have shown, the motor reliability depends on the system, therefore possible test approaches are limited. The current test approach to use the system as a test vehicle seems the most feasible and changes will require a detailed analysis to test various technologies equally.

4.1.3 Cable and return mechanism

To determine the durability of the return mechanism, cyclic tests are performed by consumer organisations with the number of cycles exceeding the number required during the estimated product lifetime [22]. Damages occurring during testing are assessed. Currently, the tests are based on EN 60335-1 for the return mechanisms with a defined number of use cycles. Failure of the cable itself makes up a small fraction of these failures. These are most likely failures due to misuse of the customer, e. g. sharp folding or squeezing of the cable between or around doors. Cables are standardized in DIN EN 61242 and a minimum requirement for robustness is given.

Generally, the failures for cable and return mechanism are covered by current tests, but discussions about fine-tuning of the test procedure, e. g. angle of pull and release, might return more realistic test results.

4.2 Mobile Phones

For mobile phones, it can be noted that a significant number of reported issues are software-related. The focus will be on hardware-related reliability issues as long term software reliability is difficult to test and might require other solutions like regulations for minimal support period.

4.2.1 Battery

For batteries, there are no specific durability tests implemented. Most commonly, battery functionality is tested in the initial state, i. e. usage time (capacity) and charge time. The applied drop tests can be counted as testing the mechanical robustness, though the applicable real-world scenarios are limited. Drops of the phone constitute an overstress for the battery. In case of failure, this means breaking of the battery housing and allowing humidity to interact with the lithium or short-circuiting the battery, possibly setting the device on fire. Drops are one possible kind of overstress while other possible scenarios include bending of the phone due to various circumstances. With regard to the battery, such mechanical overstress tests permit conclusions about safety rather than lifetime.

Durability tests for batteries have to determine ageing, i. e. the change of capacity due to temperature and number of charge cycles. Similar to battery tests of other products, the battery management system has to be considered. Parameters like charge rate and maximum and minimum stored energy as defined by the battery management system are influencing the lifetime.

4.2.2 Screen

The standard test procedures for mobile phones already include tests for the most typical causes of screen failures. These tests are:

- tumble tests for shock resistance (based on EN 60068–2–31) which typically lead to cracks or dead screens
- scratch resistance tests (based on ISO 1518) which test the resistance of the screen against scratches with a hardness test pencil under five different loads and
- water resistance tests (based on EN 60529) which could lead to diverse failures, including various problems with the screen

All current tests cover faults associated with robustness against overstresses which are also some of the most common failure causes for screens of mobile phones. Failures due to degradation of the screen over lifetime are not covered. As lifetime degradation of the screen is less common, it has to be evaluated if the effort for such tests is in proportion to possible issues. When designing a test covering screen burn-in, the mitigation technologies described in section 3.2 have to be taken into account.

The functional relevant screen components offer very little robustness in regards to humidity, therefore protective measures are implemented. This usually starts on the level of the singular LED/OLED and extends to the housing of the screen and phone itself. These protective measures can degrade over the lifetime of the phone. Current tests are not able to evaluate the long-term degradation of these protective measures. Since a mobile phone has various possible entry points (frame, speakers, connectors and camera) for water, different measures are taken for protection against water [23]. This results in water resistance being very system dependent which has to be accounted for when developing tests for water resistance over lifetime. Tests need to either be done on system level or a very complex evaluation of multiple individual parts is required. Also, it should be kept in mind that manufacturers do not claim their phones are to be used in water or high humidity environments and declare such uses as misuse.

4.2.3 Connector

Current testing programs include the connector when testing for water resistance and mechanical drops. In both cases the system-wide robustness is tested. In real life condition connectors are exposed to repeated mechanical loads by plugging in and unplugging.

While customer organizations are not specifically testing the connectors for cyclic reliability, there is already an industrial certification program available (USB Implementers’ Forum (USB-IF) Integrators List (IL)). Such a certificate requires a durability test based on EIA-364 for electrical connectors. In this test program, for USB micro family connectors, 10.000 cycles of insertion and extraction are required.

4.2.4 Speaker

Durability related failure causes for speakers are mechanical loads and ingress of humidity, water and particles. The standard test procedures related to these issues are:

- tumble tests for shock resistance (based on EN 60068–2–31) which can damage the speaker but also the water protection mechanism
- water resistance tests (based on EN 60529) which can damage the speaker when bypassing the protective mechanism

The current water resistance test does not assess the durability of the protective mechanism. Mechanical shock and other environmental loads can degrade these protective mechanisms, causing failure later on in product life. As explained in [23], protective methods differ between smartphones and use various materials. These will degrade under different conditions and require various specific tests (e. g. humidity, temperature, UV light and various chemical tests).

4.3 Washing Machines

Washing machines are commonly subjected to endurance tests by consumer organisations. These tests consist of a number of various washing cycles approximately corresponding to the number performed during the expected lifetime of the machine. There are no reliability tests for specific failure causes or components.

4.3.1 Electronics

The currently employed endurance tests also stress the electronics in the washing machine, but since washing cycles are repeated in close succession the tests will naturally not perfectly replicate real conditions. For electronics, this can result in smaller thermal cycles if the system cannot cool down fast enough. Active power loss can also reduce or slow down humidity ingress into the electronics. This can result in the test being less harsh on the electronics than the real life use condition.

Currently there are no specific tests for electronics employed. Alternatively to a test of the complete washing machine, the electronics can be exposed to tests (e.g. based on IEC 60068 test procedures) individually or even broken down further into it sub-components, e. g. capacitors. In such cases, suitable test conditions and requirements have to be defined. Developing such tests will be challenging, even more so as the tests need to be accelerated and suitable for various types of washing machines.

4.3.2 Shock absorbers/bearings

Currently, there are no specific tests for bearings or shock absorbers employed. The current endurance tests stress the bearings and absorbers as they are used in the application. Individual testing may be feasible and test results may allow to determine the robustness in a relative measure but extrapolating test results to product lifetimes will be difficult. For a lifetime estimation, an ageing model is needed which connects the test results to lifetime results. There is a standardized approach to calculate lifetime of bearings (ISO 281), but this model does not account for all reliability influencing factors. Also, washing machines may include sensors to handle imbalances which may change lifetime results during real life application.

4.3.3 Motor

The current test program covers the reliability of the motor. , Sufficiently long cool-down phases are necessary to avoid deviation of test results from real life application due to the quick succession of cycles. To implement an individual test of the motor, ageing models are required which can differ between washing machines and motors. Therefore designing such tests can be challenging. Investigating if an individual test or quality check for the carbon brushes can deliver more easily information about the durability might be worthwhile as the brushes are one of the more critical components of the motor.

4.4 Television Sets

Current tests of consumer organisations are only conducted with new devices and include inspections of image and audio quality, usability and environmental characteristics. The tests neither involve disassembly and inspection of internal parts nor reliability tests of the television set or sub-assemblies [24].

The typical use profile for television sets involves mainly thermally induced stresses and long periods of use. Therefore, possible reliability tests need to induce accelerated ageing, possibly by means of constant high temperature or temperature cycling.

4.4.1 Screen

Tests by consumer organisations include visual inspection of the screen to check for manufacturing defects. Reliability tests of the screen are not currently conducted by consumer organisations. Mechanical damage of the screen can likely be attributed to misuse. As most failure mechanisms of the screen are activated by thermally induced stress, feasible tests may include thermal cycling, constant high temperatures or a combination to cause accelerated ageing. Tests can also include active use to induce power loss, which will cause increased temperatures more similar to the application.

4.4.2 Power Supply

Current tests concerning the PSU only include measurements of power consumption in various modes of operation and do not test the reliability of the power supply. Failures of the PSU are likely caused by either thermomechanical degradation of the PCB assembly or degradation of electrolytic capacitors accelerated by high temperatures. Therefore, suitable tests also involve thermal cycling, constant high temperatures or active power cycling.

4.4.3 Connectors

Currently, consumer organisations perform visual inspections to evaluate the usability of external connectors. There are currently no tests for connector reliability. As internal connectors are vulnerable to thermally induced stress, reliability tests can be conducted along with those for PCBs. Reliability tests for external connectors require either repeated bending or plugging and unplugging of connectors. Typically external connectors plugged and unplugged only a few times over the product life, so the time for such test can be reasonably short.

5 Conclusion

The current durability testing programs have to balance the challenge of being feasible, treating every device of a category equally and delivering results that are understandable and comparable. This leads to different categories of tests.

System tests: the product is repeatedly used as is to replicate its lifetime in an accelerated manner

Partial system tests: a specific function or component of the product is tested as part of the complete system (e.g. motor tests for vacuum cleaners)

Robustness tests: loads that can be considered overstress but may happen a few times during normal use over the lifetime are applied to the product

These tests have the advantage that they can be applied to any product of its category since the product is not manipulated or altered and used as intended by the manufacturer. This is especially true for robustness and system tests. Partial system tests for vacuum cleaners have already shown in the discussion about the filling level of the dust bags/receptacles how equitable testing of dissimilar products belonging to the same category can become a challenge in the development of more specific tests. Nevertheless, system tests are not a panacea as they are usually of long duration and can only be applied to products with relatively few cyclic uses during their lifetime. Television sets are a good example with a system test taking years to complete.

For cases such as televisions, accelerated tests have to be developed which may also only test specific subcomponents. Such tests still have to ensure equitable testing for all products which will be challenging. Typically, accelerated tests focus on specific failure mechanisms and as shown failure mechanisms are manifold, especially in complex electronic systems. Specific tests will have to accommodate for product-specific design choices to enable fair and comparable testing.

6 Acknowledgement

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We want to thank all of our PROMPT project partners for the feedback and information on currently reported faults and testing programs.

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Assessment of the influencing parameters of the tumble test for robustness testing of smartphones

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Abstract

In the wake of increasing attention being paid to robustness and durability of electronic products in general and smartphones in particular, the tumble test is gaining relevance when it comes to emulate real life scenarios of falls and accidental drops. Unlike other drop tests, the tumble test is a fast way to simulate random falls close to real life accidents. There is currently a standard (IEC 60068-2-31) for such testing that sets certain parameters (i.e. the spinning speed, the fall height…) depending on the size and weight of the device under test but leaves enough room for calibration.
This study aims to take a closer look to the effect of a variation of those parameters in the experiment. For that, several devices are tested under different conditions and indicators like the fall statistics are collected and then correlated with the test variables. To achieve this, a high-speed camera is used in order to be able to see what happens during impact.
As an outcome, this leads to a better understanding on how these parameters can lead to a more accurate simulation of real life conditions as well as the current limitations of the procedure.

1 Introduction

A common approach to evaluate the hardware reliability of electronic devices such as smartphones is to use standardized tests. For specific failure modes or specific field loads different tests are used. Based on the hardware features of a smartphone and common use cases, typically devices are tested against physical shock, water ingress and durability of connectors [1][2].

To test the structural integrity of smartphones against physical shocks caused by accidental drop a free fall test is often used. This kind of tests are characterised by offering a very controlled environment with a set of precisely definable parameters, such as drop height and impact surface. On the other hand, the tumble test allows automated testing of a device with random drop orientations and many consecutive impacts. Smartphone manufacturers and consumer organisations are using those tests for quality control and product evaluation. The standard IEC 60068-2-31 (and others [3][4]) defines parameters for both, the free fall test and the repeated free fall test for small electronic devices, but not for smartphones in particular. In this paper parameters of the repeated free fall test (tumble test, based on IEC 60068-2-31) are investigated for robustness testing of smartphones. Therefore understanding the effect of such parameters helps to optimize the tumble test.

2 Test environment

The standard IEC 60068-2-31 defines some of the parameters for the repeated fall test conforming a baseline general test environment, which can be summarised as the following. The tester device is a tumbling barrel, which is designed, following the standard, for the probe to fall from already defined heights of 0.5 m or 1 m with every turn. The impact surface is hard wood covered by a steel plate. The rotation speed allows a reproducible impact of the probe in the middle of the impact area. A conclusive evaluation of the test regarding suitability and reproducibility is not available yet.

3 Test parameters

The IEC 60068-32-1 standard sets values for some of the test parameters while others are more open to be specified depending on the device under test. This section will therefore show a brief description of those and comment on their suitability for smartphone testing. The next section will then put the focus on the considered main test parameter.

3.1 Fall height

As commented above, the standard sets the fall height for the tumble test at either 500 mm or 1000 mm. Unlike the free fall test without repetition, in which greater flexibility is shown, the tumble test fall height is limited by the structure of the tester itself, which is a barrel

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of fixed dimensions. For setting the height, the severity level of the test has to be considered i.e. how hard the test conditions are for the device under study. The standard provides a suggestion of severity levels, based on fall height and probe weight. This should be set keeping in mind the expected conditions in which the real life fall is expected to occur.

3.2 Spinning speed

The standard sets the required spinning speed at around 10 turns per minute. During the tests within the scope of this paper, it has been seen that this is the spinning speed needed for the probe to fall in the centre of the impact surface, avoiding possible interference like hitting the walls and allowing recording and/or visual inspection of the impacts. Variations of this value could however be justified either by practical reasons or in order to adjust the severity level of the test alongside other parameters.

3.3 Surface properties

The IEC 60068-32-1 standard sets an impact surface consisting of a steel layer backed by hardwood. The standard does nonetheless leave room open for changes in this regard if relevant specifications require otherwise.

During use, accidental falls of smartphones can occur onto various surfaces (i.e. wood, concrete, tiled floors, carpets…) and therefore the surface on which the test is performed should be accounted for when assessing the severity level of the test as well.

3.4 Number of falls

The test standard offers values between 50 and 1000 drops to choose from. The number of falls should be determined based on the specific device under test.

3.5 Sample size

The standard does not specify the amount of samples for carrying out the test. When determining the sample size for smartphone testing two aspects have to be considered. On the one hand, the statistical significance of the results. High variation between individual devices' results means that several devices for testing might be needed for having enough certainty. On the other hand, the usability of the test might impose its own practical restrictions. For instance, if the tumble test is to be used in market surveillance for smartphones, the use of numerous probes might be impractical.

4 Functional Requirements

The standard defines the failure of a device as an inability to fulfil the functional requirements set in advance, which the standard does not specify. The list of failures that can occur during a tumble test can be divided into four categories, as they relate to the usability of the smartphone, defined as follows:

Class I: Failures that make any use of the phone completely impossible, e.g.: display sensitivity loss.

Class II: Failures that make a normal use of the phone impossible, e.g.: irresponsive buttons, severely shattered front glass.

Class III: Failures that make a normal use of the phone inconvenient, e.g.: ingress protection loss, moderate glass cracks.

Class IV: Failures that affect the aesthetic appearance of the phone but do not alter its usability, e.g.: scratches and aesthetic impairments.

In order to define the severity level appropriate for smartphone durability testing, the pass/fail criteria for the tumble test is a relevant aspect to be defined. Setting responsiveness as the central criteria, the appearance during test of failures belonging to classes I and II could be read as a bad result while class IV failures could be read as a pass. As for class III failures, they could be further subdivided based on the expected use of the device or serve as a basis for a grading system that allows differentiating between better and worse performing smartphones.

5 Effects of fall height

From all parameters commented above fall height and number of falls are considered to be the most relevant, since the standard allows for variation of those and they directly affect the severity level of the test. Functionality requirements and sample size are considered not to be part of the test conditions per se but rather of the context of the test, which will vary depending of the intended use and technical capabilities of the tester.

Due to technical limitations this paper has focused on the fall height more than the number of falls. The number of falls was set to 200, as it was necessary to achieve the highest number of falls for a certain number of devices under test for a limited time frame.

5.1 Methodology

The tests were conducted using a tumble tester which meets all requirements to perform the repeated fall test according to DIN EN 60068-2-31. In order to further analyse the devices' behaviour during the moment of impact, a high-speed camera was used. It was connected to the trigger output of the tester to record a short clip with every rotation. Also external lighting equipment was used, which produces no flickering effect, while filming with a high-speed shutter. A maximum of 200 falls was defined for each test device. If the damage of the device was too high (e.g. extended glass shattering) the test was stopped before the maximum number of falls was reached. The test conditions are listed in Table 1.

Fall height	500 mm / 1000 mm
Rotation speed	10.6 rpm
Max rounds per device	200
Frame rate	2000 fps
Shutter speed	1 / frame rate
Resolution	768 x 768 pixel
Clip duration	1500 frames / impact

Table 1: Test conditions

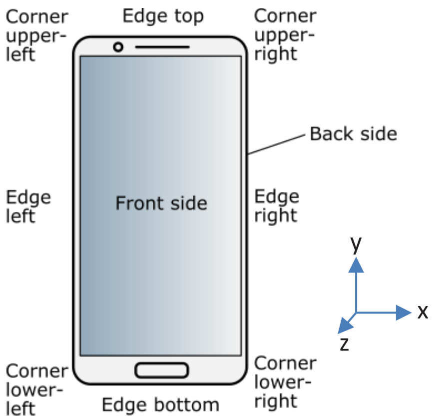

Figure 1: Defined impact areas on the smartphone

Areas on the smartphones were defined to differentiate the impact areas during the test. The first differentiation was made between impact on the front side (display), back side or frame. If the impact angle towards the front is smaller than 45°, the impact is counted as a front side impact. The same applies to the back side. The frame is further divided into subsections (see figure 1). If the impact is on the frame, the impact angle to the next edge has to be smaller than 15° so that it counts as an edge impact. Figure 2 shows the impact of one test device on the lower right corner. In this case the impact angle to the right edge is more than 15°.

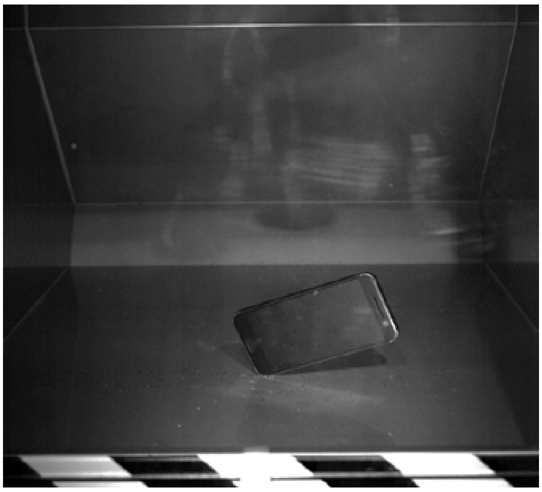

Figure 2: Moment of impact; smartphone in tumble test

5.2 Test samples

Five smartphone models were selected, with attention to a wide range of sizes. Since there are different combinations of materials used to manufacture the smartphones, they also differ according to their weight, see Table 2.

Although each of the devices under test has a different design, most smartphones share a very similar internal structure and its different parts are arranged very similarly. A balance test performed in-house, shows that the center of mass of all evaluated devices is very similar and close to the middle of the devices, see Figure 3. For model A and B it is slightly shifted to the lower half. For model C, D and E it is slightly shifted to the upper half of the device. For model E it's also shifted to the left side.

The weight distribution along the z-axis depends on the smartphone design. The front and back cover of Model A, B and E are made of glass. The back cover of Model C is made of polymer. The back cover of Model D is combined with the frame and made of aluminium. These material differences suggest that the mass could be distributed unevenly between the frame and the back for some models.

Table 2 shows a summary of the physical specs of the models under study showcasing variety in terms of size and weight, with models A to C in the higher end and D and E being the lighter ones. There are also differences in the used housing materials, the possible effects of which are commented below in Impact Orientation.

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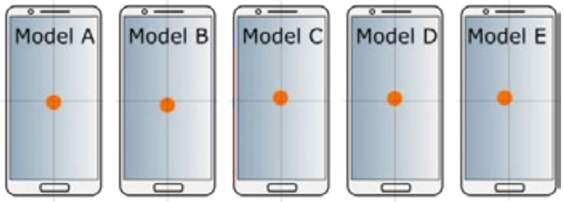

Figure 3: Centre of mass of evaluated devices

ID	Display size	Body size (mm³)	Weight
A	5.8”	144 x 71 x 8	177 g
B	6.2”	158 x 78 x 8	208 g
C	6.5”	158 x 72 x 10	189 g
D	5.2”	146 x 72 x 9	161 g
E	5.1”	143 x 71 x 7	138 g

Table 2: Properties of the smartphone models

5.3 Impact orientation

The tumble test was conducted with one specimen for each of the five models and with both fall heights, 50 cm and 100 cm. The relative share of impact orientation can be seen in Table 3.

Model	Fall height	Frame	Frontside	Backside
A	50 cm	100,0 %	0,0%	0,0%
	100 cm	97,0 %	3,0%	0,0%
B	50 cm	100,0 %	0,0%	0,0%
	100 cm	100,0 %	0,0%	0,0%
C	50 cm	100,0 %	0,0%	0,0%
	100 cm	93,5 %	0,0%	6,5%
D	50 cm	84,5 %	11,0%	4,5%
	100 cm	72,0 %	15,0%	13,0%
E	50 cm	100,0 %	0,0%	0,0%
	100 cm	97,5 %	0,0%	2,5%

Table 3: Percentage of impact orientation

For all models and both drop heights, most impacts were registered in the frame. The exception was model D, which for both fall heights showed a relevant share of the impacts happening on the front- and backside of the smartphone. In all cases it is also seen that for the 1 m fall height, the impacts are not exclusively concentrated on the frame.

In figure 4, frame impacts are shown in greater detail, for a fall height of 100 cm. Among the tested smartphone models different behaviours can be seen. For models A and B, most impacts were registered in the long edges i.e. right and left edges, followed by the lower corners. Model C shows a similar trend for the lower corners.

Model D displays a different behaviour, with most impacts being registered on the upper part of the device most prominently the top edge. For model E, the long edges (especially the right edge) show the highest impact incidence, followed by a slight trend towards the upper side i.e. upper right and left corners.

As explained above, the mass centre of the devices are slightly shifted to the upper end for models C, D and E and a bit towards the lower end for models A and B. This does correlate with the impact distribution of all models with the exception of model C. The center of mass on the x-axis for models A, B, C and D is positioned fairly in the middle of the device. As a result one would expect a random distribution of impacts on the left and right side. This can be seen in the results of the experiment. Model E has its centre of mass slightly shifted to the left side and here the experiment shows a higher accumulation towards the right.

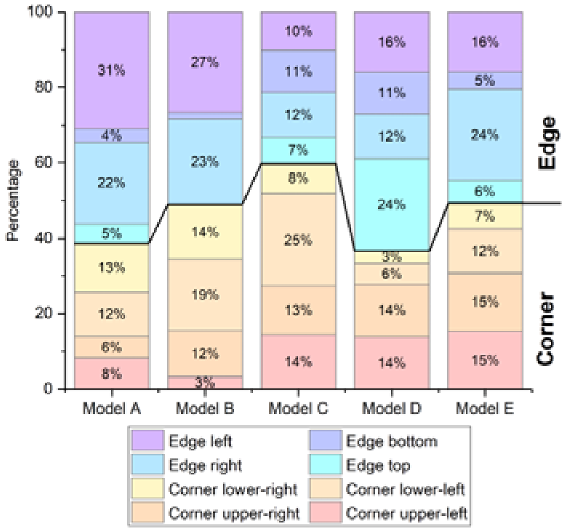

Figure 4: Distribution of impact areas only on frame (Fall height: 1000 mm)

The material choices and their combination, as mentioned before, might imbalance the centre of mass in z-axis. This could lead to a greater tendency towards spinning while falling. Device B would then show a stronger tendency to fall directly on the frame while device D would show more impact variation (due to the mid-air spinning). This seems to be the case as seen in Table 3. This spinning would then result in a more random distribution in figure 4, for instance.

The same impact orientation analysis was conducted for the fall height of 50 cm (figure 5). The distribution differs from 1 m fall height. For model A, B, C and E

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the share of impacts on the edges increased. And for all models the distribution is more homogeneous, in accordance with the observations recorded in Table 3. A possible explanation is, that the effect of the imbalance and the aerodynamic behaviour during fall are increasing with the increased fall height.

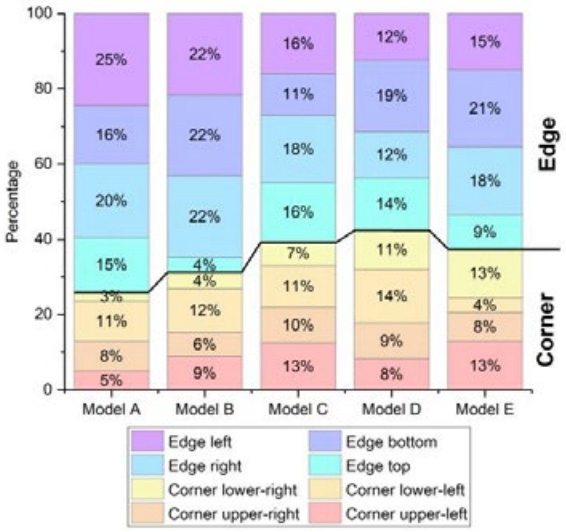

Figure 5: Distribution of impact areas only on frame (Fall height: 500 mm)

In order to give context to the described results, the sample size of model A was increased to 15 devices. Just like in the individual tests, the most impacts (accumulated for all samples) are registered in the frame (98.8 %). The impact distribution on the frame as mean value with a confidence interval of 95% is shown in figure 6.

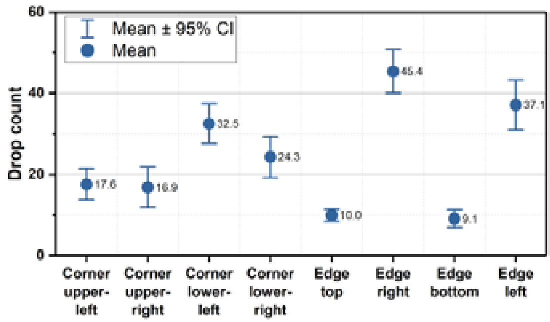

Figure 6: Impact distribution for model A

The aggregated results do not differ greatly from the individual ones (+/- 5% at most and almost none at times) and the main hotspots are still coherent with what is shown in Figure 4, which suggests greater uniformity between individual tests.

6 Conclusions

From the results presented above, the following facts were observed:

- Different smartphone models show different fall orientation patterns.
- For both 100 cm and 50 cm heights, most impacts are predominantly on the frame for all tested devices.
- With 100 cm fall height, the impacts on the frame edges and frame corners are rather balanced while the 50 cm height shows greater edge impact incidence. With 100 cm fall height the difference between models is more pronounced.

Additionally, based on the observations, the following hyptheses and conclusions were made:

- Mass distribution has been studied as main hypotheses to explain model-level differences.
- When given enough time/space during fall (1 m) smartphones tend to show a fall orientation pattern coherent with their mass centre position.
- The material combination chosen for the housing structure is also suggested as a potential explanation for the divergences in the frame-front-back impact distribution.

At this point it is worth noting that this paper has focused on fall orientation. Although attempts have been made to measure and modelling the impact stress of a smartphone for drop test conditions [5][6], shocks by fall are a complex phenomenon and there is not necessarily a direct correlation between the durability and the impact orientation. It is therefore advised to take those conclusions with caution since they do not necessarily work as a proxy for durability.

To conclude, we would like to make some final remarks on what those results imply in relation to the adequacy of the test conditions defined in the standard to the smartphones product group:

- Based on the design and behaviour differences as well as the openness of the functionality requirements, it could be the case that subgroups should be made for the test within the smartphone product group, based on main features, key design aspects or expected use.
- The differences in fall orientation between 1 m height and 50 cm height suggest that the same devices could perform differently in both, making this a relevant aspect of the test process.
- Also the results suggest that from the design of the smartphone the major impact point when falling can be estimated. This does not apply to all tested models, however, design rules may be derived by further studies.

In this study the parameters of the tumble test were discussed. Especially the effect of the fall height on the test was shown by experiments. In future works the influence of the impact surface conditions and the statistical relevance of the test has to be analysed.

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Design for circularity: a review of tools and implementations in electronics-related products

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Abstract

Over the last decade, several design guidelines and tools for the circular economy have been introduced worldwide. However, in the electronics industry, very few have been practically applied by manufacturers. Most tools have remained unused or not even tested yet after being developed. This systematic review aims to analyze the characteristics of circularity design tools that are valid available, identify the implementation cases, and propose the potential for future tool development by screening through both academic and professional literature. The selection criteria are the closed-loop integration, the value creation, and the practicality of tool development. Sixteen tools for electronics-related products are presented by describing their key performance and discussing both limitations and the best application. For future research, a circularity design assessment and supporting tool need to be developed further to prevent overclaim and facilitate designers to enhance the circularity level of their prospective products towards the circular economy.

1 Introduction

A circular economy (CE) is an industrial economy that is restorative through careful design aims to maintain products and materials at their highest value and performance by leaning on renewable energy, reducing toxic chemical usage, and eliminating waste [1], [2]. Cradle to cradle design is one of the key design concepts of CE [2]–[5] that has been used to respond to growing concerns about resource scarcity and unsustainable business [6]. Linder and his colleagues reviewed several definitions of the CE from previous literature and found out that they all mainly focus on closed-loop cycles [7]. Idealistically in the closed-loop economy, wastes do not exist. The products and materials are reused, upcycled, and indefinitely preserved by keeping them in the economic system [8]. In the electronics industry, several laws and directives such as the Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) have been adopted and come into force to facilitate the End of Life (EoL) treatment for recycling, remanufacturing, and reusing, as well as, mitigate environmental damage.

Circular design (CD) was described by Medkova and Fifield [9] as a design principle that searches for an approach to deliver a functional product or service by optimizing materials used for the best performance, including minimizing their negative impact along the entire life cycle. CD could be considered a component of the design for sustainability which is emphatically focused on resource efficiency to achieve closed-loop systems [10]. Referring to the butterfly diagram of CE illustrated by Ellen MacArthur Foundation [1], [11], this design principle aims to optimize resource yields by circulating products, components, and materials for the best functionality over multiple lifecycles, including simultaneously maintaining their economic viability [10]. Thus, the CD is a design for repairing, remanufacturing, refurbishing, or recycling to keep products, components, or materials circulating in and contributing to the economy, for example, the improvements in material selection and product redesign. Bakker and her colleagues [12] also emphasized five characteristics of circular product design, namely, elevating design to a system level, striving to maintain product integrity, cycling at a different pace, exploring new relationships and experiences with products, and being driven by different business models. Over a decade, several CD tools have been proposed to challenge a generation of products and materials in an approach that minimizes the primary raw material use, curtails a value loss embedded in the products and materials, continues to circulate them in closed loops, and naturally inspires at the end of life [9].

Even though several CD guidelines and tools have been introduced over the last decade, very few were practically and regularly used by electrical and electronic manufacturers. Most tools were utilized only once when they were developed by the innovator [13] and they were not used in practice [14]. Moreover, the 2019 global e-waste report shows that the vast majority of global e-waste which is around 80% was incinerated or dumped in landfills, and only 20% was formally recycled [15]. There are enormous sustainable challenges

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that lie ahead for integrating CD into the design process and manufacturing in this industry to accomplish the closed-loop systems. The aim of this study is to analyze the characteristics of the available circularity design tools, identify the practical implementations, and propose the potential for future tool development.

2 Materials and Methods

The systematic literature review was conducted from August to November of 2019, followed a guideline of Okoli and Schabram [16]. The guideline includes four steps which are planning, selection, extraction, and execution (see Figure 1).

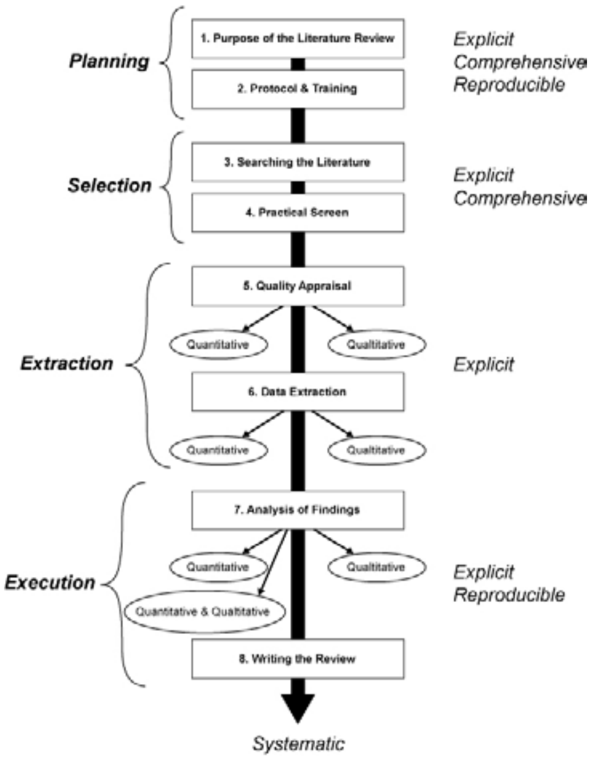

Figure 1: Systematic guide to literature review development, adapted from Okoli and Schabram [16].

2.1 Planning

For planning, the review aims to analyze the newly developed tools for CD, identify its best applications, and recommend the potentials for further research. In addition, two research questions were drafted for the reviewers to clarify the purpose and scope of this systematic literature review, as follows:

- What are the characteristics of CD tools presented recently in the market?
- Which tools can an organization apply to the product and service design of CE in practice?

2.2 Selection

Then, literature searching and practical screening were performed using the following article search keywords: “circular design,” “circular economy strategies and tools,” “design for the circular economy,” “product design in the circular economy,” “circular design methods and tools,” and “circular product design”. On the basis of these keywords, relevant academic journals, books and e-books, conference proceedings, and reports were collected from the National Taipei University of Technology library catalog and other important online databases, such as Google Scholar, Science Direct, Scopus, Springer, Taylor and Francis, and Wiley. Besides, data sources from other governments and non-governmental organizations’ web pages, such as the Ellen MacArthur Foundation, the Circular Design Guide, and Taiwan Design Center, were included. Practical screening of the literature was performed simultaneously while searching the topics, abstracts, and introduction sections. Articles on circularity-related design tools not in the main content or discussion were excluded.

2.3 Extraction

After the practical screening, information about the tools; such as descriptions, target users, the scope of implementation scenes, implementation approaches, year of publication, categories, and case studies, were extracted from the reviewed paper.

To scope down into electronics-related applications, the selection criteria for circularity design applied in this stage are:

1. The tools must be relevant to the tightness of either materials or energy cycles.
2. The tools are related to product dematerialization, longevity, and life span.
3. The tools take into account value creation and/or preservation.
4. The tools must be developed and/or implemented with the electronics industry.
5. The tools must be empirically tested and documented in the publication.

2.4 Execution

Analysis, and synthesis of the tools were executed based on the data extraction. In the previous review of CE theories and practices, four implementation scenes regarding the scope have been identified including business model, product design, material sourcing, and value chain [4], [5], [17]. Consequently, the implementation scenes in this study were presented accordingly. Moreover, all the selected tools were categorized based on a usage-oriented classification (i.e., guideline, framework, procedural, analytical, and assessment tools) and previewed its implementation on either top–down (e.g., owners of a company and top–level managers) or bottom–up (e.g., designers and engineers) approach. Also, the findings were discussed practical applications and limitations of those tools.

3 Results and Discussion

Sixteen tools were derived from practical screening and data extraction by using the keywords and following the selection criteria. However, some other related tools that indirectly use “circularity” or “circular design” as the main keywords or in the titles might be missing. Based on a usage-oriented classification of the tools, Table 1 and 2 list the implementation scenes, approaches, and cases of each tool.

To answer the first research question, there were five design frameworks, three design guidelines, three procedural tools, three analytical tools, and two assessment tools for electronics-related products. From the Cambridge Dictionary, “Guideline is a piece of information that suggests how something should be done,” and “Framework is the ideas, information, and principles that form the structure of an organization or plan.” A guideline is a non-specific rule or principle that provides direction to action, whereas a framework is the arrangement of support criteria that represent the overall concept or model. In the field of environmental design and management, procedural tools focused on the procedures and the connections to its societal and decision context, whereas analytical tools focused on technical aspects of the analysis [27]. Analysis and assessment slightly differ. To analyze a concept, the whole must be divided into its component parts which help to simplify something complex into basic elements. On the contrary, an assessment is defined as the act of making a judgment about something, representing a single score and a quantitative form. In this preliminary study, Material Circularity Indicator (MCI) was solely an assessment tool that deals with technical cycles and non-renewable materials of products and companies’ material flow. Also, the previous study of Elia and his team showed that only the MCI includes the product durability and the loss of materials in the analysis [28]. Thus, further research on these types of tools should be conducted to facilitate designers to assess their products’ performance and quantify circularity at the product-level.

	Scene					
Tool	Business Model	Product Design	Material Sourcing	Value Chain	Approach	Case
Guideline						
Circular Design Guideline [18]		x	x		Bottom–up	Upcycling PCB waste into artificial stones by Super Dragon Technology and Renato Lab
Circular Design Strategies + Business Model Archetype [19], [20]	x	x	x	x	Top–down/ Bottom–up	Products as a service for leasing Nokia® mobile phones, product life extension for Philips Health™ medical equipment
Natural Principles [1], [11]		x	x	x	Bottom–up	Comet Circle™ by Ricoh, home-made carbonated drinks by Sodastream
Framework						
Backcasting and Eco-design for the Circular Economy (BECE) [21], [22]	x	x	x	x	Top–down/ Bottom–up	Reducing the complexity of manufacturing and the supply chains of a vacuum cleaner, use of bioplastics and graphene, replacement of copper as well as reframing the concept of cleaning and introducing product multifunctionality
Circular Strategies Scanner [23]	x	x	x	x	Top–down/ Bottom–up	Multi-functional devices such as smartphones combine the functionality of multiple devices in a single device
Design for Circular Behavior (DfCB) Process – Model of Circular Behavior [24]	x	x		x	Top–down/ Bottom–up	Optimist toaster concept from The Agency of Design, no overcharged batteries of Toronto Tool Library, return parts of the headphones by Gerrard Street
R-strategies [25]	x	x	x	x	Top–down/ Bottom–up	Collecting and refurbishing used computers by Stichting Recover-E®, service contracts for multifunctional photocopiers and printers by Ricoh, purchasing and refurbishing used smartphones by Telga telecommunications company, service contracts for modular headphones by Gerrard Street, ‘pay-per-lux’ a service contract to sell the provision of light by Philips and Turntoo
Six Potential Business Models for a Circular Economy + Circular Product Design Strategies [26]	x	x			Top–down/ Bottom–up	Launderettes, leasing phones, offering consumers cash for electronics and selling refurbished electronics by Gazelle, functional life span of white goods by Miele

Table 1: Circularity design guidelines and frameworks for electronics-related products

Tool	Scene: Business Model	Scene: Product Design	Scene: Material Sourcing	Scene: Value Chain	Approach	Case
Procedural						
Business Cycle Canvas (BCC) [29]	x				Top–down	Telecom company, baby monitor, phone leasing, repair services, phone-to-money, modular phones, reused and remanufactured phones, phone-to-dongle, battery repair service, full-body check and additional services for phones
Circular Business + Circular Design [9], [12]	x	x			Top–down/ Bottom–up	Miele 20-year lifespan household devices, classic long life Thorens turntables, a toner cartridge system and a modular design concept of Xerox Versant 80 Press, refurbished and remanufactured printing machines by LMI, Pay per Lux systems by Thomas Rau and Philips, upgrading with modules in Waves, a product service combination for gamers, by Telmen Dzjind, FAIRPHONE an easy to repair and upgrading smartphone
Circular Design Guide [30]	x	x	x	x	Top–down/ Bottom–up	Pay per Lux systems by Thomas Rau and Philip, a collaborative community focused on redesigning hardware technology by the Open Compute Project, build to think toaster by the Agency of Design, internet-enabled pay-per-wash by Bundles, FAIRPHONE an easy to repair and upgrading smartphone
Analytical						
Circular Economy Strategies Toolbox [4]	x	x	x	x	Top–down/ Bottom–up	Amazon-textbooks, refurbishing and repairing donated computer by WorldLoop, Cisco certified refurbishment, option for trade-in by Vodafone, Repair cafes
Circular Network + Four Design Models [9], [31], [32]	x	x	x	x	Top–down/ Bottom–up	A handheld reusable non-invasive breath test for blood glucose monitoring and diabetes self-management by Applied Nanodetectors Ltd., using bio-polymers for Dyson products, return to sender, circular design for an economy power tool, and ProjectBox by Kingfisher Plc., closed-loop LED bulb and connected closed-loop kettle by the Agency of Design Ltd.
Circular Product Design Vision + Spider Map [5]		x	x	x	Bottom–up	Designing a luminaire by Philips Design Lighting
Assessment						
Circular Design Guidelines Group [33]		x	x		Bottom–up	Improving the level of circularity for Small Electrical and Electronic Equipment (sEEE) such as extending the life span of vacuum cleaners and coffee makers; redesigning hand blenders for longer lifetime, reusing and recycling components and materials; extending the life span of irons, rearranging product's structure, reusing and recycling components and materials; product reuse for toasters and juicers; improving product architecture of kettles; extending product life span for sandwich makers and dryers
Material Circularity Indicator (MCI) [34]			x	x	Bottom–up	Replacing ABS with aluminium for Widget products, increasing recycling levels for white goods, the rental approach for a cordless power drill, materials substitution for a flame retardant and the polycarbonate used in the tablet

Table 2: Circularity design procedural, analytical, and assessment tools for electronics-related products

The implementation scene of product design played an important role in the CE. As a support to the previous statement by Landeta Manzano and his team [35] that the reduction of environmental impacts is more economical at the design stage than at the subsequent stages, various tools have been developed to facilitate designers in the design process. Sumter and her colleagues [10] suggested that product design also includes the design of the associated service. Therefore, product- and service-oriented design guidelines are necessary for guiding designers toward CE principles [21], [22], [33]. Consequently, recent studies have promoted and focused mainly on developing new business model implementations rather than on proposing product design guidelines [14], [26], [33]. Eleven tools highlighted the need for a new business model for electronics products. Leasing, sharing, and repairing of the products are also significant services offer to endorse eco-effectiveness in the product system.

Ten tools can be applied to top–down and bottom–up approaches. For example, the BECE bridges the gap between the strategic and operational levels by combining backcasting and eco-design [22]. Mendoza and his colleagues emphasized that holistic CE frameworks must be applied which incorporate top-down (business model) and bottom-up (product-service design) considerations. In the electronics industry, planning for obsolescence is one of the biggest obstacles on the pathway to product longevity [28], [35]. To create a novel circular business model, increasing the value durability of products and including product life extension into account during the design process is highly required.

3.1 Practical Applications

The success factor of the practical tools is the collaboration between a tool innovator and an organization while developing the tools and fully implementing the design of market-ready products and services. For instance, the well-known CE model of the organization and service contracts, created using the Natural Principles and R-strategies, such as Comet Circle™ by Ricoh, are considerably successfully and practically applied on multifunctional printers and copiers [1], [2], [11], [25]. Besides, Philips has applied various tools to improve products and services and to transition the company toward the CE, such as the Circular Design Strategies and Business Model Archetype to promote product life extension for Philips Health™ medical equipment [19], [20], a service contract to sell the provision of light called "Pay per Lux systems" collaborative with Thomas Rau by applying R-strategies as a framework, and Circular Business and Circular Design, and Circular Design Guide as procedural tools [9], [12], [25], [30], and the Circular Product Design Vision and Spider Map for designing a luminaire for Philips Design Lighting [5]. Furthermore, Kingfisher has applied the Circular Network together with the Four Design Model Diagrams to create a concept of a return to sender, CD for an economy power tool, and a ProjectBox [9], [32], and the MCI to assess its material cycles [34]. The ProjectBox includes "a package of quality professional tools, materials, and detailed instructions on how to complete a required job" that could avoid loss of time and resources [9]. This can improve the resource efficiency and productivity of the company. Thus, most of the tools have already been developed and implemented with products, services, and systems by international companies and well-known manufacturers.

3.2 Limitations and Future Research

Even though the review of sustainable product design tools by Ahmad et al. [13] showed that most tools were implemented only once while being developed by innovators, circular product design tools, especially in electronics, demonstrate various applications in different implementation scenes by large and reputed companies. However, only a few small- and medium-sized enterprises (SMEs), as well as startups, are recorded in the participation of CD tool development. Also, the existing CD assessment tools could not yet tackle all the implementation scenes just like other guidelines (e.g., Circular Design Strategies and Business Model Archetype), frameworks (e.g., BECE, Circular Strategies Scanner, R-strategies), procedural (e.g., Circular Design Guide), and analytical (e.g., Circular Economy Strategies Toolbox, Circular Network, and Four Design Models) tools.

Future studies should be conducted to implement these tools in the context of SMEs and startup businesses. Also, a CD assessment tool should be developed further to measure the circularity level of a business model, a product, a service, and a supply chain. As enhanced to previous studies supporting the establishment of methods and/or tools to measure circularity at the micro-level, the development should embed not only products but also business considerations and guide the design strategies toward the system innovation [6], [7], [28].

4 Conclusions

The characteristics of circularity design tools valid available for electronics-related products are mostly design frameworks accounted for five tools. All those tools emphasize business model creation and product design development and can be executed by bottom–up and top–down approaches. Based on the usage-oriented classification, each type of the tools shows a certain level of improvement to cover all scopes of the implementation scenes, except the assessment tool. Measuring the circularity level of a business model is still lacking. For the electronics industry, the implementation cases in a reputed organization such as Ricoh, Philips, and Kingfisher are good examples for a pragmatic circularity design tool application. However, academia, innovators, and tool developers should also consider those SMEs and startup businesses as a collaborative partner for further tool development. For future studies, a circularity design assessment tool for a business model as well as a product design follow-up tool should be developed with holistic consideration to prevent overclaim and escalate the circularity design level of the prospective electronics-related products and services in the transition to the CE.

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Challenges of ICT Equipment regarding Circular Economy

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Abstract

Circular economy (CE) has severe implications on the product design. Since CE over time must separate from the linear take-make-sell-forget model, maximum re-use has to be considered in the initial product design phase. For certain ICT (information and communications technologies) products, this may be contradicted by specific technical and operational aspects. Amongst others, this holds for the long product lifetime which is typical for certain classes of ICT equipment. This severely limits reuse, one of the key concepts of CE. Further challenges result from the fact that environmental impact of core ICT equipment is dominated by use-phase energy consumption, which can be derived from lifecycle analyses (LCA). This necessitates a focus on energy efficiency, which may be conflicting with design in support of CE. Increasing energy efficiency of successor product generations also sets an upper limit to maximum lifetime. Above this limit, further use of old equipment becomes net-negative, e.g., for the global warming potential, according to LCA. Components reuse is also limited by the fast ICT development toward ever increasing bitrates. Combined with long average system lifetime, this leads to components, systems and functionality obsolescence.

Together, these aspects seem to indicate that for certain ICT equipment classes, there needs to be a focus on recycling and business models like product-service systems that best support this.

1. Introduction

The EU Horizon-2020 project C-SERVEES [1] investigates improvements of circular economy business models (CE BMs) in the electrical and electronics sector. This includes as main work packages theoretical analyses of possible CE BMs, the use of ICT tools in order to support the business models, and four demonstrators with different equipment classes that aim at proving the respective CE BM findings. Further work packages deal with LCA, lifecycle costing and social LCA, replicability and transferability of results, exploitation and dissemination, respectively.

CE has severe implications on the product design. For certain ICT products, this may be contradicted by certain technical and operational aspects. This is particularly true for ICT infrastructure products that completely fall into the B2B (business-to-business) area. Amongst others, it can severely limit reuse, one of the key concepts of CE.

These problems are investigated in the C-SERVEES EU project, which will show parts of the improved CE BMs and the respectively designed products in large-scale demonstrators. At the time of the presentation, the project runs for 28 months already, with another 26 months yet to come (of which six months are an extension period due to SARS-CoV-2).

Within the project, ADVA represents the ICT sector, with special focus on photonic infrastructure equipment. Parts of this equipment define the upper bound of product lifetime. They have target lifetime of several decades. This makes various CE aspects challenging and must be considered in the related business models.

2. ICT Environmental Status

The main components of the ICT sector, or the Internet, are wired (access and backbone) and wireless (access only) networks, data centers, and end-user equipment. The networks split into backbone or core and access (incl. wireless) parts. The core networks consist of aggregation switches, routers and fiber-optic WDM (wavelength-division multiplexing) long-distance transport. For these *infrastructure* equipment classes, some 80-90% of the environmental impact are determined by the use-phase energy consumption, which can be derived from lifecycle analyses [2]-[4], also refer to Ch. 3. This is particularly true for the global warming potential (GWP), that is, emissions of greenhouse gases (GHG, i.e., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3)).

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Part of the use-phase dominance is owed to ICT bandwidth or bitrate growth, which is forecasted to persist also for the next couple of years [5]-[7]. This is shown in Fig. 1, together with the resulting global ICT energy consumption according to [8], [9] and the associated GWP. For calculating the GWP, electricity emission factors that are linearly decreasing from 0.4 $kgCO_2e/kWh$ in 2020 to 0.3 $kgCO_2e/kWh$ in 2030 have been used.

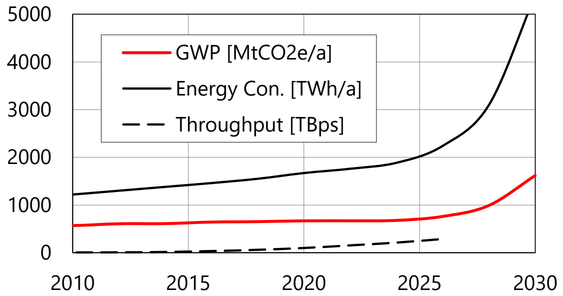

Fig. 1. ICT throughput based on [5]-[7] (extrapolated to 2026), and related growth in energy consumption [8], [9] and emissions

In Fig. 2, the ICT emissions are displayed in the total global GWP context according to [10]. Beyond 2020, these emissions may lead to total global GWP increase despite the necessity to massively decrease emissions, following the Paris Agreement [11]. However, this effect may positively be over-compensated by emissions savings in other sectors like manufacturing, energy (e.g., the power grids), buildings, mobility, and agriculture that are enabled by proper use of ICT services [12]. This effect is sometimes referred to as Green-by-ICT, it is also shown in Fig. 2.

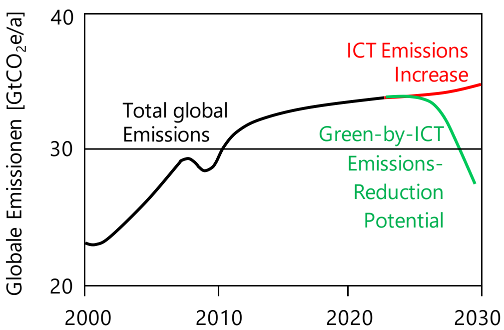

Fig. 2. Development of global carbon emissions [10] and possible development between ICT emissions increase [8], [9] and ICT-enabled emissions decrease [12]

ICT energy consumption must be tackled by improvements in energy efficiency. This is discussed in detail elsewhere [14]. The related emissions can be reduced over time by improving the electricity emissions factors. In addition, they are over-compensated by carbon abatement in other sectors [12]. This poses the *optimization problem* as to which extent invest in ICT – including the added emissions! – should be forced to speed up this carbon abatement.

Increasing energy consumption and related emissions are not the only environmental ICT burden. Raw-material consumption and waste electrical and electronic equipment (WEEE) generation are also increasing. The development of the EU WEEE generation is shown in Fig. 3 [13].

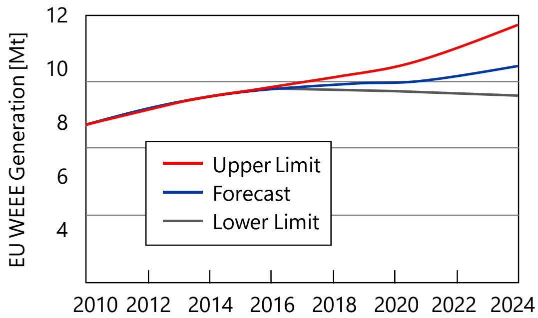

Fig. 3. Development of WEEE generation in the EU [13]

WEEE generation is one of the main aspects to be improved by CE. CE also aims at minimizing raw-material intake. This is particularly relevant for the ICT sector. Fig. 4 shows materials regarded critical by the EU in 2017 [15].

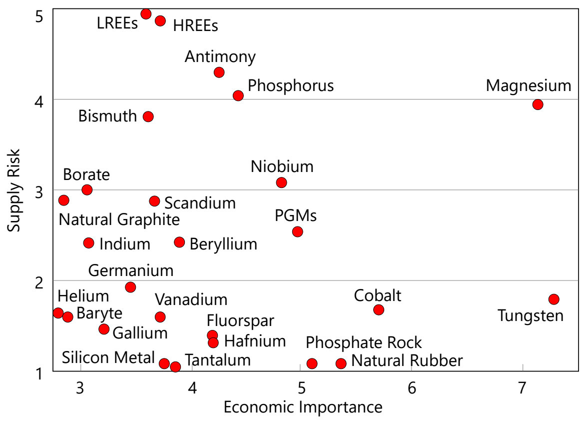

Fig. 4. EU critical raw materials 2017 [15]. LREE/HREE are light and heavy rare-earth elements, and PGMs are Platinum-group metals, respectively.

At least one half of these elements are critical for the ICT sector. Therefore, maximum efficiency of the related CE mechanisms is important.

3. LCA and Power Consumption

As indicated in Ch. 2, lifecycle analyses (LCA) are important to derive the areas of maximum environmental impact of any (ICT) products. This is necessary in order to identify those areas that require most attention for further improvements. In Fig. 5,

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examples for LCAs for ICT infrastructure equipment (wavelength-domain multiplex (WDM) transport equipment, Ethernet network interface devices (NIDs)) are shown.

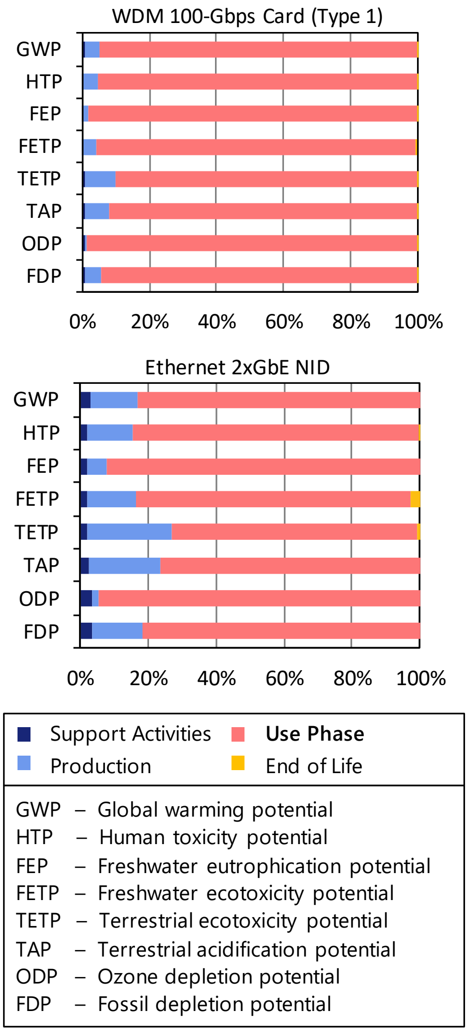

Fig. 5. Lifecycle assessments for WDM 100-Gbps channel card (top) and Ethernet NID (middle)

For both classes of infrastructure equipment, WDM transport and Ethernet NIDs, all impact categories shown are dominated by the use phase. The same can be shown for Ethernet switches and IP routers [4]. This necessitates continued work toward better energy efficiency since use-phase impact is driven by the related energy consumption. In turn, this may be *conflicting with design in support of CE*, at least in those cases where total development effort is limited.

LCA can further be used to demonstrate several effects that are related to the use-phase energy consumption and other impact parameters. Fig. 6 shows a comparison of two generations of a WDM system.

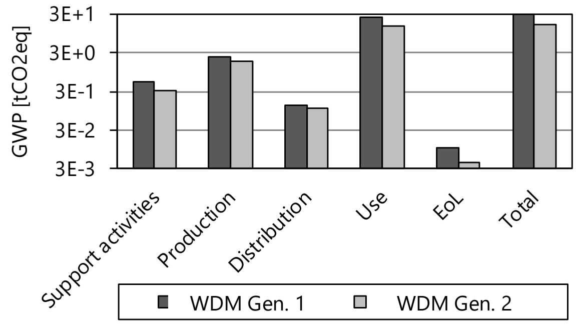

Fig. 6. LCA comparison of two succeeding WDM system generations. Note ordinate-axis log scale.

It can be seen that in this particular case, the impact of all lifecycle phases on the resulting GWP improved. Nonetheless, the use phase maintained its dominance (note the log scale of the ordinate axis!). To decrease this dominance to certain extent, the emission factors of the electricity used for operating the equipment must improve since improvements in efficiency are limited [14]. The impact of different emission factors – resulting from 100% renewable energy vs. EU grid mix 2017 – is demonstrated in Fig. 7.

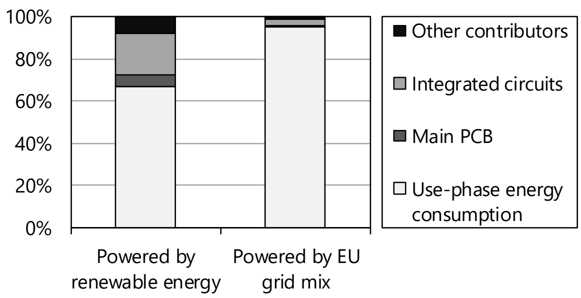

Fig. 7. LCA comparison for WDM system operated with renewable energy vs. EU grid-mix energy (2017)

Fig. 7 shows that even with 100% renewable energy, the use phase maintains its dominance, although now the next relevant phase, production, becomes more apparent. The figure also identifies the most relevant components in production, namely integrated circuits and printed circuit boards (PCB). Consequently, these are the components most relevant for further CE considerations.

So far, effort for ecodesign had to go into increase of power efficiency. This holds for ICT infrastructure equipment, due to the common always-on use mode with relatively long lifetime. For end-user equipment, with different use mode and much higher production numbers, the situation is different and beyond the scope of this paper. As an example, the power-efficiency development for (our) WDM transponders is shown in Fig. 8 [16]. It followed a straight trend in log-log scale.

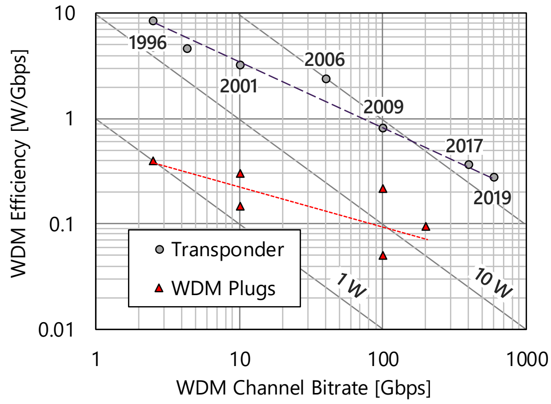

Fig. 8. Power efficiency development for WDM [16]

Efficiency improved from ~10 W/Gbps in the beginning in the mid-90s to almost 0.2 W/Gbps for the latest generation in 2019. A similar trend is shown for pluggable WDM transceivers that in general have less performance, less functionality, smaller form factor and better efficiency. Obviously, the efficiency improvements could not cope with the bitrate increase. This can be derived from the fact that the trend lines cross the isolines of constant power consumption.

However, the development of equipment throughput (e.g., total WDM system transmission capacity) *did* cope with global ICT throughput, as shown in Fig. 9.

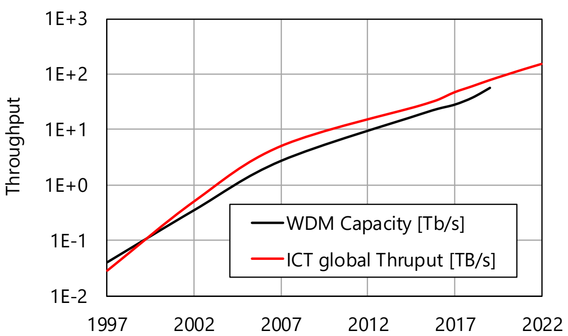

Fig. 9. Internet throughput increase [5]-[7] and WDM system-capacity increase [16]

Here, WDM system capacity and ICT global throughput are displayed in ordinate log scale. Both curves have similar slope. Similar slope can also be derived for other infrastructure equipment (switches, routers) [14]. This means that the amount of equipment and WEEE is growing slower than its energy consumption. (It is growing somewhat due to other effects in network infrastructure roll-out.) This can also be seen from Fig. 3, where WEEE generation has moderate, almost linear, growth rate.

As a first conclusion, components and raw-material aspects of ICT infrastructure gear are important, but less important than energy-efficiency.

4. CE Challenges

Given the alarming result of Fig. 4, effective CE measures are a must. They must be complemented by energy-efficiency improvement for ICT infrastructure equipment. In general, CE is about longevity, that is, the approach to keep material in closed loops as long as possible, as indicated in Fig. 10, which is based on the technical-material part of the well-known CE diagram [17].

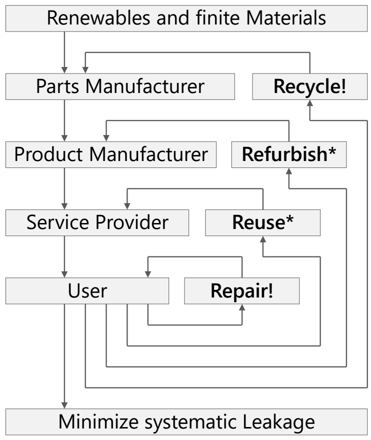

Fig. 10. Circular-economy loops for ICT equipment, based on [17] for technical materials.

As indicated in Fig. 10 by the asterisks, the CE concepts reuse and refurbishment / remanufacture are strictly limited for infrastructure ICT equipment and effectively, should not be followed.

Long lifetime – often in the range of 10-15 years, is given for this equipment. It is enabled by modular design (a key CE concept) and supportive technical functions and business models for maintenance. These include permanent, and even predictive, remote supervision and maintenance contracts, the latter being a first entry level to product-service systems (PSS). However, further lifetime extension (2nd life, reuse, etc.) does not make sense for the equipment class under consideration. Ironically, this is due to the strong improvements in energy efficiency.

Due to the fast pace of ICT development, energy efficiency of successor product generations is also rapidly increasing, albeit at a lower rate than ICT throughput itself. *It therefore sets an upper limit to maximum lifetime*. Above this limit, further use of old equipment becomes net-negative, e.g., for the Global Warming Potential, according to LCA. This is a combined effect of strong efficiency increase and the always-on use mode. It leads to the fact that, after a certain lifetime, using a new product generation is more efficient even if its production is considered.

This is shown in Fig. 11, again for a WDM system, where both generations have similar functionality.

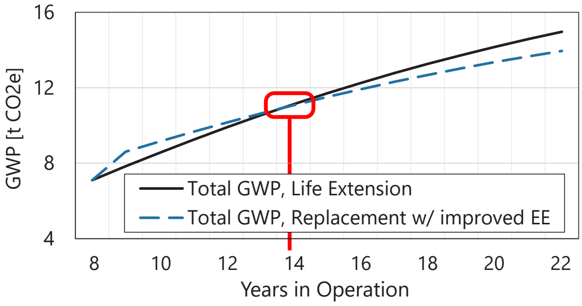

Fig. 11. Lifetime optimization with LCA

Here, a lifetime of eight years has been considered for the first system generation. This is in the range that we see today for WDM equipment, and it is the reason why the time axis starts with 8. Further relevant and realistic assumptions include the decrease of emission factors for the considered period of 22 years by 50%, and a next-generation energy-efficiency improvement of 25%, where such next generations are available after some 10 years. It can be seen that the replacement generation performs better, including its production, after six years. The example shows that after a nominal lifetime (eight years here) plus a certain limited extension (six years here, for a shorter second life), the equipment must be taken out of service in order to prevent negative effects.

Components reuse is also limited by the fast ICT development toward ever increasing bitrates. Combined with the long average system lifetime, this fast pace leads to components, systems and functionality obsolescence.

We conducted an analysis for the main components groups with regard to their reusability:

- Electrical parts, PCBAs, etc.
  - Strong trend to functional obsolescence. Example: around 2010, electronics in ICT transmission had to support bitrates of 10 Gbps or 40 Gbps, respectively. 10 years later, this changed to 100…600 Gbps.
  - Successor parts become much more energy-efficient, see analysis in Fig. 11
- Optical parts (~60% of product cost)
  - Passive optics do not age significantly
  - They seem to be perfect for parts reuse, but
    - Complex and costly optical filters, interleavers, gratings etc. become obsolete. Example: in 2000, WDM filters provided 16×200 GHz channels, 10 years later this changed to 40×100 GHz, and there was no use for the old filters anymore.
    - Simple, cheap 3-dB couplers etc. already pose a disassembly-cost hurdle
- Mechanical parts (~5% of cost)
  - Smallest components fraction regarding both, cost and LCA environmental contribution
  - Reuse of small plastic parts, screws etc. regarded difficult / cost-prohibitive
  - Shelf / chassis reuse? Regarding *weight*, this is the majority, but not regarding LCA impact. So far, it was not possible to design chassis that support several system generations since this would require predicting needs of a system some 10-15 years in the future. Moreover, metal chassis are the components area where a relatively high content of recycled material is in use already.

Together, this limits the CE loops shown in Fig. 10 to lifetime extension up to the LCA optimum (but not beyond), and to optimization of recycling. The former is given today already for many ICT infrastructure products. The latter is an area of ongoing discussion and research, e.g., in the EU H2020 project C-SERVEES [1].

One of the questions currently under consideration is to what extent recycling (and other lifecycle stages) can be improved using ICT tools, i.e., shared data bases (DB). This is indicated in Fig. 12.

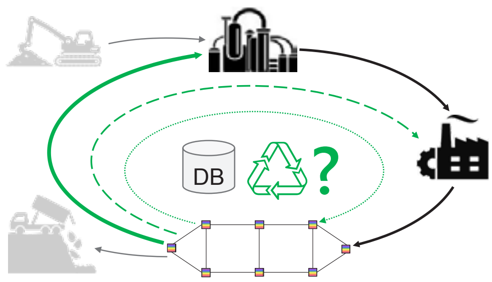

Fig. 12. The open role of ICT in circular economy

Aspects of ongoing research include data-base access, security and integrity and how such DBs can improve value along the value chain (components manufacturers, product manufacturers, service partners, customers). Regarding improved recycling, this currently is not clear yet. One of the reasons is that there is dissent regarding the DB content, i.e., the type, complexity and structure of the data that is to be provided to the respective value-chain members.

One proposal that ranges toward the high end of data complexity suggests to store product material declarations in the DB. Material declarations are known from the REACh regulation. They declare, for all the components of a product, the weight percentages of all contained material (substances). For complex products, this poses several severe problems.

First, compiling complete declarations can lead to substantial effort, in particular in complex supply chains. Then, it is completely unclear how such a level of detail shall help recycling. Complex products can contain 4-digit numbers of components, which in turn leads to very complex declarations. First feedback that we collected from WEEE recyclers says that this data is completely useless in order to improve recycling.

This leaves two questions not answered yet. First, what data can help recycling? The second question is what changes are required in recycling in order to make use of any additionally available data. This may include aspects of reverse logistics that aim at aggregating WEEE with similar characteristics.

CE depends on supportive business models. It is commonly agreed that product-service systems (PSS) best support CE. Different PSS are possible, ranging from selling products together with maintenance services to retaining product ownership and selling fully-managed services [19], [20]. An overview on PSS and their primary advantages is given in Fig. 13.

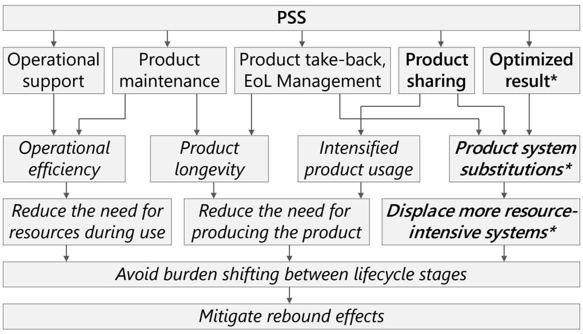

Fig. 13. Overview on PSS, based on [19]

In particular, PSS where product ownership is retained are considered very efficient in supporting CE. The main reason is that due to the retained ownership, the manufacturer has highest interest in getting the highest value out of the (hardware part of the) PSS, once the hardware cannot be kept alive as is anymore. That is, maintainability, upgradeability, repair, disassembly, components reuse and recycling yield must be considered from the beginning, before production. In return, these CE aspects can be supported more efficiently, thus potentially decreasing total lifetime cost or even increasing revenue.

However, as can be derived from Fig. 13 by the asterisks, those PSS paths regarded most efficient ("optimized result") are the ones that do not work for infrastructure ICT equipment.

Equipment sharing between lots of customers is done in core networks by default. Concepts like virtualization, Infrastructure as a Service, etc. are used to maximize utilization. However, these concepts must be managed by the network operator, not the vendor, since no successful vendor-operators exist. This narrows PSS paths for the equipment vendor. In addition, utilization in core networks is upper-bound by queueing (communications) theory.

Product system substitution, the PSS regarded most efficient, is no general option. The (core) ICT infrastructure cannot be substituted. In turn, ICT is replacing physical meetings, travel and other resource-intensive systems, see the Green-by-ICT discussion in Ch. 2. Again, this complicates the PSS paths at the right edge of Fig. 13.

Conclusion

Within the ICT area, the infrastructure equipment (telecommunications networks, data centers) behave differently when it comes to the various circular-economy concepts, compared to end-user equipment.

Differences result since infrastructure equipment, e.g., WDM systems, in most cases have long lifetime, are supported by maintenance functions and contracts, have modular system design (which in turn enables long lifetime and maintainability), and aim at highest energy efficiency. To first approximation, the total environmental footprint of infrastructure vs. end-user equipment is the same. This also means that certain classes of infrastructure equipment are produced in small numbers.

For the infrastructure ICT equipment, these characteristics have massive impact on certain CE concepts, including the related PSSs. The equipment is often obsolete in terms of its technical functions after its regular lifetime, which can be as long as 10-15 years. Further lifetime extension is therefore difficult at best. This is also true since after such periods, equipment becomes available which is significantly more energy-efficient. These limitations in reuse also hold for most components, in particular those with high cost and environmental footprint – they are getting obsolete, too.

Similarly, some of the PSSs regarded highly efficient for CE are not suitable for ICT network equipment. This holds in particular for product-system substitutions. Here, the opposite is true – ICT is already substituting other systems like physical travel. This – positive! – ICT effect is one of the so-called Green-by-ICT effects that help saving energy and (raw) material in relevant other areas.

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Due to these combined characteristics, at least infrastructure ICT equipment must be rated differently (e.g., compared to consumer products) when it comes to CE requirements and regulations. It is less suitable for reuse etc. and *must be taken out of service* at the end of an efficiency-optimized lifetime. Recycling may also be affected since for certain equipment classes (e.g., WDM equipment, routers, aggregation switches), in general no big equipment numbers can be aggregated for recycling, which would enable dedicated, optimized treatment.

This leads to some of the interesting, still open questions. To which extent can ICT tools, i.e., data bases that are accessible in the cloud, help making recycling more efficient? What is the related content and complexity of these data bases? Is the availability of this data sufficient, or are massive changes in the recycling and logistics processes are required as well? Which other steps in the value chain can benefit and how? These questions are still open. To some extent, they will be answered in the second half of the C-SERVEES project. In addition, further research going this direction is regarded necessary.

Acknowledgement

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Resource Efficiency that reflects the quality of resource recycling such as horizontal recycling and cascade recycling

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Abstract

In recent years, efficient use of material resources by circulating resources, for example by reuse, refurbishment, remanufacturing and recycling, is regarded as important globally. Therefore, we had developed a resource efficiency indicator for products in order to promote resource circulation. The indicator has two features. The first feature is that it represents the changes of offering product value due to reuse, refurbish and remanufacturing products. The second feature is that it represents differences in environmental impact by material types. However, no indicators, including our own, have been established that reflect differences in resource circulation, such as horizontal recycling and cascade recycling. In this development, we attempted to expand the indicator to reflect the quality of the circulation by setting a resource circulation level for each material cycle. For example, in iron recycling, a higher level was set for recycled blast furnace sheets than for castings. As a case study, resource efficiency is calculated using a Panasonic refrigerated showcase as a model case. In this presentation, we first present a review of existing methods for measuring resource efficiency of products and present our proposing method. Then, we introduce the refrigerated showcase product business of Panasonic Corporation. Next, we present the product lifecycle scenarios which we developed, and the application of our method. The effectiveness of the measurement method is discussed.

1 INTRODUCTION

In recent years, shortages of material resources have been worsening due to population growth and worldwide modernization. Therefore, to end humanity's widespread reliance on a single-use economy that consumes and discards resources, developing a "circular economy" pervaded by reuse and recycling practices has been a subject of considerable investigation, especially in Europe.

Society's expectations regarding sustainable resource use are growing, especially in countries where the importance of the circular economy is widely acknowledged. Given this trend, even at the G20 Ministerial Meeting on Energy Transitions and Global Environment for Sustainable Growth, held in Japan in 2019[1], the importance of participation by companies in helping to promote the circular economy was emphasized.

Sustainability is especially important for manufacturers, who use resources intensively in their manufacturing processes.

Panasonic undertakes initiatives such as reusing iron and plastic from end-of-life products in our own products, in accordance with a scheme that we call "Product to Product.".

Recycling rates of household appliances are generally used as indicators to evaluate the effectiveness of recycling efforts, but these methods can evaluate only the total amount recycled or the total waste reduced. There is no established index to quantitatively measure resource efficiency, i.e., the extent to which resources are effectively circulated and thus reused.

Therefore, Panasonic and AIST jointly developed a resource efficiency indicator for products.

2 Resource Efficiency

2.1 Resource Efficiency Indicator [2]

The framework for the indicator to measure resource efficiency was established as follows.

Resource efficiency

$$= \frac{(\text{Number of years of product use} \times \text{Usage value})}{\text{Resource impact in the product life cycle}} \quad (1)$$

This formula expresses the extent of value and the length of the value provision period with respect to the environmental impact of resource use (hereinafter referred to as the "resource impact").

The usage value in Equation 1 is the value provided to the product user by the function of the product. Although the usage value is a very important factor in

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measuring the resource efficiency of products, for this paper we assigned it a value of 1 so as to focus on resource impact.

The resource impact in the product life cycle (the denominator in Equation 1) will be explained in detail in the next section.

2.2 Resource Impact Evaluation [2]

The calculation image is shown in Figure 1. The resource impact was set as follows.

$$\text{Resource Imapact in the product life cycle}$$
$$= \text{Product Material Value(PMV)} - \text{Rretained Product Value(RMV)}$$
$$= \sum_m W_m \times (1 - R'_m) \times V_m + \sum_m W_m \times R'_m \times V_m - \sum_m W_m \times R''_m \times V_m \quad (2)$$

W in the equation 2 represent the weights for each material type among the resources that make up the product, and V in the equation 2 represent coefficients that apply to the environmental impact for each type of material resource. In addition, R' in the equation2 represents the weight ratio of recycled materials (recycled materials and reuse parts). Also, R" represents the weight ratio of recycling after End of Life. By performing a multiply-accumulate operation, it is possible to accumulate the resource impact of the product based on that for each of the material types constituting the product.

The first and second terms of Equation 2 represent resource inputs during the product life cycle. The first term of Equation 2 denote inputs of virgin material into the product system, the second term of Equation 2 indicate inputs of recycled materials. The sum of these terms represents the resource impact of input resources. The third term of Equation 2 expresses the reduction in environmental impact arising from the reuse of resources due to product recycling after use.

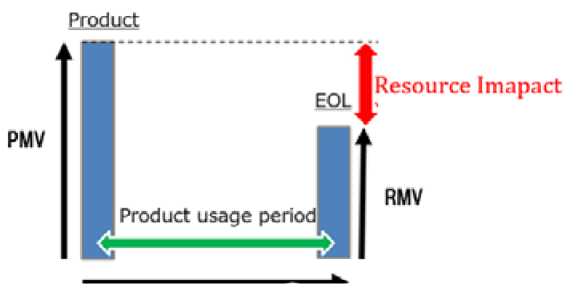

Figure 1 Image of Resource Imapcet

2.3 Quality of resource circulation

As shown in 2.1, the basic structure of resource efficiency index was constructed. The indicator has two features. The first feature is that it represents the changes of offering product value due to reuse, refurbish and remanufacturing products. The second feature is that it represents differences in environmental impact by material types.

However, this index does not distinguish between cascade recycling and horizontal recycling. That is, if the same material is reused or recycled, it is considered to be equivalent. Therefore, when the purity of the recovered material is increased for horizontal recycling, the recovery amount may decrease, resulting in deterioration of resource efficiency.

Therefore, we expanded the formula to reflect the quality of resource circulation based on the indicator of 2.2. As a method, we have tried to introduce allocation according to resource circulation level.

3 Resource Circulation Level

3.1 Formula organization

In order to introduce the resource circulation level and allocation, we arranged it as shown in Equation 3.

$$\text{Resource Imapact in the product life cycle} = \text{PMV} - \text{RPV}$$
$$= \sum_m W_m \times (1 - R''_m) \times V_m + \sum_m W_m \times R'_m \times V_m \times C'_m \times A_m - \sum_m W_m \times R'_m \times V_m \times C''_m \times (1 - A_m) \quad (3)$$

C' and C" in the equation 3 represents the resource circulation level of the material used and after End of Life. Also, A in the equation 3 represents the contribution ratio between the recycling side and the side using recycled materials. The values of C', C" and A are set between 0 to 1.

3.2 Hearing

In order to score the resource recycling level of each material, Panasonic conducted hearings with stakeholders for recycling home appliances (air conditioners, TVs, refrigerators and washing machines). We also conducted interviews with recycling specialists in Japan. The hearing results are arranged as shown in Table 1.

Table 1 Result of hearing about resource circulation level

Resource Circulation Level	Product	Recycling method	Recycled product
1.0		(Reuse)	(Reuse part)
0.8	Copper piping	Melting	Copper products
	Enclosure (stainless)	Melting	Stainless
0.6	Printed board	Smelting	Electrolytic copper
		Smelting	Au
	Compressor (Fe+Cu)	Steelmaking	Special steel
	Resin (PP)	Manual disassembly, Dissolution	Recycled resin pellets
0.4	Enclosure (Fe,SUS)	Electric furnace	Steel plate
0.2	Recycled dust	non-functional recycling	Roadbed material
0	Recycled dust	Landfill	

3.3 Grouping

Based on the hearing results, we were able to classify each level, so we carried out grouping. Then, as shown below, we were able to roughly divide them into 6 groups.

- Level 1.0 : Reuse
- Level 0.8 : Material reuse(Example: Recycled wrought material, copper wrought)
- Level 0.6 : Horizontal recycling
- Level 0.4 : Cascade recycling
- Level 0.2 : Non-functional recycling
- Level 0 : Landfill

A case study was conducted using this resource circulation level.

4 Case Study

4.1 Product

The product for the case study was selected partly due to its involvement with remanufacturing, a topic of lively discussion among circular economy proponents. Manufacturing is a type of product reuse. The manufacturer rebuilds appliances recovered from the market and then ships them back to the market again. Products that are used for a long time and tend to deteriorate with age are suitable for remanufacturing. After some consideration, we decided to use refrigerated showcases installed in supermarkets as our case study product.

Fig. 2 displays a showcase overview. Food is displayed on each shelf, and refrigeration is required to maintain

Figure 2 Showcase overview

food freshness. Therefore, a heat exchanger is installed inside the refrigerated showcase.

In addition, steel is often used for the enclosure so that it can withstand the load when food products are displayed. However, when used for a long period of time, the inside of the showcase is humid, so care must be taken to prevent rusting.

4.2 Senarios

To carry out the case study, we examined five scenarios for the life cycle of refrigerated showcases. We set Scenario 0 as the baseline and created four additional scenarios. Scenarios, were set, and two key driver conditions were also set, so that there were 2 × 2 = 4 scenarios (four quadrants).

As shown in Fig. 3, each alternative was constructed by choosing between two choices regarding the degree of dependence on used materials and parts and also between two usage period time options, creating 2 × 2 = 4 distinct scenarios.

For the “used materials and parts” condition, the two possibilities were use of virgin materials and new parts or of recycled materials and parts. For the “usage period at one store” condition, the two options were “short” or “long.”

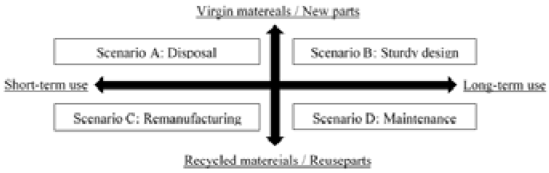

Figure 3 Relationship of each scenario

See Table 2 for a description of the four scenarios.

In this case study, the usage value is the same in all scenarios. Specifically, in the supermarket, we decided to provide the function of cooling a certain amount of food. The contents of each scenario concept were set as shown in Table 3 while satisfying the usage value.

As a major change, in the scenario where the product is used for a long time, iron is changed to stainless steel for rust prevention.

However, in scenario C, the rust is removed during remanufacturing, so there is no change to stainless steel.

In addition, in this case study the technological evolution of energy-saving effects is not considered so as to simplify the calculations. Therefore, in our comparison of scenarios, the comparison involves only one generation.

4.3 Setup Conditions

To calculate the resource efficiency in each scenario, data collection was carried out. Actual product data from Panasonic were used for the materials and weights concerning the refrigerated showcases. For TMR, which is the environmental impact coefficient, we referred to the LCA software database [3].

We used recycling test values that Panasonic had obtained for the material type and weight data through recycling. Specifically, we put discarded refrigerated showcases on the line of a recycling plant and utilized the recovery ratio for the material that was actually recovered. In all scenarios, we set the usage value at 1.

Table 2: Concepts of each scenario

Scenarios	Concept
0: Standard	Use for the typical number of years with the current material composition and dispose of everything in landfills.
A: Disposal	Reduce input material by reducing. In exchange, the product life is shortened.
B: Sturdy design	Ruggedly designed parts (Enclosure) that are difficult to replace are used, and the product life is extended through daily routine maintenance.
C: Remanufacturing	The unit is used for 8 years, leaving only the collected items in the case, regenerating core parts such as heat exchangers (Reman), and used by another user for 7 years as a reman product.
D: Maintenance	We replace parts every three years so that we can use the product for a long time, but we replace old parts with reused products.

Table 3: Contents of each scenario

Scenarios	Usage priod	Material type		Recovery ratio through recycling	Resource Circulation Level
		Enclosure	Color panel		
0: Standard	11 years	Steel	Steel(Painted)	0%	Level 0
A: Disposal	4 years	Steel	ABS	70%	Level 0.4
B:Sturdy design	15 years	Stainless	ABS	70%	Level 0.4
C:Remanufacturing	8+7 years	Steel	ABS	99%	Level 0.8
D: Maintenance	15 years	Stainless	Stainless (repainted)	70%	Level 0.4

4.4 Caluvulation Results

For the calculation results, the resource efficiency of Scenario 0 was expressed as 1 and the resource efficiency of each of the four alternative scenarios was expressed as a relative value. The calculation results are shown in Figure 4. The remanufacturing scenario yielded the best score, whereas the disposal scenario achieved the worst score.

The reason why that Scenario A turned out worse than the others seems to be the extreme shortening of the life span. In other words, if the product has the same material composition as in the baseline scenario, and if the life span can be made longer than X years, the resulting score will be better than in Scenario 0.

On the other hand, Scenario C outperformed the others because the product was designed with remanufacturing in mind. The product could be easily disassembled for recycling after use, and recycling of recovered materials with high purity could be carried out.

In Scenarios B and D, the enclosure material was changed from steel to stainless steel to allow longer-term use. As a result, the resource impact of the input materials increased, but as a result of recovering material with high purity for recycling, the score was better than the baseline Scenario 0.

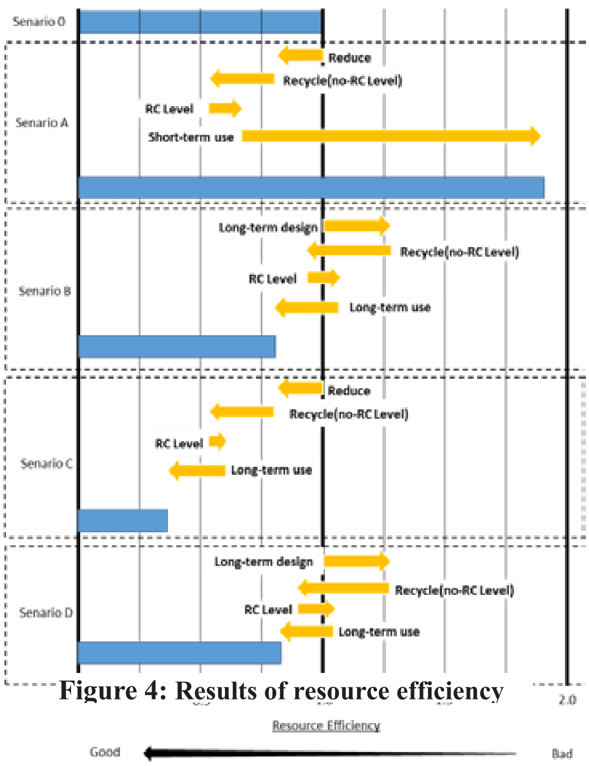

Figure 4: Results of resource efficiency

4.5 Discussion

In the result of FIG. 4, arrows indicate the factors that changed the resource ratio of each scenario from the standard scenario 0.

In scenario C, the recycling of each material is possible due to the dismantling of parts by Remanufacturing, so the resource circulation level is high, and the recycling effect is higher than in other scenarios.

In Scenarios A, B, and C, since the whole product is put into the crusher, it becomes cascade recycling, and the recycling effect is small. Also, reflecting the resource circulation level, it can be seen that in scenarios B and C, when not used for a long time, it becomes worse than the standard scenario 0.

From these results, it was possible to reflect the recycling effect that reflects the quality of resource circulation.

5 Summary

In this study, we attempted to develop a resource efficiency index that reflects the quality of resource circulation. We have shown the options that regulate the quality of resource circulation and presented the circulation level for each option. Also, we then conducted a case study on refrigerated showcases, testing four scenarios and examining the quantitative results. As a result, we found that the quality of resource circulation can be reflected by the level of resource circulation.

In the future, in order to deal with various products, it will be necessary to improve the resource recycling level and the recycling contribution ratio. We also need to conduct case studies with other products and to consider whether this approach can be effectively applied to various types of products.

6 Literature

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Toward Circular Economy Implementation: A Tool for Integrating Circularity Indicators into Portfolio Management

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Abstract

One of the barriers for companies to implement circular economy (CE) principles is creating a portfolio of CE projects. Circularity indicators can evaluate circularity for managing products in circularity perspective. However, existing circularity indicators are either lacking a holistic facet of CE or too complicated for practical usage, which could be barriers for practitioners to manage a CE project portfolio. The aim of this study is to develop a highly intelligible CE portfolio management tool to visualize circularity calculated by circularity indicators with holistic criteria. The CE portfolio mapping tool was built through semi-structured interviews with a case company, identifying three main requirements for general CE portfolio management tools and revealing four contributions of the developed tool. This study contributes to integrating practitioner view into the research context of circularity indicators and taking first step toward further research in CE portfolio management.

1 Introduction

The circular economy (CE), decoupling economic development from resource consumption, is a new economic concept that replaces traditional linear ("take, make, dispose") economy for keeping products, components, and materials at their highest utility and value [1]. As companies are seeing the underlying profitability in CE, an increasing number of companies have approached the idea of CE into their business. This transition (from linear economy to CE) in companies could be supported by effective portfolio management, evaluating the current status and making strategic decisions [2][3]. The former, evaluating the current status, is regarded as one of the key factors for accelerating the transition to CE [4], which have promoted increasing number of researchers and organizations to develop circularity indicators.

In the past decade, a number of circularity indicators have been developed for estimating the circularity of products and business to use in product design, internal reporting, procurement, and investment decisions [5]. These indicators give scores of resource efficiency, waste reduction, or greenhouse gases reduction in CE strategies, hence, can contribute to benchmarking of incremental improvements [6][7].

However, those indicators are still far from being practical in portfolio management, since most of the indicators focused on scoring circularity in a limited facet of CE [5]. A wider implementation of CE arguably requires comparing between different CE strategies. Nonetheless, few studies focus on holistic circularity indicators that can measure the circularity in every strategic aspect [6]. Additionally, existing indicators with holistic criteria of CE could result in too complicated tools for practitioners [5]. Product portfolio is commonly managed by top managers, who might have less insight than researchers and experts, therefore, the indicators applied for portfolio management need to be high intelligibility [8]. Yet, there is little research which focus on how to visualize circularity resulted from indicators [9].

These problems occurred from the lack of connection between the indicators and their practical uses in CE portfolio management [8]. The indicators have been focused on calculating circularity in a specific strategy, while portfolio management requires an ability to evaluate among different strategies. Integrating circularity indicators and portfolio management is necessary for practical use of supporting the CE transition. The aim of this study is to develop a CE portfolio visualization tool for evaluating and managing circular products and businesses, maintaining holistic criteria in various facets of CE.

2 Literature Review

CE is gaining attention in EU countries [10]. As many practitioners have tried to implement CE, various definitions, framework, and tools have developed. To clarify the standing point of this study, a literature review in CE, circularity indicators, and portfolio management tools will be described in the following section.

2.1 Circular Economy

CE is an alternative economic concept that replaces current linear consumption economy with closing material flow cycle by creating value from discarded materials. According to Kirchherr et al. [11], who reviewed 114 definitions and united them, CE is defined as "*an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating generations*".

Since CE contains various strategies in itself (e.g. recycling, remanufacturing, etc.), a variety of CE classifications have been proposed by researchers and organizations in last decade. *ReSOLVE* framework, one of the famous CE framework based on conceptual actions for CE, is intelligible and recognizable for decision-makers [12]. *CE strategies* by EEA consists of four division based on more abstracted level action for CE than ReSOLVE [13]. *CEBM* defines CE into six categories based on concrete processes for closing products flow cycle [14]. *R-framework* categorized CE into nine specific strategies as well, ordering them in circularity and innovation levels [15]. *Circular strategies* by Guzzo defines CE into four conceptual group with specific 21 strategies, maintaining both intelligibility and concreteness [16].

These CE frameworks guide firms to adopt CE into their businesses, but they offer little guidance on how to estimate circularity of products and businesses for benchmarking and decision making, which is why circularity indicators are required.

2.2 Circularity Indicators

To support decision-makers to evaluate their circular businesses and achieve circular innovations, circularity indicators have been developed to score circularity of products and businesses [11]. Circularity indicators are calculation tools that estimate circularity of products and businesses from recycling ratio, resource efficiency, and lifetime. The indicators are, based on their implementations, divided into three levels: micro level (products, consumers and organizations); meso level (symbiosis association and industrial parks); and macro level (city, province, region, and country), respectively [8]. The focus of this study is on the micro-level indicators.

In last decade, a variety of circularity indicators have developed by researchers and organizations. However, few studies in circularity indicators employed criteria with a holistic approach to CE. Instead, most studies have focused on calculating circularity score in a specific aspect of CE. *Performance indicator* by Huysman [17] calculates performance score of plastic waste, based on recycling ratio. *Material circularity indicator* [4] computes single circularity score based on material resource efficiency, including recycling ratio and reused ratio. *Circularity metric* by Linder [18] calculates circularity with a ratio of economic value from recirculated parts per the one from all the parts. As such, most previous circularity indicators cover limited area among various types of CE. Hence, it is difficult to evaluate different CE strategies using one single indicator (e.g. comparing circularity of *products made of recycled plastics* versus *remanufacturing*). This is problematic, as companies are encouraged to strive for more than one CE strategy.

Holistic circularity indicators, on the other hand, might result in complicated tools and lack intelligibility, rendering them too complicated to be practically used by decision-makers in firms which may have less knowledge and insight in CE. *CEIP* by Cayzer [19] scores circularity respectively in five CE categories based on questionnaires, which illustrates scores in spider chart with high intelligibility, lacking holistic criteria. Saidani [20] designed a holistic circularity indicator that compute single circularity score from four categories with five specific attributes per each based on a CE framework by EMF [21], which appears to be less intelligible. Pauliuk proposed a dashboard that illustrates correspondents of indicators to every specific CE strategy [9], ignoring how to display individual scores for evaluating different CE types.

As such, the existing circularity indicators are lacking practical view when they are used, since few indicators can both 1) evaluate circularity with holistic criteria and 2) display it keeping high intelligibility.

2.3 Portfolio Management Tools

Portfolio management is defined as "resource allocation to achieve the business's new product and technology objectives" [22]. Goals of portfolio management consists of following six elements [22]: 1) Projects are aligned with businesses' strategies, 2) Portfolio contains high-value (profitable and high-return) projects, 3) Spending reflects the businesses' strategies, 4) Projects are done on time—no gridlock, 5) Portfolio has good balance of projects, and 6) Portfolio has right number of projects. To visualize scores of products and businesses for supporting decision-making, several tools for portfolio management have been developed. These portfolio management tools could arguably be useful for visualizing products' circularity scores calculated by indicators. For example, one of the challenges in managing CE projects is addressed by the 1st element above, *projects are aligned with business strategies* [23], hinting that portfolio management tools could help companies to accelerate transitions to CE.

While portfolio management methods have been developed to support top managers to make investment decisions, few studies focused on integrating circularity into their criteria [24].

Still, some researchers have considered sustainability into portfolio management. Brook proposed innovation project portfolio management framework in the context of sustainability, combining strategic buckets, bubble diagram, and scoring model to evaluate and prioritize innovation projects in a view of sustainability [2]. However, this framework is limited to sustainability aspects, therefore, circularity is not enough covered with the criteria (i.e. it has a narrow focus on CO_2 emission).

As such, few studies focused on portfolio management in the context of CE. Since measuring circularity is underdeveloped, evaluating projects in portfolio with circularity is underdeveloped as well. The purpose in this study is to develop a CE portfolio management tool to visualize circularity of circular businesses with holistic circularity criteria.

2.4 Research Questions

In building a CE portfolio management tool, three research questions were raised regarding requirements for CE portfolio management tools, the developed CE portfolio management tool itself, and contributions of the developed CE portfolio management tools.

The requirements for CE portfolio management methods are not clearly raised in previous research. Therefore, the first research question is as follows: *what are the requirements for CE portfolio management tools?*

Previous literature focused on scoring circularity rather than displaying circularity. Second research question is regarding the tool itself: *How to visualize the circularity of a project portfolio with high intelligibility?*

Little previous research implements a portfolio view of CE projects. Third research question is regarding contributions of the developed tool: *How would a circularity portfolio visualisation tool work for a company?*

2.5 Tool Requirement Specification

From the CE perspective, lacking *holistic criteria of 'CE with high intelligibility* was addressed as the limitation of existing circularity indicators in the literature review. In developing a portfolio management tool, *holistic criteria of CE* was chosen for one of the main requirements for the tool since portfolio management require evaluating individual businesses that are categorized into different CE types.

- *projects can be evaluated with holistic criteria of CE*

From the portfolio management perspective, requirements are settled by referring to the purposes of portfolio management, defined by previous research [25]. As is described in literature review, the purpose of portfolio management consist of following six elements: *projects are aligned with businesses' strategies*; *portfolio contains very-high-value projects*; *spending reflects the businesses' strategies*; *projects are done on time—no gridlock*; *portfolio has good balance of projects*; and *portfolio has right number of projects* [25]. Three elements were chosen for the main requirements for the tool:

- *portfolio has good balance of CE businesses*
- *projects are aligned with businesses' strategies (high circularity)*
- *portfolio has right number of projects (for circular economy)*

3 Methodology

This research follows research-gap-driven and objective-driven framework, inspired by the objective-driven and data-driven framework from Saidani [8], to produce the CE portfolio visualization tool that can be practically used by companies. The CE portfolio visualization tool was developed both from research gap perspective and from companies' objective perspective. The first prototype of the *CE mapping tool* was built originally by the main author based on research gaps identified through a literature review. Final version of the tool was completed by iteratively modifying first version of the tool, analysing results from interviews with a case company.

Circular strategies by Guzzo [16] was introduced as criteria for evaluating circularity to reflect the first requirement, *projects can be evaluated with holistic view of circular economy,* since it has concrete contents which is suitable for visualizing holistic view of circular economy. Circularity was evaluated by counting the number of achieved CE strategies with circular products in a company (e.g. if a company holds a sharing product made with recycled materials and products made with recycled materials, scores would be [*sharing product*: 1, *recycled resources*: 2]). These circularity scores were plotted as spider chart with the criteria arranged in a circle shape.

After the prototype was built based on the literature review, interviews were conducted to highlight the requirements from companies' objective perspective in order to realize practical tools for companies. Interview methodology is described with interview guidelines, analysis methods, and the respondents in the following sections.

3.1 Data collection

To develop a practical CE portfolio management tool, requirements for the tool needed to be cleared, which is why a qualitative research approach was chosen. Semi-structured interviews were selected for the data collection method. Respondents were asked to freely talk about the current status of portfolio management (who uses, purpose of use, what valuables they use, benefits/drawbacks, etc.) and desirable functions for CE portfolio management tools based on 41 questions. The questions were designed based on instructions provided by Kvale [26], and consist of four sections: 1) *Strategy and environmental aspects*, 2) *Portfolio management,* 3) *Portfolio management and environmental aspects,* and 4) *Feedback on the proposed tool*.

All the interviews were conducted through Microsoft Skype since it enables remote interviews with some of the respondents in different countries [27]. Every interview was conducted within one hour and recorded with the respondents' agreements. The recorded interview results were transcribed and analysed. Content analysis was chosen for analysing interview results since the results should be inductively analysed to learn current status of company and requirements for the visualization tool. The results were coded and categorized by clauses based on instructions provided by Miles [28] with MAXQDA Analytics Pro 12 (release 12.3.6, Copyright © 1995 – 2018 VERBI GmbH Berlin). Categorized results are classified into several interview topics. Finally, results were settled in tables with Microsoft Excel.

3.2 Case: company X

Company X, a leading company in outdoor products, was chosen for the interview, since the company set sustainable development as one of the company goals, with a recent ambition to implement CE in its business strategy. The company is a group company, which is divided into three divisions: division A, B, and C. This company has a group level strategy, and each division has strategies to meet the strategy of the group. Each division manages their own product portfolio.

Five respondents from company X were interviewed, including a sustainability manager of the group; a director of group operation; sustainability affairs in division A; a vice president in division B; and a project manager of sustainability strategy in division C. As two respondents were from a group level, they have no direct involvement in portfolio management. However, all the respondents have responsibilities related to sustainability.

4 Interview Results

The interview results about current status of company X's strategies in sustainability and CE showed that the respondents had different recognitions regarding their company's strategies. While one of the respondents answered that sustainability is integrated in business strategies, others mentioned that sustainability is separated from overall strategies. Similarly, about CE in strategic level, one interviewee told that there are no business strategies on CE in this company, whereas others stated that it is part of sustainability strategies. As such, it seems quite necessary to share a common view when implementing CE in a company.

Concerning challenges for company X to implement CE into their businesses related to portfolio management, two main issues appeared: 1) how to evaluate products sustainability/circularity and 2) how to consider both profitability and sustainability. As for sustainability/CE evaluation, one interviewee referred to lacking capability of scoring sustainability and others stated that there are no criteria of sustainability in their portfolio reviews. Referring to managing balance of profitability and sustainability, one interviewee mentioned that it is difficult to consider both earning profit in short term and becoming more sustainable in long term. Indeed, others described that there is a dilemma between high quality and high circularity (e.g. since recycled plastics are less UV stable and more fragile).

Regarding desirable functions of CE portfolio management tools, there were also two main topics: a) how to evaluate circularity and b) what to be used for additional criteria. As for the former, a) *how to evaluate circularity*, two desirable functions were suggested: 1) estimating circularity of not only circular products but also circular business models and 2) evaluating circularity of products/business models by categorizing into corresponding CE strategies. About the latter, b) what to be used for additional criteria, three functions were suggested: 1) assessing circularity from both sustainability and *profitability* perspectives, 2) considering *environmental impact drawbacks* to ensure that circular benefits takeover the environmental impacts, and 3) evaluating *value proposition novelty* to judge if projects can be called innovation or not.

From the interview results particularly about desirable functions for CE portfolio management tools, requirements of the tool were concluded: 1) estimating circularity of circular business models, 2) evaluating circularity of the projects by categorizing, 3) incorporating environmental impact to consider CE rebounds, 4) assessing from both sustainability and profitability perspectives, and 5) evaluating value proposition novelty to judge if projects can be called innovation or not.

5 CE Portfolio Mapping Tool

A final version of the CE portfolio mapping tool was built, reflecting the feedback on the prototype by the respondents. In this section, the development of the final version is described.

5.1 Final Tool Development

CE portfolio mapping tool was built, iteratively modifying the protype of the tool by reflecting requirements extracted from interview results and five opinions given by the respondents. Figure 1. depicts an example usage of CE portfolio mapping tool. Mainly four points were updated from the prototype: 1) evaluation per project, 2) Circularity score in [0, 100], and 3) CO_2 bubbles representing environmental impact.

Firstly, evaluation was altered from overall analysis to evaluation per project. In the prototype, circularity scores of several projects were compressed in one score to show the overall score. Reflecting one of the opinions raised by the respondents, CE portfolio mapping tool visualizes each circularity score per projects to compare among them.

Secondly, the way of calculating circularity scores was changed from counting the number of achieved circular innovations to computing by existing circularity indicators in a range of [0, 100]. The point is to evaluate circularity per project and compare among them, which is why [0, 100] range was adopted. Besides, threshold level was illustrated as well in the tool as the respondents claimed. This threshold level is supposed to be determined by top-managers in a company.

Thirdly, CO_2 bubbles were included as criteria for evaluating gross environmental impacts. As one of the respondents stated, considering only resource circularity might cause larger negative environmental impacts than circularity benefits, which is why CO_2 bubbles were introduced. Environmental impacts would be assessed based on carbon footprint and evaluated as differential values from the one measured one year ago, which are finally shown as the size of CO_2 bubbles (if the value is negative, it would be shown as black-coloured bubbles).

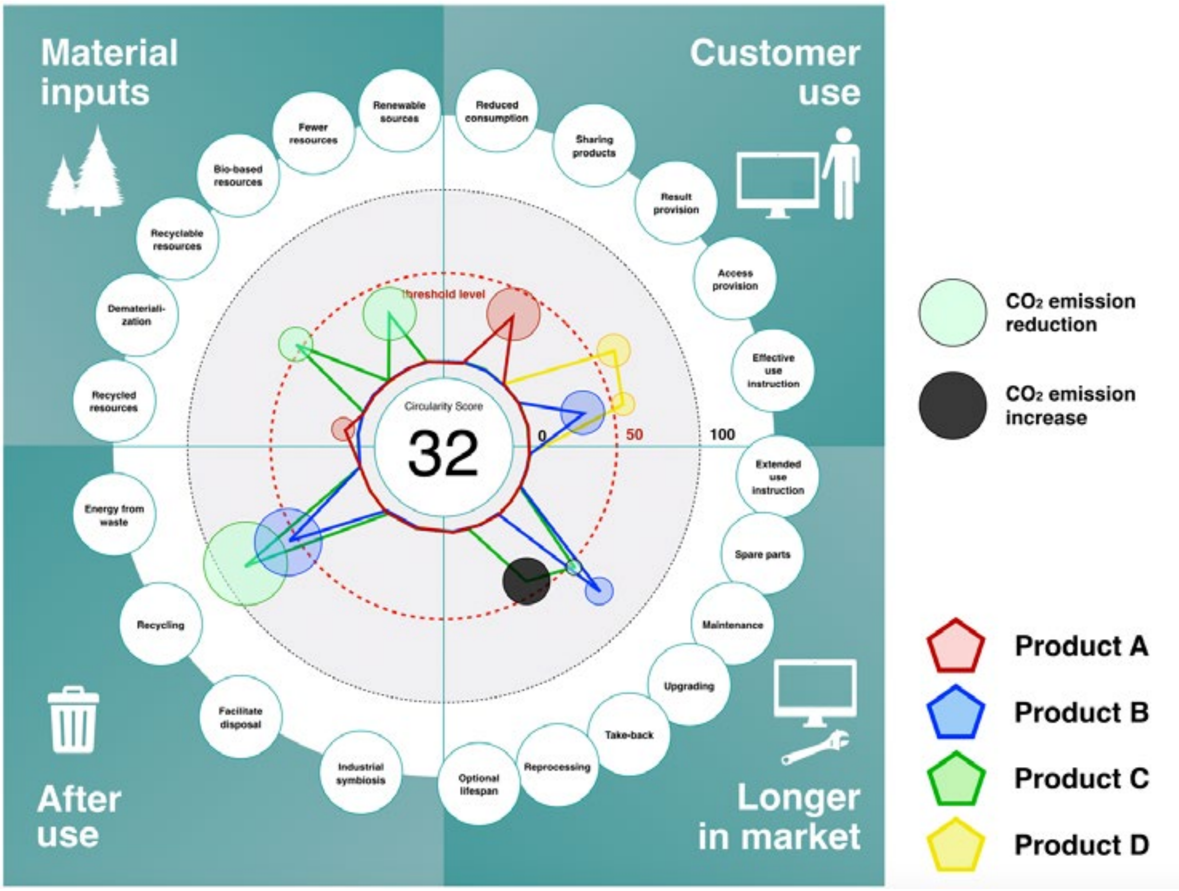

Figure 1. an example usage of CE portfolio mapping tool

5.2 Final Tool Evaluation

In total, five possible usages of CE portfolio mapping tool were suggested by the respondents: 1) evaluating business models based on circularity, 2) checking whether projects are circular innovations or not, 3) communicating internally & externally, 4) setting requirements of CE projects, and 5) defining criteria for assessing circularity of CE.

6 Discussion

The final version of the CE portfolio mapping tool has several strong points in managing CE portfolio: CE framework applied as criteria, spider chart visualisation, CO_2 bubbles. Those characteristics are discussed with previous research.

In contrast to other circularity indicators (e.g. [4], [17], [18]), the first property of the CE portfolio mapping tool is using CE framework as criteria of circularity to incorporate holistic view of CE. In this study, CE frameworks were reviewed and *Circular strategies* by Guzzo was identified preferable one to be applied for criteria of circularity since it is based on concrete actions for higher circularity and all of them are micro-scale. The CE framework in a portfolio visualization tool might contribute to supporting a company to evaluate and manage CE projects, particularly for companies that do not have their own certain definition of CE. In fact, some researchers stated that those CE frameworks could facilitate to manage CE portfolio [16].

The second feature of CE portfolio mapping tool regards the visual presentation. This tool arranges criteria of CE in a circle shape and showing circularity for each CE strategy as spider chart. Few circularity indicators visualized circularity in circle shape, while most of the indicators shows only single score of circularity in percentages such as MCI by EMF and Circularity calculator by ResCoM [4][29]. Yet, some CE frameworks are arranged in circle shape, arguably just because circle shape would be helpful to imagine circularity of material flow in CE. For instance, a model of CE is depicted in circle shape to show the circular processes of CE [13]. On the other hand, *R-framework* [15] is shown as linear to illustrate that the CE strategies were ordered in circularity. This linear order would help to consider circularity based on the hierarchy among different strategies, yet it is hard to recognize the balance of circularity levels among different strategies. In the case of visualizing portfolio, circle shape might be preferable to linear, since illustrating balance of circularity in each CE strategy is important to help to easily identify strong points or improvable points of CE projects. In fact, one of the respondents stated that *"it's easy to understand where sticking-out points are and where requirements for circular projects are"* as the positive comments. CE portfolio mapping tool arguably seemed to contribute to linking circularity indicators with holistic criteria and practical usages in portfolio management.

The third characteristic of CE portfolio mapping tool is showing CO_2 emission as bubbles to consider environmental sustainability. Some interview results indicated that circularity should be evaluated with environmental impacts within portfolio management so as to consider potential drawbacks of CE. In fact, Zink and Geyer stated that increased circular products in circular economy possibly caused rebound of environmental impacts because of increased production and consumption [30]. However, there have been little previous research in evaluating circularity with environmental impacts in CE portfolio management. Some circular indicators include environmental sustainability by assessing circularity from environmental impacts, which is not able to consider both environmental impacts with material efficiency as circularity [5]. It could be concluded that CE portfolio management tool contributed to considering both environmental sustainability and circularity (of material) in single tool to support portfolio management.

6.1 Tool Contributions

Four possible usages were identified during the direct feedback from the respondents on the developed tool: to evaluate projects based on circularity; to check whether projects are circular innovations or not; to set requirements for CE projects; and to communicate externally. Additionally, two extra contributions of the tool were suggested from interview results: internal communications; and defining criteria for assessing circularity of CE. Those six contributions are discussed with previous research.

Evaluating projects on circularity resonates with previous research in portfolio management by Cooper et al. (2000) [22]. One of the objectives of portfolio management is defined as confirming that projects are aligned with business strategies [22]. Considering this objective in CE context, it can be interpreted as follows: confirming that projects are achieving high circularity as a part of business strategies. Since most micro-scale circularity indicators have a narrow focus on measuring circularity of products [31], this result suggests that the CE portfolio mapping tool could act as the link between circularity indicators, portfolio management and thereby business strategy.

Checking whether projects are circular innovations or not was referred as a possible usage of the tool. It could be part of criteria for managing CE portfolio, since one of the respondents mentioned that the number of innovations was applied for a criterion of monitoring CE.

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Circularity indicators can be used for monitoring CE projects [31], yet judging if innovations are circular or not was not clearly mentioned in previous research, which might be new findings from this study.

The interview results showed that the tool could be used for external communications with different stakeholders (e.g. inventors or consumers). Saidani [8] revealed that some micro-scale circularity indicators (4 out of 20) are suited primarily for communications [8]. Only one circularity indicator (RI by Van Schaik), while other three indicators could only shows quantitative scores without specific visualizations [32]. The CE portfolio mapping tool, developed in this study, advanced visualizing circularity from limited aspects of CE to holistic view of CE, which could contribute to promoting external communications with people having different knowledge levels of CE, which was referred in the interviews as a challenge in implementing CE.

Additionally, the tool would arguably contribute to internal communications related to CE. Interview results illustrates that the case company has different recognitions toward the strategies of sustainability and CE, as some respondents stated that sustainability is integrated in the strategy while the others claimed not. Additionally, it was revealed that they have different criteria between the divisions, which might be challenges for evaluating and managing CE projects across different divisions. Internal communications are regarded as one of the key elements to implement CE [3]. These internal communications would help linking managers and product designers to facilitate the transition toward CE [8].

Setting requirements for CE projects, raised as one of the tool's contributions, seemed to be part of product design. It has already been stated that circularity indicators are relevant for use in product design [4]. Furthermore, visualizing circularity in the CE portfolio mapping tool could help to accelerate product design by supporting internal communications among managers and product designers as described in the previous paragraph.

Some respondents claimed that the tool would help to define criteria, which might be new idea for future research. This statement was also supported by the fact that the different respondents had different views in what criteria were currently used or could be used for CE. To promote defining criteria, it is important not only to calculate circularity score, but also to visualize those criteria, which are used for assessing circularity so as to figure out the path toward higher circularity.

7 Conclusions

In this study, a mapping tool for integrating circularity indicators into portfolio management was developed. The tool is intended to be used on several levels in a company, especially on the management level to easily visualize the projects related to CE. Therefore, the contribution is that the tool combines both circularity indicators and portfolio managements, the latter being a way of working that several companies are accompanied with already, thereby easing the adoption of CE.

We believe that managing portfolio from circularity perspective is necessary, while other researchers or practitioners focus on monitoring single CE project. This tool could act as a supporting tool on a managerial level to both get an overview of the current progress, as well as a decision-making tool for further efforts. In traditional portfolio management, short term profitability is often regarded crucial, compared to long term benefits such as sustainability and circularity. This tool tackles the fact that investments are regarded as one of the barrier for moving toward CE, since CE transitions might require radical changes such as developing circular products and finding new revenue stream.

As shown in the interview results, CE portfolio management in the case company are still under-development. We hope this study will be a step toward further research in CE portfolio management, and eventually contribute to move forward to the sustainable society.

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C.3
CIRCULAR SOCIETY VISION

Emptying drawers: Reviewing user experiences of commercial collection programmes for mobile phones

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Abstract

In a circular economy, the collection of devices is essential to enable reuse, repair, refurbishment and/or recycling at a system level. Yet, even though collection programmes are in place, consumers often store their phones after use. To close the loop from a user perspective, a better understanding is needed of how collection programmes, such as take-back and trade-in programmes, influence user behaviour, and get people to hand in their devices. Using a divestment model which represents the final phase of consumption, this paper explores the user experience of commercial programmes, identifies problematic issues, and gives recommendations on how to improve these.

1 Introduction

For a successful transition towards a circular economy, it is crucial that products are collected to be reused, repaired, refurbished, remanufactured and/or recycled at a system level. As an estimated 8.7 billion mobile phones will be in use by 2040 [1], their destination after their average two to three years of use [2] is essential for closing the loop. In the current context of ownership-based consumption, the actions of consumers controlling these destinations are key. However, for instance in Switzerland, consumers mostly store their unused phones (58%) [3], which decreases their value over time [4]. Some consumers even throw them away in household waste [5].

Although the final phase of the consumption cycle is as important and complex as the first phase (i.e., purchase) [6], the former lacks attention in literature [7]–[9]. To address this gap, this study aims to illustrate how users can be stimulated to bring back their devices after use. A desktop research is conducted to explore user experiences of existing commercial collection programmes such as buy-back, take-back, trade-in and recycling programmes.

This paper contributes to closing the loop from a user perspective by providing a better understanding of the last phase of the consumption cycle (i.e. the divestment phase) for researchers and practitioners.

First, a model of user behaviour is introduced to describe the stages of the divestment phase. Then, the set-up of the study is clarified. The study results in an inventory of the overall user experiences of various collection programmes along the stages of the divestment model. Finally, these results are discussed and recommendations are drafted on how to enhance the experiences during the divestment phase.

2 Background

The term 'divestment' refers to the last phase of the consumption cycle following the purchase and the use phases [10]. Divestment is the combination of the physical separation from the product [8] (i.e., 'disposition'), and the mental and emotional separation of the product [8] (i.e., 'detachment').

A model of user behaviour during the divestment phase was presented in a prior publication of the authors of this paper [11]. The model is elaborated on the work of Blackwell et al. [10], Roster [8], Cruz-Cárdenas and Arévalo-Chávez [12], and Hanson [13].

As visualised in Figure 1, the divestment phase is composed of six stages:

- **Dilemma recognition:** decision to keep or to end a product's use cycle and separate from it.
- **Search divestment options:** finding the possible ways to separate from the product.
- **Divestment options evaluation:** assessing the value and performance of the product and divestment options.
- **Divestment preparation:** soothing detachment by physically preparing the product, and mentally and emotionally preparing the consumer for separation.
- **Final act of disposition:** moment of physical separation.
- **Divestment outcomes:** objective and subjective results of divestment.

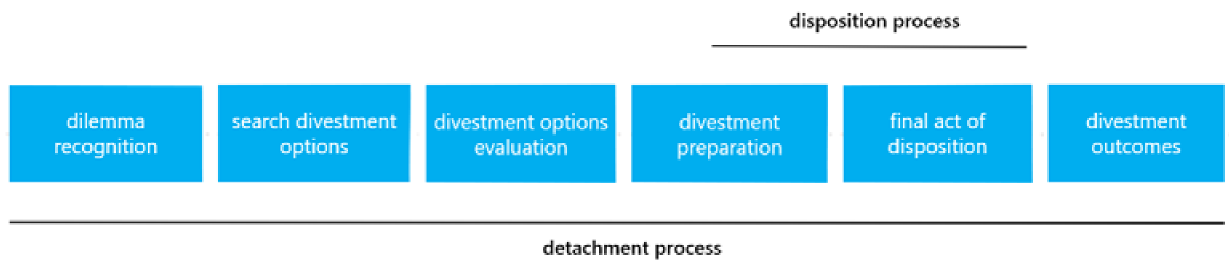

Figure 1: Model of user behaviour during the divestment phase [11]

In practice, the stages are not as clear-cut as they visually seem. However, the model serves to organise the findings regarding the divestment experience after it has occurred. The ontological and epistemological choices behind this model are explained in the to-be-published dissertation [14].

3 Set-up of the study

3.1 Research objective

To address the lack of literature on the divestment phase, a desk research is performed to exemplify the experiences of consumers in their quest of handing in their old mobile phone. The experiences of the collection programmes will be outlined along the divestment model's stages.

The starting points of the study are the two mobile phones shown below.

Figure 2: The two mobile phones meant to be returned: on the left a Nokia 3110 Classic, and on the right an iPhone 6S

The first is a Nokia 3110 classic; it is a still functioning feature phone, has 9MB memory, was originally released in 2007, has pronounced traces of aging and has a functioning charger. Its price on a second-hand market place is around 30 euros (on Marktplaats in June 2020) [15]. The second is an iPhone 6S; it is a still-functioning smartphone, has 16GB memory, was originally released in 2015, has minor use traces, and has all its accessories in good state. Its price on a second-hand market place is between 70 and 160 euros (on Marktplaats in June 2020) [16].

3.2 Scope

The study was performed in June 2020 in the context of the covid-19-related restrictions. As a result, a desk research was conducted, as opposed to a field research at physical stores. The study focuses on collection programmes available for consumers in the Netherlands.

The collection programmes within the scope of this study are options for consumers to hand in their stored mobile phones online in exchange for money if possible. Programmes from charities where consumers can donate their products (e.g. CliniClown, Stichting Opkikker, Stichting AAP, and Eeko), second hand platforms to sell their devices (e.g. Marktplaats), and national organisations collecting e-waste (e.g. Wecycle and Weee Nederland) are thus out of scope.

3.3 Selection of companies

A set of 14 companies was selected, potentially providing commercial collection programmes:

- Original Equipment Manufacturers (OEM): Apple [17], [18], Fairphone [19], Nokia [20] and Samsung [21];
- Third party retail stores: BCC [22], Bol.com [23], Coolblue [24] and Mediamarkt [25];
- Telecom Providers: KPN [26], T-mobile [27], [28] and Vodafone [29]; and,
- Other third parties: GsmLoket [30], reBuy [31] and Zonzoo [32].

Next to the companies' Dutch websites, the study was further informed by prior user research (i.e., surveys, interviews, experiments, and generative sessions) performed by Mertens [33], Polat [34] and Ren [35].

4 User experiences during the divestment phase

The experiences of the collection programmes are clustered per stage of the divestment phase.

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4.1 Dilemma recognition

6 of the 12 companies selling new phones indicated the opportunity to hand in a phone when buying a new phone on the various websites. Two OEMs (i.e., Apple and Samsung) immediately enabled users to make a quick estimation of the to-be-expected discount on the new phone if a phone was handed in.

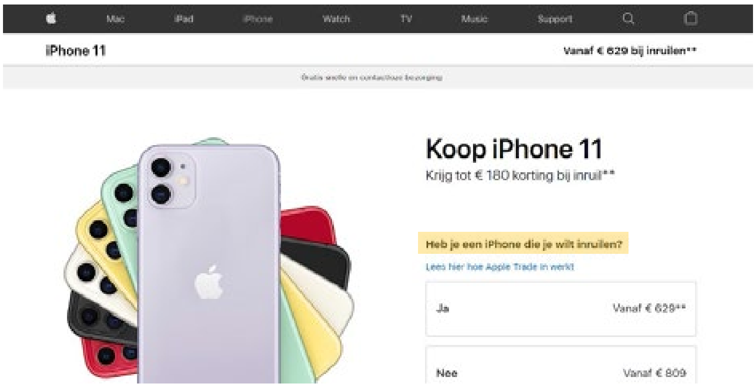

Figure 3: Visibility of the collection programmes when purchasing a new phone on the Apple website (highlighted) [18]

4.2 Search divestment options

- ***Google.*** In 10 cases out of 14, the company's collection programme could be found via Google when searching "mobiele telefoon inleveren [hand in mobile phone] + [name]" or "smartphone recyclen [recycle smartphone] + [name]").

- ***Different names.*** The collection programmes were found under various names: "inruil" [trade-in] (e.g. Samsung), "inruildeals" [trade-in deals] (e.g. Vodafone), "recycling" (e.g. Fairphone), "recyclage" [recycling] (e.g. Samsung), "trade-in" (e.g. Apple), "toestelinruil" [device trade-in] (e.g. T-mobile), or "verkopen" [sell] (e.g. reBuy and Zonzoo). The multiple denominations could be confusing for consumers.

- ***Visibility on homepage.*** The visibility of the programme on the homepages of the companies varied. In 5 of the 14 cases (i.e., Apple, Fairphone, GsmLoket, reBuy and Zonzoo), the collection programme was mentioned in the body of the homepages. Another company (i.e., Samsung) included it in the bottom menu of the website.

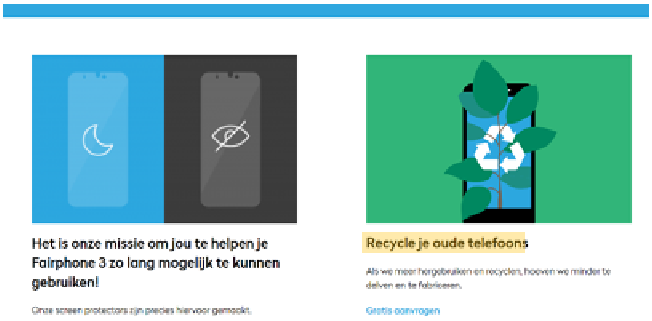

Figure 4: Visibility of the collection programmes on the homepage of Fairphone (highlighted) [19]

- ***Invisibility on website.*** For 4 companies (i.e., BCC, Bol.com, Coolblue and Nokia) where no collection programme could be found on the websites, the customer service was consulted. BCC advised to hand in the product at their store or to send it in at own costs to recycle the devices for free. Bol.com and Coolblue explained that it was currently not possible to hand in the phones online. Bol.com indicated the option to put the old phones for second hand sale on their website (i.e., out of scope). Nokia advised external options due to ownership changes. At this stage, the quest to hand in the phones through in-house collection programmes was thus interrupted in 3 cases.

4.3 Divestment options evaluation

The **interface** to gain the information on the collection programmes had different shapes:

- ***Homepage (2 cases).*** The explanation of the collection programme was done directly on the homepage of specialised third parties GsmLoket and Zonzoo. The estimation of the residual value of the phones could immediately start.

- ***Dedicated webpage (8 cases).*** Apple, Fairphone, KPN, Mediamarkt, reBuy, Samsung, T-mobile, and Vodafone provided information on the collection programmes on dedicated webpages of their website.

- ***Platform with internal communication style (2 cases).*** On top of the basic information found on the dedicated webpages, T-mobile and Vodafone redirected the consumer to another location to get further information. The visual style of the platforms nevertheless followed the company's aesthetics, giving the idea of an extension of the original website.

- ***Platform with external communication style (1 case).*** Here again, on top of the basic information found on the dedicated webpage, the Apple-site

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redirected the consumer to another location to get further information.

- ***Customer service (1 case).*** As indicated before, the customer services of BCC explained the steps to follow to send the devices to them by post.

The extent of the **procedure** to estimate the value of the phone also varied:

- ***Form (8 cases).*** The name of the phone or its IMEI (i.e., International Mobile Equipment Identity, a 15-digit number identifying a device) have to be entered in a search bar and the residual value is estimated by the company through 3-7 questions about the phone.

Figure 5: T-mobile's collection programme form [27]

- ***One fixed value (2 cases).*** Fairphone automatically estimated the monetary reward at 20€ for a non-Fairphone device when a Fairphone was bought. No information had to be filled in to gain this estimation. In our case, the phones could be sent in for free without monetary reward. The same was possible with BCC.

- ***Tables (3 cases).*** Mediamarkt and T-mobile have tables indicating the value of different brands and specific devices without needing to answer questions on the state of the phone. The value is however based on a ´good as new´ state. Apple also permitted a quick estimation of Apple devices through a table, but offered a more extensive estimation through a form.

- ***No online estimation (1 case).*** KPN only performed in-store value estimations.

The estimation of the monetary reward to be received in exchange for the phones varied between 0 and 55€ for the iPhone, and was evaluated at 0€ for the Nokia phone. In some cases where the phone could be sent in for free recycling, the costs of sending the package had to be bore by the consumer.

The **guidance** provided during the procedure differed from programme to programme:

- ***Explanation of the relevance of the programme.*** Reasons to hand in devices are provided in all the cases. They included factors concerning the environment (e.g. through responsible recycling [26]), society (e.g., through a donation [29] or by helping the company reach their goal with the community [19]), convenience (e.g. "easy, secure and flexible"[31] or the resulting "a clear conscience and less clutter" [19]), trustworthiness (e.g. "transparent" [28]), the relationship with the device (e.g. "A more beautiful way to say goodbye to your favourite device"[18]) and money (e.g. "a tidy sum for other nice things" [30]) (i.e., see *4.6 divestment outcomes*).

- ***Explanation of the overall procedure.*** The procedure to follow was explained in simple steps when introducing the programme (e.g. Mediamarkt in Figure 6). Sometimes more detail were provided on what the various steps were and how much time each step took (e.g. reBuy and Fairphone).

Figure 6: Collection programme procedure at Mediamarkt [25]

It was not always clear whether sending the package would be under warranty or not. What will happen if the package gets lost in the mail or gets damaged? Several programmes answered these questions in their Frequently Asked Questions (FAQ) section (e.g. reBuy) or extra information (e.g. GsmLoket and Vodafone).

- ***Explanation of how to fill in the form.*** The form to estimate the residual value of the phone according to the companies was composed of multiple questions with varying degrees of difficulty. Several hurdles were identified when filling in the forms:

  Finding the name and memory size of the phone. Finding the phone's specific name and memory size may need assistance for some consumers. Extra information was rarely provided.

Finding the IMEI of the phone. The same could be noted for the IMEI. Extra information was provided immediately with the question in the case of several programmes (e.g. Apple or T-mobile), while others mentioned it in the FAQs (e.g. Zonzoo). Another issue was that, when the packaging has not been kept or phones cannot easily be opened, phones have to function to get the IMEI by typing *#06#, thus automatically disqualifying non-functioning ones.

Figure 7: Information provided when looking for the IMEI in the case of Zonzoo [32]

Correctly defining the state of the phone. Support can be succinct with short sentences (e.g. T-mobile), extensive textual explanation (e.g. Apple), and sometimes visuals (e.g. Zonzoo). The required answered is mostly a Yes/No response, however a few examples have multiple possible responses (e.g. reBuy). T-mobile provided visual feedback with a green logo when the answer was positive, and a red one when it negatively influenced the estimation.

4.4 Divestment preparation

The divestment preparation stage included digital and physical actions:

- ***Digital preparation.*** The consumers were asked to remove the content of the phone and deactivate the cloud (e.g. Apple, T-mobile and Vodafone).
- ***Physical preparation.*** The consumers were be asked to remove the SIM card(s), remove the SD card(s) and fully recharge the battery. Apple and Vodafone guided consumers through these steps by asking them to tick off boxes. A shipping label may need to be printed out (or written by hand in the case of BCC) and the phone is put in a package or cushioned envelope (e.g. Fairphone, GsmLoket, and Vodafone). Apple also made a return kit available.

Several hurdles were identified when preparing the phone for divestment:

Making sure that the phone did not contain private content. Before returning the phone to the companies, several companies explicitly asked to empty its content (e.g. KPN). T-mobile and Fairphone mentioned that a DEFRA-certified partner removes the content of the received phones. Vodafone offers the paid service of deleting the phone's data.

Making sure the content of the phone was secure. As illustrated below, KPN provided information on how to make a back-up.

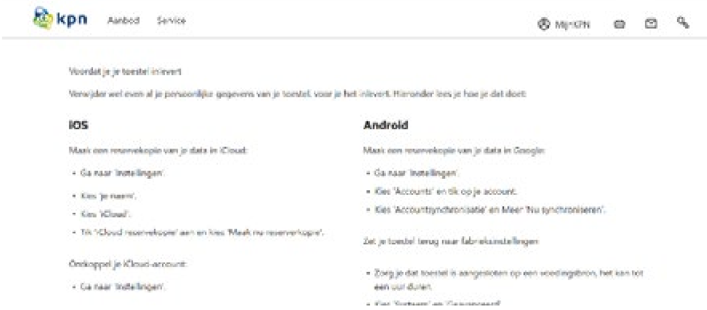

Figure 8: The procedure to make a back-up the phone's content at KPN [26]

Deactivating the cloud. More attention was given to guiding the deactivation of the cloud with textual explanation (e.g. T-mobile) or also visual explanation (e.g. Vodafone).

Apple and Vodafone support the consumer by going through a list of final checks and confirmation (i.e., quality and suitability, remove SIM card, remove data, remove SD card and charge battery).

4.5 Final act of disposition

Of the 14 studied programmes, 8 journeys could be fulfilled online:

- ***Send in for free.*** Phones could be sent to Apple, Fairphone, GsmLoket, reBuy, T-mobile, Vodafone, and Zonzoo (or their partners) for free. This was enabled by a shipping label made available by the companies or by a return kit.
- ***Send in at own costs.*** The phones could be sent to BCC at the consumer's own costs. GsmLoket's and Vodafone's service did not include a track & trace system, but this could be obtained at own costs.

The others could not be performed online:

- ***Bring to a store.*** KPN and Mediamarkt indicated to come to a store to hand in phones. As the older device could not be recognized, Vodafone proposed to hand it in at a store.
- ***Only coupled with a new purchase.*** In the cases of Samsung and Bol.com, the phone could be handed in if a new product was bought.
- ***No online programme available at the moment.*** Within the specific scope of the study and at the time of the study, both phones could not be sent to Bol.com, Coolblue and Nokia through an online collection programme.

4.6 Divestment outcomes

In the case the phone was sent to the company, the status can be checked in various ways. After receiving the package, the company checks the phone and compares it to the filled in form. If the two evaluations concur, the monetary estimation is confirmed. If not, a new estimation is made and communicated to the consumer. ReBuy explicitly mentioned that the phone is sent back for free if the deal is rejected by the consumer. T-mobile enables the consumer to follow the status of the transaction online. Other companies (e.g. Apple and Fairphone) indicate the durations to expect before a confirmation is sent or before the reward is granted.

The factors mentioned at *4.3 Divestment options evaluation* are expected to occur as an outcome of the programme. A monetary reward of 30 to 55€ for both phones is expected to be received in the shape of a giftcard (e.g. Apple), to be transferred on the bank account of the consumer (e.g. GsmLoket and reBuy), or to be donated (e.g. Vodafone).

5 Discussion and recommendations for the design of a valuable divestment user experience

The desk research showed that, in the current online Dutch context, the divestment process is an underexplored aspect of the marketing and design of collection programmes. The road to the divestment of the two phones laying in a drawer was filled with ambiguity and uncertainties from a user perspective. Smoothing out the process with more guidance and feedback, and providing enough motivation for users to go through the return procedure could significantly improve the user experience of collection programmes.

The first barrier was encountered in 3 of 14 cases, when no collection programme could be found online at the second stage of divestment (i.e., search divestment options). At the third stage of divestment (i.e., divestment options evaluation), the procedure was explained to the users and an estimation of the outcomes was made with varying degrees of guidance from the programmes. The journey was interrupted here for 3 out of the remaining 11 cases as the procedure could only be followed at a physical store, or the divestment had to be coupled with the purchase of a replacement device. The oldest device could not be handed in at 4 out of the 8 remaining cases, as the device could not be entered or found on their platforms. As a result, the journeys for both phones could be completed online at 4 out of the total 14 cases. The most recent device could be returned through the online collection programmes in 8 out of the 14 cases. The potential issues identified during the divestment phase are summarized in Figure 9.

Best practices dealt with these issues. For instance, to enhance the online visibility of the programmes, 6 collection programmes were immediately mentioned on the company's homepage. Further stimulating the visibility of these programmes, 6 cases promoted their collection programme during the purchase process of a replacement phone. Moreover, 7 collection programme pages were designed using the same visual environment as for purchase, fostering familiarity. Few cases provided clear and visual instructions directly at the corresponding places of the forms to support the users through the procedure without having to consult the FAQ section. In rare cases, the key rights and responsibilities of the user (e.g. concerning potential differences in the evaluations of the state of the device) were briefly and clearly stated during the procedure, therefore ensuring that users would not miss these points in the extensive terms and conditions of the programmes. In terms of guidance during the divestment preparation, the offered shipping labels and the return kit help counter uncertainties standing in the way of acting on the decision to return the stored phone.

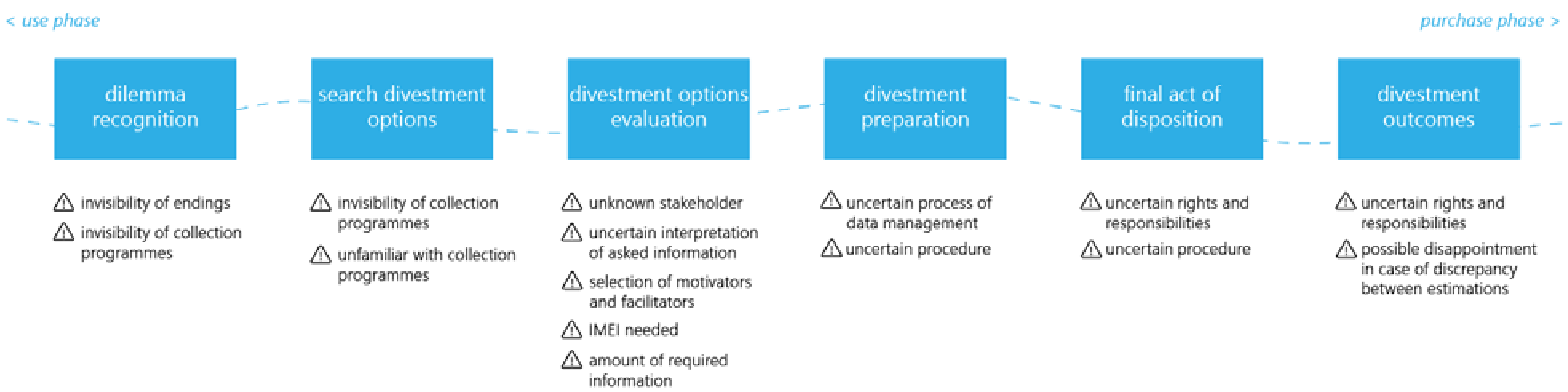

Figure 9: Inventory of potential issues throughout user experiences during the divestment phase

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The question can be raised whether all users are motivated enough by the environmental benefit or by the monetary reward often advertised in exchange for the return of a phone. As mentioned by Welfens et al. (2016)[36], emotional factors are often underestimated in this context but could be leveraged to help persuade users to return their devices. These factors could be especially valuable considering the detachment process and the meaningful relationship between the user and their phone [11]. Phones are put in drawers for various reasons, therefore the collection programmes need to propose interesting alternatives for users to mitigate the expected risks if the phones were to be taken out of their drawers [37]. The uncertainties regarding privacy concerns and data loss anxiety could be reduced by taking the user step by step through the back-up, transfer and removal of data when preparing the phone for shipping. Another question could be raised about whether current facilitators (e.g. commitment to the brand or time required to fill in the form) are effective enough to persuade all types of users. To boost a feeling of satisfaction at the end of the divestment processes [38], a confirmation can be provided upon the safe reception of the device, the positive divestment outcomes for the user could be repeated by, for instance, confirming the contribution for the environment made by the user by handing in their phone or proving that a certified partner removed the data from the device [37]. This could potentially result in repeat behaviour and larger spread of the collection practice. Inspiration to further improve the user experiences of the collection programmes can be drawn from various design projects [11], [33]–[35], [39], [40].

Several limitations of the study need to be taken into account. For example, as only two products were available, the phones could not be handed in 14 times. The results of the divestment preparation, final act of disposition and divestment outcomes stages are thus based on the expectations raised through the information gained through desk research. Also, because of the covid-19-related restrictions, the in-store experiences were not studied. Moreover, handing in the phones was not coupled with the replacement for another phone. This automatically ended the journeys for various companies who still offered collection programmes. Finally, the devices could be considered old (respectively from 2007 and 2015), in comparison with current phones that could be replaced right now as their average use cycle is estimated at two to three years [2].

As a result, additional research could be conducted to further explore the experience of collection programmes within the context of the divestment phase. For instance, procure a considerable set of phones to actually send to the companies and their partners in order to experience the full journey, study the in-store experiences, couple the return of a phone with the purchase of another one, and try to hand in a more recent phone. Internal data from the companies would also be valuable to study the effectiveness of the design interventions.

Echoing previous calls for research on divestment (e.g. [7]–[9]), this study showed room for improvement regarding the user experience of commercial collection programmes. Developing a valuable divestment experience for users is a major opportunity to divert devices from drawers and enable timely collection. If done right, we could close the loop for mobile phones from a user perspective and be closer to a circular economy.

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Quantifying impacts of consumers' expectation of product lifespan on product use duration in the circular economy

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Abstract

This study constructs a framework for quantitatively analyzing the impacts of consumers' expected remaining product lifetime on their product use duration. As a case study, we focused on air conditioners in Japan and estimated the impacts of the expected remaining lifetime on actual product use duration. We estimated parameters of a dynamic discrete choice model for the replacement of air conditioners in Japan using a dataset obtained from an online questionnaire survey. Using these parameters, we conducted scenario analyses to estimate the impacts of an increase in the expected remaining product lifetime on product use duration. The results showed that the significance of the expected remaining product lifetime for the product replacement decision is statistically supported. Moreover, the scenario analyses showed that an increase in the expected remaining product lifetime by 1, 2, and 3 years can prolong product use duration by 0.9, 1.8, and 2.72 years, respectively.

1 Introduction

Promoting longer product use is one of the key strategies for achieving a transition to a circular economy and reducing environmental impacts. Longer product use can delay the replacement cycle, reduce the replacement demand, lower material consumption in the production and disposal of products, and use the value resources contained therein for longer duration in our society.

The new circular economy action plan for EU adopted by the EU Commission in 2020 states that the commission will consider "improving product durability, reusability, upgradability and reparability" as one of the primary sustainable product design policies and "will work towards establishing a new 'right to repair' and consider new horizontal material rights for consumers, for instance, as regards the availability of spare parts or access to repair" [1]. These policies can contribute to extending the product use duration from a "physical" aspect.

Apart from improving the physical longevity of products, a psychological perspective about consumers' replacement and disposal behavior is also an important factor of actual product lifetime, because replacement or disposal of products are eventually decided by consumers. Especially, consumers' expectation to product lifetime is one of the concrete factors and several studies on consumers' expectation of product lifespan and different perspectives of the consumers' expectation of product lifespan are reported as to a variety of goods [2], [3], [4], [5], [6], [7].

For example, Hennies and Stamminger (2016) quantitatively analyzed the factors that influence product lifetime and consumers' replacement decisions for five products (washing machine, laptop, kettle, TV, and hand mixes) in German households by conducting a questionnaire survey. They found that the actual product lifespan tends to prolong as consumers' expectation of product lifespan is satisfied. They also reported the expected product lifetime for the five products, which did not show much difference from the actual product lifetime [6].

Oguchi et al. (2016) proposed three concepts definitions of expected product lifetime by consumers based on a review of previous studies: "intended" lifetime, "ideal" lifetime, and "predicted" lifetime. They also conducted a questionnaire survey about the length of the three types of consumer's expected remaining product lifetimes for four product types (vacuum cleaner, mobile phone, digital audio player, and digital camera) in Japan. They found that the expected remaining lifetime of "ideal" lifetime tends to be longer than that of "intended" lifetime or "predicted" lifetime [7].

If policies for promoting longer product use as stated in the circular economy action plan are implemented, consumers' expected product lifetime can be longer than before, and these changes will affect the actual product lifetime or product use duration. Therefore, it is important to analyze the impacts of changes in the consumer's expected product lifetime on actual product use duration. Although previous studies investigated the length of the expected product lifetime or roles of consumer-oriented factors in product lifetime

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extension, they did not quantitatively analyze the impacts of changes in the expected product lifetime on consumers' actual product use duration. More concretely, the answer to the following research question is unknown: How much does an increase in consumers' expected product lifetime promote an extension of actual product use duration?

From the above research background, this study attempts to construct a framework for quantitatively analyzing the impacts of consumers' expected product lifetime on consumers' product use duration. As a case study, we apply the constructed framework to estimate the impacts on- air conditioners (AC) in Japan and discuss how effective policies for increasing consumers' expected product lifetime are to promote longer product use.

2 Methodology

2.1 Estimation of the dynamic discrete choice model for AC

This study uses a dynamic discrete choice model (DDCM), which is an econometric model to quantitatively analyze the relationship between consumers' replacement choice and factors that affect the replacement choice [8], [9], [10], [11], [12], [13]. In this study, we assumed that a consumer i decides whether they to replace their old AC with a new one or does not replace and keeps using their old AC. When making the replacement decision, they consider annual electricity consumption of a new AC and the old AC, e_i^{new} and e_i^{old}, product price of a new AC, p_i^{AC}, and "expected remaining product lifetime" of their old AC, EL_i. In this study, we adopted "predicted" *remaining* product lifetime as values of EL_i defined by Oguchi et al. [7], which means "the length of time for which consumers predict a product will last." The AC replacement decision chosen by a consumer i is represented by a binary variable a_i. When $a_i = 0$, the consumer decides not to replace and "keep" his/her old AC. When $a_i = 1$, the consumer decides to "replace" his/her old AC with a new AC. The utility obtained by choosing "keep" ($a_i = 0$) and "replace" ($a_i = 1$) are expressed in the following functional forms:

$$u_i(a_i) = \begin{cases} \theta_0 + \theta_1\left(e_i^{old} - e_i^{new}\right) + \theta_2 EL_i + \varepsilon_i & \text{if } a_i = 0 \\ \theta_3 p_t^{ac} + \varepsilon_i & \text{if } a_i = 1 \end{cases} \quad (1)$$

where θ_0, θ_1, θ_2 and θ_3 represent the parameters of DDCM in this study and ε_i represents the unobserved error term. In equation (1), $e_i^{old} - e_i^{new}$ can be interpreted as an excessive electricity consumption in using AC due to not replacing. We expect that signs of the parameters θ_1 and θ_3 are negative because excessive electricity consumption and price of a new AC means an increase in economic and/or environmental costs, resulting in a decrease in utility by choosing "keep" ($a_i = 0$) and "replace" ($a_i = 1$), respectively. However, we also expect that the sign of the parameter θ_2 is positive because the increase in the "predicted" *remaining* product lifetime" of the old AC means prolonged use duration by consumers, considering their product is still functional, and thus, they can increase utility by choosing "keep" ($a_i = 0$). In this study, we assumed that consumers' AC replacement decisions are determined based on a forward-looking value function represented by the Bellman equation as described in equation (2):

$$\begin{aligned} &V\left(e_i^{old}, e_i^{new}, EL_i, p_t^{ac}\right) \\ &= \max_{a_i=0,1}\left\{u_i(a_i) + \beta EV\left(e_i^{old}, e_i^{new}, EL_i, p_t^{ac}, \varepsilon_i \middle| a_i\right)\right\} \end{aligned} \quad (2)$$

where β ($0 \le \beta < 1$) describes a discount factor. We further assumed that the variables of annual electricity consumption and product price of a new AC, e_i^{new} and p_i^{AC}, respectively, follow a first-order Markov transition process. We assume that the expected value, $EV\left(e_i^{old}, e_i^{new}, EL_i, p_t^{ac}, \varepsilon_i\right)$, can be expressed as follows:

$$\begin{aligned} &EV\left(e_i^{old}, e_i^{new}, p_t^{ac}, EL_i, \varepsilon_i\right) \\ &= \int_{\tilde{e}^{new}} \int_{\tilde{p}^{ac}} \int_{\tilde{\varepsilon}_i} V\left(e_i^{old}, \tilde{e}^{new}, \tilde{p}^{ac}, EL_i, \tilde{\varepsilon}_i\right) f\left(\tilde{e}^{new}, \tilde{p}^{ac}, \tilde{\varepsilon}_i \middle| e_i^{new}, p_t^{ac}, \varepsilon_i\right) d\tilde{e}^{new} d\tilde{p}^{ac} d\tilde{\varepsilon}_i \end{aligned} \quad (3)$$

where $f\left(\tilde{e}^{new}, \tilde{p}^{ac}, \tilde{\varepsilon}_i \middle| e_i^{new}, p_i^{ac}, \varepsilon_i\right)$ describes a conditional joint probability function for the transitions of, e_i^{new}, p_i^{AC} and ε_i. This study also assumed that the distribution of the unobserved error term ε_i follows an identically and independently distributed (iid) type I extreme value distribution, as in previous studies [8], [10], [12], [13]. Using the method of discretizing the respective conditional transition probability function by Tauchen [14], we can obtain numerical values of the expected value function $EV\left(e_i^{old}, e_i^{new}, EL_i, p_t^{ac}, \varepsilon_i\right)$ by a fixed-point algorithm [8]. In this study, we set 30 grid sizes for each state space of e_i^{new} and p_i^{AC}. Thus, the total number of state space becomes 900.

By using the numerically obtained values of the expected value function and the assumption of iid type I extreme value distribution for distribution of the error term, we can express the probability of choosing "replace" ($a_i = 0$) and "keep" ($a_i = 0$), $P(a_i = 1)$ and $P(a_i = 0)$, as the following logit form:

$$\begin{cases} P(a_i = 1) = \dfrac{\exp\left\{u_i(a_i = 1) + \beta EV\left(e_i^{old}, e_i^{new}, EL_i, p_t^{ac} \middle| a_i = 1\right)\right\}}{\sum_{\tilde{a}_i=0,1} \exp\left\{u_i(\tilde{a}_i) + \beta EV\left(e_i^{old}, e_i^{new}, EL_i, p_t^{ac} \middle| \tilde{a}_i\right)\right\}} \\ P(a_i = 0) = 1 - P(a_i = 1) \end{cases} \quad (4)$$

Based on the logit model as described in equation (4), we can obtain the parameters by maximum likelihood estimation.

2.2 Estimation of the dynamic discrete choice model for AC

Using the obtained parameters from equation (4), θ_0, θ_1, θ_2 and θ_3, we estimate impacts of the "predicted" *remaining* product lifetime by consumers on product use duration of AC. Following equation (4), which describes the probability of choosing "replace" ($a_i = 1$) and "keep" ($a_i = 0$), we can also formulize the probability of choosing "replace" and "keep" in year t for a consumer who owns an AC with class c of cooling capacity, $P(a_{c,t} = 1)$ and $P(a_{c,t} = 0)$, as follows:

$$\begin{cases} P(a_{c,t}=1) = \dfrac{\exp\left\{u_{c,t}(a_{c,t}=1) + \beta EV\left(e^{old}_{c,t}, e^{new}_{c,t}, EL_{c,t}, p^{ac}_{c,t} \middle| a_{c,t}=1\right)\right\}}{\sum_{\tilde{a}_{c,t}=0,1} \exp\left\{u_{c,t}(\tilde{a}_{c,t}) + \beta EV\left(e^{old}_{c,t}, e^{new}_{c,t}, EL_{c,t}, p^{ac}_{c,t} \middle| \tilde{a}_{c,t}\right)\right\}} \\ P(a_{c,t}=0) = 1 - P(a_{c,t}=1) \end{cases} \quad (5)$$

where subscripts c and t are subscripts for the cooling capacity class of AC and year of replacement decisions, respectively. In this study, we considered 8 classes of the cooling capacity (2.2 kW, 2.5 kW, 2.8 kW, 3.6 kW, 4 kW, 5.6 kW, 6.3 kW, and 7.1 kW) based on a list of Japanese ACs sold in 2019 by the Energy-saving Performance Catalog [15]. It is noted that when $t = 0$, $P(a_{c,t} = 1) = 0$ and $P(a_{c,t} = 0) = 1$. If increase in the "predicted" *remaining* product lifetime is expressed as ΔEL, probability of choosing "replace" ($a_{c,t} = 1$) and "keep" ($a_{c,t} = 0$) when the "predicted" *remaining* product lifetime increases by ΔEL can be described as following equation (6):

$$\begin{cases} P(a_{c,t}=1|\Delta EL) = \dfrac{\exp\left\{u_{c,t}(a_{c,t}=1|\Delta EL) + \beta EV\left(e^{old}_{c,t}, e^{new}_{c,t}, EL_{c,t}+\Delta EL, p^{ac}_{c,t} \middle| a_{c,t}=1\right)\right\}}{\sum_{a_{c,t}=0,1} \exp\left\{u_{c,t}(\tilde{a}_{c,t}|\Delta EL) + \beta EV\left(e^{old}_{c,t}, e^{new}_{c,t}, EL_{c,t}+\Delta EL, p^{ac}_{c,t} \middle| \tilde{a}_{c,t}\right)\right\}} \\ P(a_{c,t}=0|\Delta EL) = 1 - P(a_{c,t}=1|\Delta EL) \end{cases} \quad (6)$$

The probability of choosing "replace" ($a_{c,t} = 1$) and "keep" ($a_{c,t} = 0$) in equation (6) indicates the probability of choosing each alternative in a certain year t. Therefore, the probability that ACs with a class c of cooling capacity are replaced in year s when the "predicted" *remaining* product lifetime increases by ΔEL can be expressed as the following joint probability:

$$\tilde{P}_{c,s}(\Delta EL) = \left\{\prod_{t=0}^{s-1} P(a_{c,s}=0|\Delta EL)\right\} \times P(a_{c,s}=1|\Delta EL) \quad (7)$$

In equation (7), the replacement probability of ACs is described as a joint probability that an alternative "keep" ($a_{c,t} = 0$) is chosen from year 0 to year $s-1$ and a alternative "replace" ($a_{c,t} = 1$) is chosen at year s. In this study, the probability that ACs are replaced in each year in the case of business as usual (BAU) can be calculated by equation (7) when $\Delta EL = 0$. Moreover, we define a "predicted" *total* product lifetime for ACs with cooling capacity class c as TEL_c whose value means the number of *total* usage years from purchase to replacement (or disposal) predicted by consumers. Representing a value of TEL_c in the BAU case as $\overline{TEL_c}$, we set values of "predicted" *remaining* product lifetime of ACs with cooling capacity class c at year s, $EL_{c,s}$ in equation (7), in the BAU case as follows; $EL_{c,s} = \overline{TEL_c} - s$ when $s = 1,2,3,...,\overline{TEL_c} - 1$ and $EL_{c,s} = 0.5$ when $s = \overline{TEL_c}$, $\overline{TEL_c} + 1$, $\overline{TEL_c} + 2$, … , Y_{max}, where Y_{max} describes the maximum number of years of physical product lifetime for ACs. Similarly, we can set values of $EL_{c,s}$ if the consumers' "predicted" product lifetime increases by ΔEL as follows: $EL_{c,s} = (\overline{TEL_c} + \Delta EL) - s$ when $s = 1,2,3,...,(\overline{TEL_c} + \Delta EL) - 1$ and $EL_{c,s} = 0.5$ when $s = (\overline{TEL_c} + \Delta EL)$, $(\overline{TEL_c} + \Delta EL) + 1$, $(\overline{TEL_c} + \Delta EL) + 2$, … , Y_{max}. Finally, using equation (7), we can calculate the expected value of consumers' AC use duration as follows:

$$E(UD|\Delta EL) = \sum_c \sum_{s=0}^{Y_{max}} \lambda_c \left\{\tilde{P}_{c,s}(\Delta EL) \times s\right\} \quad (8)$$

where λ_c is the share of ACs with a class c of cooling capacity to the total number of ACs in Japan.

3 Data

To obtain data about the dynamic discrete choice model estimation, we asked the Japanese survey company INTAGE Inc. to conduct an online survey for their online monitors in November 2019 and February 2020. We first asked the monitors of the company whether they replaced their AC with a new one in 2019. Further, we asked the monitors who did replace with new ACs the following information: model code of their replacing (new) AC, the replacement cost, whether they changed cooling capacity of their new AC, brand of their previous AC, usage years and "predicted" *remaining* product lifetime of the previous AC. As to the monitors who did not replace their ACs, we asked them the following information: model code, *total* usage years and "predicted" *remaining* product lifetime of their (old) AC, whether they have a specific AC considered as replacement, information on the specific AC if they have (e.g., model code, brand, intending replacement cost), and whether they think they have changed cooling capacity of their new AC from that of the old one when replacing.

From the model codes, we can identify annual electricity consumption (or APF) and cooling capacity of replacing (new) AC for monitors who replaced their AC in 2019 and (old) AC for monitors who did not replace them in 2019. However, it is difficult to find identical information on previous (old) ACs for monitors who replaced their ACs and on new ACs for monitors who did not replace them in 2019. Therefore, based on the above information, we presume the information on previous (old) ACs for monitors who replaced and new ACs for monitors who did not replace, would purchase. We used "Shinkyu-san," a web application that shows the degree of reduction in electricity consumption using replacement and supply data of electricity consumption of home appliances in Japan by size and production year, provided by the Ministry of the Environment of Japan [16].

We obtained 4127 respondents through an online survey, from which we excluded some due to incorrect or inconsistent answers. For example, we excluded respondents who did not answer model codes incorrectly or chose the alternative "I do not know/remember" for the questions about replacement cost, usage years, and expected remaining years of previous (old) ACs. Among respondents answering not replacing in 2019, we also excluded respondents who answered "equal to or less than 1 year" for question about usage years of their own ACs or answered model codes that corresponds to ACs firstly sold in 2019. After excluding the respondents as described above, we finally obtained 2366 respondents and used them for the estimation in this study.

We set the value of $\overline{TEL_c}$ as 13 years in this study. This value comes from the median of "predicted" *total* product lifetime in the sample obtained by the questionnaire survey, whose value is calculated by adding "predicted" *remaining* product lifetime to product use duration years of their previous (old) ACs. Moreover, since the highest AC use duration is 30 years in the sample, we set the value of Y_{max} to 30 and assumed that $Y_{max} = 30$ holds even if the consumers' "predicted" product lifetime increases.

For the prices of new ACs of each class of cooling capacity of monitors who did not replace ACs in 2019, we used the website Kakaku.com (https://kakaku.com/). This website provides data on the retail prices of a variety of ACs. We used the median values of prices on November 15, 2019 (mid-day of the month of the first online survey) for each cooling capacity class of AC. In calculating the impacts of the "predicted" *remaining* product lifetime by equations (7) and (8), we also used price data from this website.

For the annual electricity consumption of each cooling capacity class of ACs in calculating the impacts of the "predicted" *remaining* product lifetime by equations (7) and (8), we also used data from "Shinkyu-san" regarding replacement with energy-saving products [16].

Regarding λ_c in equation (8), we calculated its values for each cooling capacity class (2.2 kW, 2.5 kW, 2.8 kW, 3.6 kW, 4 kW, 5.6 kW, 6.3 kW and 7.1 kW) based on the 2366 respondents. However, the class of cooling capacity of some respondents did not match these classes. Hence, we included such respondents in the nearest cooling capacity class. Specifically, we included respondents with 4.5 kW class ACs with the 4 kW class, those with 5 kW ACs with the 5.6 kW class, and those with 8 kW ACs with the 7.1 kW class. Next, we calculated the values of λ_c for each of the eight cooling capacity classes.

4 Results and discussion

4.1 Parameter Estimation of DDCM

Table 1 shows the results of the DDCM parameters obtained in this study using different parameter settings. Models 1 and 2 show the parameters of DDCM without "predicted" *remaining* product lifetime, and Models 3 and 4 show these values with "predicted" *remaining* product lifetime. As we expected in Section 2.1, the signs of the parameters θ_1, θ_2 and θ_3 are reasonable for all the models. This table shows that the values of log-likelihood ($\log L$) in Models 3 and 4 are significantly higher than those in Models 1 and 2, implying that including the factor of the "predicted" *remaining* product lifetime significantly improves the values of log-likelihood. We also conducted likelihood ratio tests using the log-likelihood values. The tests show that the null hypothesis $\theta_2 = 0$ was rejected at a significance level of 1% for both $\beta = 0$ and $\beta = 0.9$. These results statistically support the fact that "predicted" *remaining* product lifetime affects consumers' replacement decision of ACs in Japan.

Focusing on Models 3 and 4 based on the above information, we also show that the values of the log-likelihood in Models 3 and 4 have almost no difference. We conducted a likelihood ratio test to test the null hypothesis of $\beta = 0$ using values of the log-likelihood in Models 3 and 4. The test showed that the null hypothesis was not rejected, implying that including $\beta = 0.9$ in the DDCM is not statistically significant. Due to the above results and computational burdens, we use parameters of Model 3 in Table 1 to estimate the effects of the "predicted" *remaining* product lifetime on consumers' product use duration of ACs in Japan.

	Model 1	Model 2	Model 3	Model 4
θ_0	0.08	0.08	-1.41*	-1.54
	(0.66)	(0.739)	(0.71)	(1.08)
θ_1	-1.39*	-0.86*	-0.89*	-0.29
	(0.44)	(0.26)	(0.41)	(0.41)
θ_2			0.35*	0.36*
			(0.06)	(0.09)
θ_3	-0.85*	-0.85*	-0.71*	-0.75*
	(0.25)	(0.28)	(0.25)	(0.37)
β	0	0.9	0	0.9
$\log L$	-735.08	-734.96	-646.16	-646.51
N	2366	2366	2366	2366

Bootstrap standard errors are in parentheses.

*Statistically significant at the 5% level

Table 1: Estimation results of DDCM parameters

4.2 Impact of expected product lifetime on product use duration of ACs

Figure 1 shows the replacement probability of ACs in Japan in the BAU case and in cases where the consumers' "predicted" product lifetime increases by 1 year, 2 years, and 3 years (i.e., $\Delta EL = 1$, $\Delta EL = 2$ and $\Delta EL = 3$) estimated by equation (8), respectively. Further, figure 1 shows that a peak of the distribution of the replacement probability moves to right-side of the graph as the "predicted" *remaining* product lifetime increases. These results indicate that increase in the "predicted" *remaining* product lifetime can prolong consumers' use duration of ACs in Japan. We also calculated the expected values of the use duration for each case using equation (9). The expected value of the use duration for the BAU case is 10.3 years, whereas the expected values of the use duration if $\Delta EL = 1$, $\Delta EL = 2$, and $\Delta EL = 3$ are 11.2, 12.11, and 13.02 years, respectively, and the increase in the expected value of the use duration compared with the value in the BAU case are 0.9, 1.8, and 2.72 years, respectively.

These results showed that product use can be prolonged by increasing consumers' expectation of the *remaining* product lifetime of ACs. This implies that consumers may keep their ACs if policies or services that persuade them to consider their ACs as being in an adequate condition for use are implemented properly. For example, providing repair and maintenance services to consumers owning ACs whose ages for example, are around average product lifetime may prolong consumers' product use duration. Such services can persuade consumers to view their *remaining* product lifetime longer than that before conducting the service, resulting in a product lifetime extension. A labelling system that warrants product durability and reparability, such as a scoring system on reparability [17], may also be effective in prolonging product use duration. This can increase consumers' "predicted" product lifetime when purchasing products and accordingly achieve longer product use. Although additional research is necessary to discuss what type of policies and systems can be effective for extension of product use duration, the framework and results obtained in this study.

These results also indicate that the product use duration can be extended by values that are almost equal to the length of increases in the "predicted" product lifetime. Hence, improvements in physical durability and longevity can bring an effect of extending the consumers' product use duration almost as long as those improvements because it can be assumed that prolonging the physical durability of products will increase consumers' expected product lifetime. Although the relationship between physical durability and expected product lifetime needs to be scientifically analyzed in the future, efforts to improve product design to enhance physical durability and longevity are one of the key factors for promoting longer product use from physical as well as psychological perspectives.

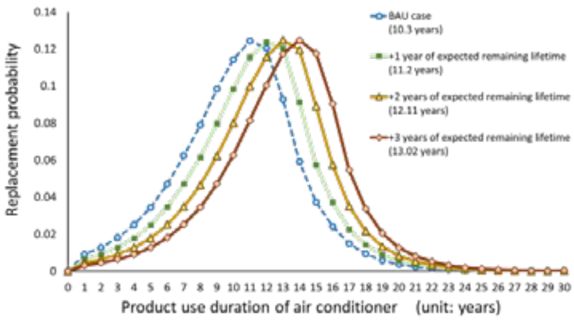

Figure 1: Discretized replacement probability distributions of AC for each case of "predicted" *remaining* product lifetime increase

This study constructed a framework for analyzing the impacts of consumers' expectation of product lifetime on actual product use duration. It analyses quantitative effects of consumers' expectations for product lifespan on product use duration, and the results can help us to design policies for longer product use with a consideration of a change in the consumers' expected product lifetime as the consumers' psychology about the product changes.

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Development of an Analysis Method for Circular Economy (CE) Business Creation

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Abstract

Alongside changes in consumer lifestyles, there is now a growing trend for consumers to use only specific functions of a product, rather than using or owing the whole product. In Europe, the realization of a circular economy that does not rely on resource consumption and aims for sustainable economic growth has been positioned as one of the economic strategies, and expectations for the circular economy are rising worldwide, along with changes in consumer values. On the business front, the use of circular economy approaches may lead to the creation of new businesses. In this study, we clarified the definition of businesses contributing to the circular economy and developed an analysis method to find the key functions and elements for CE business creation. The characteristics of each business model can be summarized by examining the preceding specific business using this analysis method.

1 Introduction

As our customers' lifestyles change, they are more likely to use specific features rather than use or own the entire product. In Europe, one of the economic strategies is to realize a circular economy that does not depend on resource consumption and to aim for sustainable economic growth. As consumer values change, expectations for a circular economy are rising worldwide.

In line with this, policies on the circular economy have been formulated at the government level. At the same time, we conduct academic and technical research. On the business side, the use of the circular economy approach may lead to the creation of new businesses.

In this study, we clarified the definition of the business contributing to the circular economy and developed an analysis method to visualize key points for designing the CE business.

2 Developing an Analysis Method

2.1 Approach

First, we believe it is important to clarify the requirements and objectives for designing products, services and solutions for a circular economy. For this purpose, the Quality Function Deployment (QFD) method was applied. QFD is a method of identifying the important quality elements from the relationship between them using a binary table of quality that describes the quality desired by the customer and the elements that can be directly controlled by the company. By using QFD, it is possible to grasp what kind of functions and elements are strongly related to the requirements, and whether the target performance has been achieved to satisfy the requirements. This effective method is used to design products, services, and solutions [1].

In this study, we set each CE business model as the specification desired by the customer, and created a binary table setting the functions and elements that the business should manage, and took the approach of extracting the functions and elements that are important for the CE business.

2.2 Defining CE Business Models

CE business models handled in this research is arranged in two axes of “Service / Solution types” and “Product types”. The service / solution types are classified into "Product as a service" and "Sharing platform" that they deliver a streamlined product functionality to the customers. Next, we organized the product types into "Repair/Maintenance", "Refurbish" and "Remanufacturing" which maximize the value and the life of products by reusing products themselves and parts used in the products.

Furthermore, from a business perspective, an important factor is the acceptability of the customer to these models, i.e. whether the value and benefit are obtained from the customer perspective. The definition of each model in this study and the value of each customer are shown in the following: 2.2.1 and 2.2.2.

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Recycling businesses that circulate materials, which is another important factor in the circular economy, are not included in this analysis because they are common to all models mentioned above.

2.2.1 Service / Solution types

They will deliver a streamlined product functionality to the customers.

1. Product as a service

   It is providing the functional value of a product as a service instead of selling the product. By managing the products, the customer value will increase throughout the lifecycle.

2. Sharing platform

   It is providing an environment where a product (feature) can be used by multiple people when they need it. The customer can reduce the cost of the ownership.

2.2.2 Product types

These will increase their product values.

3. Repair / Maintenance

   Repair is the recovery of a product's specific functionality. Maintenance manages to ensure that certain features of the product continue to proper functions or optimal performances. The customer can extend the product life.

4. Refurbish

   It is repairing and cleaning products on the market to restore the overall functionality of the product. The customer benefits are the reduction of the product acquisition costs, the availability, the maintenance of quality and the performance (the minimization of ageing degradation).

5. Remanufacturing

   It means demolition, repair, and cleaning of products on the market to restore and rebuild all products to the same level as new products. The customer benefits are the reduction of the product acquisition costs, the availability, the maintenance of quality and the performance (the minimization of ageing degradation).

2.3 Defining Functions and Elements in CE Business models

It is discussed that the formation requirements, functions and elements of CE businesses like the business model of reuse and remanufacturing should be considered on the basis of the product life cycle [2] [3] [4].

In this study, we extracted the following twelve functions and elements in CE business models from three points: “How things are used”, “Life cycle cost of customers” and “Regional characteristics of markets”.

2.3.1 How things are used

By optimizing the use of products and services by customers and the points of contact between business operators and customers, it is possible to improve the durability, upgradeability, and repairability of products and contribute to the improvement of resource efficiency and customer value.

1. Business type

   It determine if the product or business is business to customer (B to C) or business to business (B to B). B to C and B to B have different touch points for business operators and customers, and different forms of product maintenance and take-back.

2. Expected life time

   We assess the life of current products and consider extending the life of products. For CE business models, longer product life is more valuable.

3. Utilization rate / Frequency of use

   We examine the applicability of sharing and maintenance. Infrequently used products are considered to have a high potential for sharing. For products with high availability, proper maintenance can be applied to predict or prevent product failure and reduce loss of customer value.

4. Product hardware upgrade frequency

   It means the frequency to release a new models of the product. In the case of products with rapid technological innovation and frequent release of new products, such as laptop computers, the business model of service provision and sharing of goods is considered to have higher user benefits than the conventional model. It depend on the product technology maturity.

5. Software upgrade

   There is an upgrade function by software or not. It considers the applicability of repair / maintenance services. It also contributes to longer product life.

2.3.2 Life cycle costs of customers

The optimization of the life cycle cost contributes to the profit opportunity of business operators and cost reduction of customers. This identifies "hidden cost" and understands the lifecycle cost of products and services.

6. Initial cost

   It evaluates the applicability of the servicing of products like rental and lease models. Customers may have difficulty making expensive initial investments.

7. Maintenance and management cost

   It investigates the applicability of product servicing, repair and maintenance. If the frequency of inspection is high and the maintenance cost is high, it is considered that there is a business opportunity of maintenance service.

8. Running cost

   It is annual power consumption and the cost of consumables such as batteries and filters. It studies the applicability of product servicing and maintenance services. When the running cost is high, it is possible to reduce the running cost and increase the customer value by analysing the usage status of the customer's product and performing appropriate maintenance.

9. Disposal cost

   It is the cost at the end of the product use. It examines the applicability of services to goods. It depends on the countries and regions.

   If there are customer demands for CE business in the region, it would drive the creation of CE businesses. If some CE businesses of the other competitors are already on the market, it would have an influence for creating new CE businesses.

2.3.3 Regional characteristics of markets

The legal requirements, the second hand market, customer requirements, and the existence of competitors' CE businesses will drive the creation of CE businesses. They differ by country and region.

10. Legal requirements

    If laws or regulations related to product disposal or recycling are currently in force in the region or will be in force within the next two or three years, the situation would drive the creation of CE businesses.

11. Secondhand markets

    If the region has a used goods market (secondhand market) from third parties, recyclers, retailers, and producers in the region, the existence of it would be considered to have a high possibility of CE businesses' applications.

12. Customer demands / Competitors

    If CE business models based on customer demands were already on the market, they would drive the creation of others.

2.4 Analysis Table for CE businesses

The analysis table used with the functions and elements of 2.3 are shown in Table 1. By characterizing the products, services and solutions and deploying their components in the functions and elements of 2.3, CE business models in 2.2 can be characterized.

3 Evaluation of Analysis Table

A case study of the CE business model was conducted to evaluate the effectiveness of the analysis method. This information was gathered from products, services, and solutions available on the websites. Table 2 shows the estimated results of the CE business models based on the collected and examined information.

Table 3 shows the consolidated results of the analysis of the functions and elements defined in Table 1 based on each company's business models in Table 2. Since the information available on the website is limited, a

Business models	Key functions and elements of CE business models												Circular Economy Business models	
	How things are used					Lifecycle costs of customers				Regional characteristics of markets				
	1. Business type; B2C / B2B	2. Expected product lifetime	3. Utilization rate / Frequency of use	4. Frequency of product hardware upgrade	5. Software upgrade	6. Initial cost	7. Maintenance / Management cost	8. Running cost	9. Disposal cost	10. Legal requirement	11. Second-hand market	12. Customer demand / Competitor		
Products / Services / Solutions	---	---	---	---	---	---	---	---	---	---	---	---	Product as service	Service / Solution type
	---	---	---	---	---	---	---	---	---	---	---	---	Sharing platform	
	---	---	---	---	---	---	---	---	---	---	---	---	Repair / Maintenance	Product type
	---	---	---	---	---	---	---	---	---	---	---	---	Refurbish	
	---	---	---	---	---	---	---	---	---	---	---	---	Remanu-facturing	

Table 1: Analysis Table for CE business

Company name	Business for this case study	CE business models (Estimated)
Bridgestone	Tire for truck and bus solutions	Product as a Service, Maintenance
Bundles	Subscription for washing machine and dishwasher	Product as a Service, Maintenance
Caterpillar	Construction machinery	Remanufacturing
Daikin	Air conditioner	Refurbish
Dyson	Cordless cleaners, air conditioning appliances and hair dryers	Product as a Service, Maintenance
IKEA	Crib	Refurbish, Sharing platform (Reuse)
Kaeser	Compressed air sales service	Product as a Service, Maintenance
Michelin	Tire as a Service	Product as a Service, Maintenance, Refurbish
Philips	MRI systems	Product as a Service, Maintenance, Refurbish
Philips	Lighting	Product as a Service, Maintenance

Table 2: Case studies for CE Business Models

Business models	Key functions and elements of CE business models												Circular Economy Business models	
	How things are used					Lifecycle costs of customers				Regional characteristics of markets				
	1. Business type; B2C / B2B	2. Expected product lifetime	3. Utilization rate / Frequency of use	4. Frequency of product hardware upgrade	5. Software upgrade	6. Initial cost	7. Maintenance / Management cost	8. Running cost	9. Disposal cost	10. Legal requirement	11. Second-hand market	12. Customer demand / Competitor		
Products / Services / Solutions	---	---	---	High	Yes	High	High	High	High	---	---	Yes	Product as service	Service / Solution type
	---	Long	Low	High	Yes	High	High	---	High	---	Yes	Yes	Sharing platform	
	---	Long	---	High	Yes	High	High	High	High	Yes	Yes	Yes	Repair / Maintenance	Product type
	B2B	Long	---	---	---	High	High	High	High	Yes	Yes	Yes	Refurbish	
	B2B	Long	---	---	---	High	---	---	High	Yes	Yes	Yes	Remanu-facturing	

Table 3: Result of CE Business Analysis

comparative and qualitative analysis was conducted for each evaluation. The characteristics of the CE business model for items that cannot be judged by related functions and elements are all described as "-".

4 Discussion

The results of CE business analysis are described for each requirement definition shown in 2.3 as below.

4.1 How things are used

First, as a business type, we can see that refurbish and remanufacturing are specialized in B to B business. This is expected to make it easier for B to B to set up collection schemes from customers. Second, longer product life is more advantageous. Frequently upgraded products, both hardware and software, are well suited to a customer-centric business model.

4.2 Life cycle costs of customers

It can be seen that the CE business model is likely to be adopted in all business models for the purchase, use and disposal of high cost products. At each stage, it is important to build a business model that allows customers to diversify their required costs.

4.3 Regional characteristics

The market in which customers use products also has a significant impact. It is assumed that business is conducted in consideration of social trends, markets, and customer behaviour in each country.

5 Summary

In this study, we applied the concept of QFD and clarified the characteristics of the CE business model using a binary table that sets the CE business model, its construction requirements, and functions. This time, we conducted qualitative assessments as examples of other companies, but in the future we plan to conduct quantitative assessments using our own examples. Quantitative assessment can find more specific CE business requirements.

We also want to apply the method developed in this study to the determination of existing linear business models. By comparing and analysing the results with those of the CE business, we believe that we can extract the issues of the existing linear business model from the viewpoint of the life cycle of design, procurement, production, and use. We believe that resolving these issues will lead to the creation of a CE business model that maximizes customer value in various business fields.

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(How) can service design and digitalization be used to transition to the circular economy?

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Abstract

While eco-design for products according to closed loop life-cycle principles is a pre-requisite to achieve full circularity of material flows, it might not be sufficient to meet the targeted resource consumption on a global scale. In the context of Circular Economy, new possibilities around digital solutions and services are discussed as great step towards achieving a globally sustainable economy based on the principle of circularity as they can create synergies and sufficiency in resource consumption more effectively. Moreover, by allowing to keep track of products over their entire life cycle(s) and exchange data amongst all stakeholders they allow for constant incremental improvement and adjustment.

It is a striking fact that although technical development happens at an unprecedented speed, and new, disrupting or improving operations are technically feasible, we only see little ideas - see products - reaching markets. In order to understand the driving and limiting factors for transitioning towards circular business models, we interviewed experts in the Baltic Sea region about their experiences. We asked them about their needs as well as visions and outlooks they have to implementing sustainable business solutions for a digital CE.

The qualitative interviews were analysed to retrieve re-occurring challenges, understand practical solutions and underlying opportunities as well know-how deficiencies. From the findings, we expect to be able to develop tools that will on an operational level help designers to integrate sustainability in their work process and on a strategic level support the development of sustainable business innovation through service design.

1 Introduction

In the discourse of how current economies can become sustainable, digitalization's role as an important enabler of the Circular Economy (CE) is widely accepted. [9, p. 46] . Direct benefits can be observed in industrial processes where digital solutions help closing the loop of material streams or provide information to more efficient resource usage. In traditional "take-make-waste" scenarios the environmental impact was only controllable for the phases of production to distribution directly. New digital technologies and capabilities such as the Internet of Things (IoT) and Big Data promise to establish information networks that allow for control and sovereignty throughout entire life cycles. [10]

Since the 1990s, Product Service Systems (PSS) have been heralded as one of the most effective instruments for moving society towards a resource-efficient, circular economy. [11, p. 76] They promise to improve resource efficiency by extending the product lifetime and promote a shift from selling just products to selling the utility, through a mix of products and services while fulfilling the same client demands with less environmental impact. [12, 13] They allow value recovery strategies, such as repair and remanufacturing and new relationships between companies and customers, who become temporary users of products. [14–16] Thereby they are seen as mean to create entirely new business models and revenue streams. [17] Such approaches require new types of service offerings and service skills. [18, p. 293]

The European Commission emphasizes the role of design in the EU action plan for the circular economy as "better design can make products more durable or easier to repair, upgrade or remanufacture". [19] In addition, more and more authors emphasize the beneficial design and innovation opportunities of the CE (e.g., De Pauw et al. 2014; Braungart et al. 2007; McDonough and Braungart 2013) and argue for the importance of supporting *eco-efficiency* with *eco-effectivenes*.[12]
The design discipline is seen as an intermediary between industrial developments and the user and thereby has supposedly power not only on whether products are designed in a sustainable resourceful way but also on how they will be used. It has been suggested by a number of authors that designers can play a role in moving

towards a circular economy, through their ability to understand and influence business and consumer behaviour.[20] Adequate design can inform the user e.g. not only on how a product can be maintained or recycled but also how to make use of services so that they increase efficiency, create synergies and thereby avoid or reduce negative environmental impacts. [15]

There is a growing body of research outlining the role of design in a circular economy and suggesting useful frameworks, tools and strategies for implementing circular design principles. [20]

Yet, although the awareness and responsibility amongst designers and experts rises, the overall "economic circularity" even shrank in between 2018 and 2020. [21] To understand the impediments for service design and digitalization to use their designated influence, we interviewed leading experts in the Baltic Sea region who are active in both fields. We asked their insights on how data and service design can be supportive for the CE, what barriers and needs they face in their field of activity and what outlook and forecast they have for digital technologies as a front-runner for sustainable business strategies.

2 Method

In 9 qualitative interviews we talked to experts about the barriers and drivers of circular economy in connection with digitalization and service design. The experts were therefore chosen upon one essential criterion: They had already a good understanding of the concept of circular economy and they had a professional background in either digital technologies and/or service design. The following fields of activities were represented: IT-system development (2), Service design agencies (2), research centres (2), data management & artificial intelligence (1), Innovation consultancy (1) and platform provider (1). All interviewees had roles in leading positions.

The interviews were conducted in a conversational style with a duration of 60-80 minutes each. An interview guideline with questions to cover was designed beforehand. First, the experts were asked about their experience in the field of Circular Ecocnomy (CE) and digitalization and second whether they had already conducted projects where both aspects played a role. Further questions were more detailed about barriers and challenges as well as solutions and potentials in this field. In order to find out what kind of knowledge and trainings would be needed as support for them and their clients we asked open questions about the methods they use successfully or tools they are missing. Finally, we also asked for their outlook, visions, and steps they would take today to reach them.

The interviews were conducted and resumed by the project partners and then collected for analysis. With support of the analysis software AtlasTi all interviews were screened for the five following indicators:

Barriers: Obstacles in implementing or applying sustainable projects where neither a solution is seen nor any stakeholder could be a change driver.

Challenges: Can either be challenges the customer faces and needs help by experts or challenges the experts find in their business. Often / Sometimes Challenges can already reveal opportunities

Opportunities: opportunities that might be entrance points to initiate change and are arising through digitalization and services.

Solutions: tangible clear suggestions or scenarios that solve a challenge

Examples: existing approaches that demonstrate a way making something different.

During the analysis, we found that most of them can be sorted in following similar categories:

Management and stakeholder, business model and strategy, data and information, design, user/customer, technologies and legacy, legislation.

Another information we scanned for were **sources of information and knowledge** the specialists use to inform themselves.

3 Results

3.1 Barriers & Challenges

The biggest barriers mentioned by all interviewees occur within companies and more specific in management and corporate culture. "People's current way of thinking is the largest obstacle to digitalization in companies„ [1] and "companies' mind-set is still heavily based on linear business operations". [2] A missing common vision and understanding or "not taking sustainability seriously is a big barrier in organizations" [3], too. Siloed working as well as siloed data or information lead to "departments within one company not cooperating and having no common understanding or vision for sustainability" [4]. This also leads to slowness within companies. [3] All together companies "lack both the tools and the competence" [2] and the bigger the company the more costly and more difficult it is to initiate change.

For the experts in consequence this also leads to the barrier of not being able "to sell design as it is not easily understood " [5] and "no precedence make the sell even harder as companies are very risk averse" [4]

3.1.1 Business & management

All experts agree that the most "challenging part is to build a clear business case around the topic of sustainable development: what kinds of business advantages companies could achieve, how circular economy can help with developing competitiveness and what kind of competitive edge organizations could gain from approaches that follow sustainable development." [6] "Clients need to see monetary benefit before considering anything" [7] and "ideas have to be very concretely justified" [5].

Not being able to measure sustainability with indicators is especially challenging with bigger companies: "Listed companies following the quarterly cycle of economy must be able to argue for and prove the business advantages of circular economy during each annual quarter". [2] But even for the experts, it can be very challenging, e.g. " how to even measure the the impact of digital waste against printing?" [7]. "Social value produced by circular economy is also difficult to transform into financial advantages" [2]

A lack of seeing the bigger picture is preventing innovative thinking within companies as well as understanding where opportunities for improvement of both business and sustainability could be. "Companies and governments need to see bigger picture and bigger opportunity in sustainability, they need holistic sustainability strategy" [3] and they require help to form these [2]. „Corporate internal understanding" [4] and "changing their own operations to follow a new kind of business model of circular economy is the companies' biggest challenge, and it requires changing the way they think." [1] For example "marketing would prefer quick win greenwashing and eco-hype than longer term supply chain goals that customers may not see/or care about." [4]

To draw a common understanding or vision "we need leaders who have the energy and ambition to lead the change in companies" [1] and those "business leaders have to address people's fears and communicate strategies." [3] The transformation takes time and is not easily implemented as "even achievements from one project wouldn't necessarily be learnings for the next project. It's very much the Long Game" [4]. "To change their habits, people require plenty of repetition". [2] Which is true for companies and for customers.

"For now, sustainability remains an external requirement, and the companies lack the tools to promote it, especially on a strategic level." [6] , "sustainable development equals corporate responsibility in many companies". Additionally "where business models aren't disrupted the business doesn't feel compelled to change" [3]

All experts at some point mentioned that "companies require more competence on how to start modifying the business model" [1] but there is a "different readiness and capacity for forward thinking, there's a big chaos still in many of them. Organisational cultures vary significantly" [5]

"Large companies that have followed a linear model for a long time, fine-tuning their supply chains and internal operations, face large risks if they transition to circular economy; they need to make large investments and process changes. Changing the company mindset and business logic, as well as the organisation's internal change, create challenges especially to these kinds of companies." [2] Additionally "there's too many stakeholders and moving parts to think about" [7] and "as the supply chains are so entrenched, top-down decision needs to be taken early and all stakeholders given the possibility and support to transform" [4]. On the other hand, "companies need to understand that circular economy operations require a wider network than just their current partners; an ecosystem that enables providing new kinds of services." [1]

This leads to a situation where "most actions are related to materials, and the multifold options to complement the existing production, for example with the help of digitalisation, are not considered" [1]. Post agrees that for most of their clients "CE is not interesting because [they] want to sell more products." [8]

As long as these challenges are not overcome it is very hard for experts as well, to build a proficient business around sustainability because "sustainable development has relied on the forerunners. From a business perspective, this group does not create a large enough market for *Hellon*[1], for example, to invest in it significantly more than it already does." [6]

From the perspective of sustainability drivers, Polaine sees one challenge in the fact that "activities often focus too much on research, trying to find THE one solution in one step". [4]

3.1.2 Data and technology

It was already mentioned that not having indicators or measurement tools for sustainability is one challenge

[1] Hellon: Finnish customer experience design agency

for companies, this seems to correlate with the challenges of data (made) available: "I'm often asked what are the key figures of circular economy. It depends on what we want to measure: the generated emissions, the material savings or maybe the company would like to measure customer value?" [1] Arponen explains. But there is a general uncertainty of how to connect information correctly and Kruus ask: "What are the patterns of behaviour that can reveal future problems? E.g. does the weather influence anything?" [5] Clarke, who uses data on a daily base for their business sees the biggest challenge in legacy and IT-Systems and mentions a need for "integrated data access and infrastructure." [3] This is confirmed on a technological level: "it is difficult to combine all machines [and] it is super expensive to develop software for the clients mainly because each piece of machinery comes with a different software and data logic, using different file formats" [5]. As these systems are fairly complex, there is also "a question of entry point. Who builds the entry point infrastructure?" [7] which relates to the challenges of the business modell.

3.1.3 User

In some companies "marketing would prefer hiding the sustainability to the customers" [4] yet, "most companies just don't know how to communicate their efforts to their users." [8]

Most companies do not see benefits or possibilities how to integrate end-customers in their business operations and Polaine gives an example: "malfunctioning products could be refurbished (e.g. one main failure cause is programming mistakes by the user) but there was very limited desire/incentive for the user to return, so retrieval rates were very low". [4] From a user's perspective he also refers to the effects of "*Eco fatigue* and lack of customer awareness: most customers are lost on the decision path"[2] [4]. Post describes related phenomena: "Customers delegate the job of creating a sustainable product/service to the company" and explains: "they already change their own lifestyle through going by train they expect that the mobility service is sustainable." [8]

Yet for most companies, it's a big challenge how to communicate to their customers and here Post sees an additional "function for agencies to visualize data and find the touch points [and] structure the information in a way so that it is relevant to the end-client." [8]

[2] (he herein references the BCG "Capturing the green advantages for consumer companies)

3.2 Solutions & opportunities

Besides the sometimes implicitly mentioned opportunities, the experts provide tangible solutions of how to foster CE through service design and digitalization as well as occurring opportunities:

3.2.1 Business & Management

As we've already seen, indicators and measurement tools are essential to sell sustainability. "*Hellon* utilises a large number of reports from different research institutes, such as Forrester, which reveal how the financial results of companies investing in service design are better than for those businesses that do not invest in customer experience and service design. Figures proving financial success facilitate sales work and are good arguments for managing directors who ask why their companies should invest in e.g. service design. Finding or compiling similar reports about companies utilising business models that adhere to the principles of sustainable development, for example on an European level, would facilitate "selling" circular economy to companies. […] Showcasing various business cases and clear communication about them would also help argue for circular economy. [6] Hellon has developed a tool[3] using artifical intelligence (AI) "to support design processes and it is often combined with qualitative research. AI helps achieve a whole new level of trust in research results, as it makes it possible to process such a high number of quantitative responses." [6] The expert could see similar effects when using AI for sustainability research but they havn't done this yet.

"There is a need for systems modelling that takes in account a broad picture with manufacturing, service design, sharing economy, international constraints, logistics, energy consumption - analysis of the entire system or product chain [and] any framework or toolset needs to identify what should be done and help focus on what could be done." [4] and Post even thinks further: "Develop a LCA based tool how to calculate environmental impact of digital services." [8]

"We should highlight how circular economy offers chances for growth without increasing the use of raw materials. [at the moment] financial advantages and the customer are not talked about as much" [1] Digitalization offers "great opportunities in sharing economy and product-as-a-service." [4] "A shared economy means

[3] See: "Aino" https://www.hellon.com/aino/

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to reduce natural resource load per person which is nowadays rarely pitched as sustainable benefit" [3] . "Digitality supports the efficiency of companies processes, enables new revenue models and helps develop almost any kinds of services to customers. It enables real-time monitoring of products and materials as well as continuous interactions with the customers." [1]

In order to explore "how companies produce value not only to their stakeholders but also to their customers, the environment and society, *VTT* utilizes their own version of Business Model Canvas, which has been modified by bringing in a circular economy value to the Value Proposition section." [2].

Another solution is using "games and digital tools designed for circular economy, which help companies test their own choices and new business models. Board games and gamification are great ways to demonstrate the business models' different effects." [2] "Games help facilitate conversation on what kind of change drivers there will be in the future, how the different management models will change, what kind of infrastructure we will use, how climate change will affect our living environment, etc." [6] Where it comes to implementing new concepts Post sees a need for "prototyping tools for prototyping digital enhancement of physical products." [8]
For the management "it is vital to include people from different levels and sectors of the business in the development work, as a multidisciplinary group will produce good end results." [1] Another opportunity lays in "democratic leadership" as companies thereby can understand what the masses want. [3]

Kronqvist believes that the role of tools that help facilitate thinking between different operators and look for common ecosystem solutions will grow in the future.

Besides the need for simple, concrete tools [2] "spotting action opportunities in the bigger picture is key" [3] Post describes how they "build stepping stones, helping brands to take the first step in the learning path towards CE: We talk with clients about a digital twin and they see the advantage of selling additional services. Next the market value is increased through upgrades which also is an incentive for end consumer and keeps products alive (longevity)." In his experience clients can sell those ideas internally better than selling "not commercially viable sustainability". [8] His solution for companies is to "start not with a fully circular model, but start with one product and upselling." "[Clients] need best practices and an understanding for the possibilities in iterating approaches." [3] "Understanding *lean* and *agile* to capture markets that weren't there before" [3] would be one approach for companies to start shifting to sustainability.
Consequently "companies have to understand the needs and behavior of consumers and how those can be molded into profitable business. […] The value proposition must be an integral part of the company. [2] "If customers pay only for the service, companies would produce products that last longer or can be easily refurbished" says Polaine and gives a simple example: "Why have a gloss black virgin plastic router that sits on a shelf gathering dust? What is the rationale for this, when it is the broadband speed, security and reliability that really matters?" [4]
Companies could gain the commitment of their customers and use service design to "improve the customer experience and use it for interaction with the customer which would also increase loyalty AKA brand stickiness". Eventually there could be "services which are valuable for end consumers which would create a win-win situation: Companies would gain data to optimize services and processes and consumers can see, what the data is used for and can optimize their behavior based on this" [8] Providing these services would "make not owning stuff accessible and attractive to people." [8]

Generally, Clarke observes positive change in communication: "30 years ago it was a barrier as it was restrictive, punishment, avoidance. Communication should be looking into opportunities and value creation." [3]

3.2.2 Legislation

"Large companies should be drivers as they can scale easily and they also have the power over governments to a certain degree (which can be barrier and gain)." [3] On the other hand "Start-ups […] are often well-informed and it is easier for them to base their entire operations on circular economy's business models right from the start." [2]

While there is a strong focus on promoting sustainability through business advantages two interviewees mentioned consciese propositions of how legislation could be supporting: "Greenwashing companies should be held accountable." [3] and "Taxation on virgin vs. recycled materials could be a game changer." [4]

In general "it should be made concrete to companies that making business changes proactively is beneficial, for example before potential legislative changes by the EU come to force." [2]
On the other hand, "science based target initiative and other programs as silos, they don't regard the system. Furthermore countries can drop out." [3]

3.2.3 Data

There are also opportunities in using data on a secondary level which Clarke explains on the example of a food rescue app: "Primary gain is to match consumer and producer and avoid waste. The bigger gains could be the second level insights as "data harvesting": What dates or time is the app used, are there customer preferences for food, when should companies produce what food for whom?" [3]

"If used properly: Insights from marketing and operations data can be used to improve every aspect of business" says Clarke. She expounds: "AI and data usage can solve unsustainable use of resources, make processes/operations more efficient which saves money and resources and emissions."

She also sees a business advantage in the "usage of data & Ai for R&D fast track innovation: Companies could optimize their research pipelines, calculate manifold options and quickly sort apart promising from flopping research approaches." [3]

For the various solutions proposed "it is necessary to have a centralized union or something that standardizes the IT side of machinery and sets the structure, file formats and what not for easier compatibility with other machinery and central management platforms." [5] The first question regarding such platforms is "who builds the frame where all products and devices can be added and connected between companies?" [7]

A further idea to use data is to "develop the audit method further and combine it with IT. Lean management, ecodesign business combined with management dashboard. KPI-s are determined and you get live feed of circular performance and material inefficiencies. A kind of Power Business Intelligence. Yet it would be difficult to create such an add-on for management software for better decisions." [7]

The IT-companies also pondered the possibilites to "develop software where fragments could be reused and new programs would not always be created from scratch" [5] "The reuse of IT solutions would be part of a circular economy by eradicating inefficiencies which can also have ecological benefits." [7]

Most experts promote hidden opportunities for companies to leverage impact and create new business by understanding the entire system network. A way to really spur sustainable thinking would be to "internalize external costs. e.g. if the delivery is part of the product, you will think of energy and fuel, traffic and air pollution." [4] An example of how databased predictive maintenance would reduce internal and implicit costs such as user satisfaction were passenger ships, where maintenance itself costs a lot but it's also inconvenient for the passengers.

Whether experts or clients, "companies that improve the business operations of others by providing intelligent production, logistic or digital solutions to wider business ecosystems are the unicorns of the future" [1]

3.2.4 User

Another opportunity for sustainability through data usage is to "create awareness and provide information at all decision points for customers through service design and storytelling. Consumer power is overlooked but could become an important leverage if the general awareness rises." [4]

Helping the consumer to take responsible decisions "service design and storytelling help promote the difference of sustainable products." [4] But after all, sustainability shouldn't be the only value created: "Focus should be on the credentials of the product itself, not on the ecologic impact. Sustainable must be the most convenient option available" [4] "Sustainable solutions must be better than the existing ones" [2]

On the other hand, "values for certain goods need to be questioned. For example diamonds: we value authenticity, creating social and economic injustice, where we have modern technology solutions." [3]

Post sees an opportunity in influencing user decisions through "real time data communication" and provides an example: His agency was asked to design an interface for scientist to evaluate mobility patterns. They had the idea to feed the data into a cockpit for drivers so that those could compare their driving behaviour and were incentivized to find more efficient ways to reach a destination.

According to Post depending on the "way how to communicate, people can change their behaviour." [8] Clarke emphasizes on the fact that education should enable people to relate on a personal level: "Create awareness through emotion: address emotional not scientific (rational) understanding. Make it tangible and easy to identify with the experience or content, trigger emotional responses." [3] Yet she also warns that "if you place the burden on someone to act you have to give them the (full) capacity to act." [3]

To help companies to determine how they should communicate outwards about their sustainability is where the designers come in. [7] Designer "order and structure the information in a way so that it is relevant to the end-client or the "outside world". The creative part is to visualize information, create images and infographics, and draft the story how to communicate and report status, goals and progress. If we tell a story where people can link to then they find it interesting and share it with others because it's a story instead of just facts" [8] Polaine agrees that "closing the loop „in the story" and tell the story of the afterlife can enhance both, willingness and awareness." [4]

Data accessibility from the user perspective supports the repair movement with instructions and 3D-printing which will enhance circularity and also create local ecosystems, while reducing transport etc. It could also force companies to change their strategy to design for repair. [4]

"Re-manufacturing, modularity and aftermarket for used products are starting to become a part of everyday operations in larger companies" [1] Expanding the idea of predictive maintenance and digital twins to the customer level, offers opportunities to extend the lifetime of products but also to "democratize data usage and increase data literacy." It opens up new ways to "incentivize to contribute "collectively" to a more sustainable lifestyle." [8]

To identify potentials of impact in the entire system but also to evaluate the actual impact of actions it is important to "look into each case and get feedback to align the "designed services" with the actual customer experience." "User experience design MUST work closely with a CE specialist and believe in the CE" [4] in order to really create synergies and avoid negative effects with unseen interdependencies.

4 Discussion and outlook

"Responsible companies miss out on their possible impact. We need projects that raise the level of awareness of how CE can change things and need to change mindset. Digitalization and CE in a mix contain a lot of hope!" [3]

It became obvious that all experts believe in the possibilities of digital solutions to be a driver for the circular economy. Yet nominations of real examples and use cases are rare and the examples named are on a very strategic level and stay vague. Hence, although theoretical potentials are named, the reality in business applications differs hugely. Whereas we found some examples for digital based CE cases this is even more striking for the role of service design. This might have two reasons: On the one hand, the role of service design is only one aspect to creating service oriented business models and as depicted, the creation of those can only be an interdisciplinary effort. On the other hand, it seems that the importance of service design and the dependency on the quality of this work is implicitly understood amongst the experts.

Yet, the primary reasons for the lack of examples is in the same time one of the most mentioned demands: there are few only – we need more.

It became clear that the transition towards circularity can only be a cooperative effort across departments, companies, network partners and even sectors. Digital business models as well as circularity need to be understood by all actors in order to obtain throughout sustainability. This requires changes that neither digital experts nor designers can initiate solely.

Yet, the experts named some specific tools and means that would help to encourage business to venture into sustainable digital business models:

Information and measurement tools

In order to argue for and proof the reliability of new business models the experts need examples and indicators that underpin the benefits. Although arguable whether it is sufficient to apply current metrics of business success to new models or whether the CE requires altering, new performance indicators, these could be the most important mean for starting the transition.

Complexity and system understanding

All experts see the need for complex infrastructures and collaborative networks to work sufficiently. System modelling tools that display systems from end to end and the interdependencies are needed. They can help to grasps the bigger picture and indicate action points for impact creation. Data analysis and Ai could be a game changer here.

Actionable and profitable first steps

Although a new network of partners and business operations might be essential on the long term, identifying first steps that companies can take is one key solution to initiate the transition towards sustainability and/or services.

Two approaches were illustrated:

(1) Expanding current business models rather than changing it e.g. adding value through services.
(2) Draw the bigger picture and a future vision then identify steps that could lead to direct benefit.

4.1 The role of service design

One key benefit of digital product solutions for sustainability is their opportunity to involve (end-)users on an entirely new level. This allows for now forms of interaction and could be one important step for the stakeholder to control the entire lifecycle. Through ongoing interaction and the exchange of data, loops that so far have been difficult to close and the impact during the use-phase may become controllable. It could also be the enabler for consumers to take their responsible role in the circular economy. Design has an important role in designing the touch points with the customer. Moreover it can contribute by co-creating the complex systems in a way that responsibilities are assigned to the best suited stakeholder and everyone has the necessary information to act accordingly.

It became apparent, that digitalization and service design can help transition towards circular business models. Yet for this purpose, it is essential to integrate sustainability on a strategic level as well as understand the strategic role of services and design. Only then, service design and digital solutions can fulfill their share for the Circular economy on an operational level.

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Capturing Complex Value for Policy: applying value mapping in the WEEE EPR system context

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Abstract

The European Commission describes a Circular Economy (CE) as an economy "where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised." But what is value in this context and how should CE policies consider value? Extended producer responsibility (EPR) policies are an important part of an EU CE Action Plan. However, there is a need to evaluate these policies in light of CE objectives, including how to retain value(s) in this context. This contribution gives background to this issue and an overview of previous work mapping and assessing stakeholder and multidimensional value. It presents a value mapping tool refined through stakeholder consultations and a workshop to consider stakeholders in an EPR policy system for WEEE. The potential use of such tools for exploring how policies can further capture economic, environmental and social value is discussed.

1 Complex Value in a CE

The European Commission describes a Circular Economy (CE) in its CE Action Plan as an economy "where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised."[1]. However, the term "value" remains undefined and poorly understood both theoretically and empirically [2].

In fact different theories of value, i.e. what it is and how it is created and captured, abound. Two prevalent economic theories of value are often referred to as shareholder theories (i.e. where producers maximize exchange value in the form of profits for shareholders) and stakeholder theories (i.e. where producers maximize value, which can be in different forms, for stakeholders) [2], [3].

A public policy perspective must also consider value from different stakeholder perspectives and the contributions of different stakeholders to create public value. This involves considering value from different dimensions, e.g. economic, social and cultural, political, and ecological, and such values beyond economic values are expressed in public policies [4]. This is true also for the EU's CE Action Plan CE policies which, mirroring sustainability dimensions, express both social and environmental values in addition to economic values.

In addition to considering the multiplicity of values derived from multiple stakeholders and dimensions, there is also interaction of values resulting in trade-offs between different values in systems [5], [6].

1.1 EPR Policies for WEEE

Extended producer responsibility (EPR) policies are an important part of an EU CE Action Plan to ensure that waste products, like waste electrical and electronic equipment (WEEE), are collected and reused or recycled. Despite the overall rationale for EPR which is to enhance both upstream changes and downstream changes, the implementation of EPR policies predominantly focussed on the improvement of strained municipal waste management system. However, discussions on waste prevention and circular economy renewed over the past 10 years sheds renewed light on EPR policies' potential to the implementation of waste hierarchy and influencing design to prevent waste and improve reuse and recycling.

The WEEE Directive (2002/96/EC) first entered into force in 2003 and was recast in 2012 (2012/19/EU). There are few explicit mentions of "value" in the Directive. One is in reference to the value of "loss of valuable resources" (Preamble (23)). There are also related terms used for negative values in terms of economic costs for managing end-of-life WEEE.

There is also a positive value reference to "retrieval of valuable secondary raw materials" (Preamble (5). In what ways are these materials and resources valuable? They can be sold for economic value. They also represent saved resources and diverted waste. The latter relate to other dimensions of value alluded to the in Directive in its stated environmental and societal aims to "preserve, protect and improve the quality of the environment, to protect human health and to utilise natural resources prudently and rationally" (Preamble (2).

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1.2 Systems mapping and stakeholder identification

The first step to examining value is scoping the context and system in which the value is occurring. This background, or baseline analysis, is important for understanding the system under examination and identifying stakeholders [6]. Often systems are modelled with material flow analysis, but a policy can also be treated as a system.

Theory-based policy evaluation constructed an intervention (or programme) theory, or map of the policy, by breaking down the policy to its inherent assumptions about actors and actions that lead to immediate, intermediate and long-term outcomes [7]. The policy mapping also outlines the public policy values (in the form of the policy objectives). The simple intervention theory of the WEEE Directive shown in Figure 1 shows the policy system of actors and actions necessary for achieving the stated policy objectives.

The identified actors are also the stakeholders directly involved in the implementation of the official EPR policy system; however, they are not the only policy stakeholders in practice. Identifying these stakeholders requires considering not just the policy in theory, but the policy in practice. In this regard, the practitioners identified by the intervention theory can be instrumental in identifying the stakeholders they believe either *influence their work* in implementing the policy or *are influenced by their work* in implementing the policy. To capture these stakeholders, and with them, additional value perspectives, we used a value mapping method.

2 Value Mapping

The value mapping tool developed by Bocken et al. [8], [9] maps multiple dimensions of value for multiple stakeholders, involving six steps:

1. Specifying the unit of analysis: In the business context this might be a product or the business itself.
2. Specifying relevant stakeholder groups. In the sustainable business context the value mapping tool includes shareholders/investors, consumers, employees, suppliers, network actors, the environment and society.
3. Specifying the Purpose: Originally, this involved a discussion of the purpose of the business.

After specifying the system, stakeholders, and purpose, key questions help guide the mapping of value.

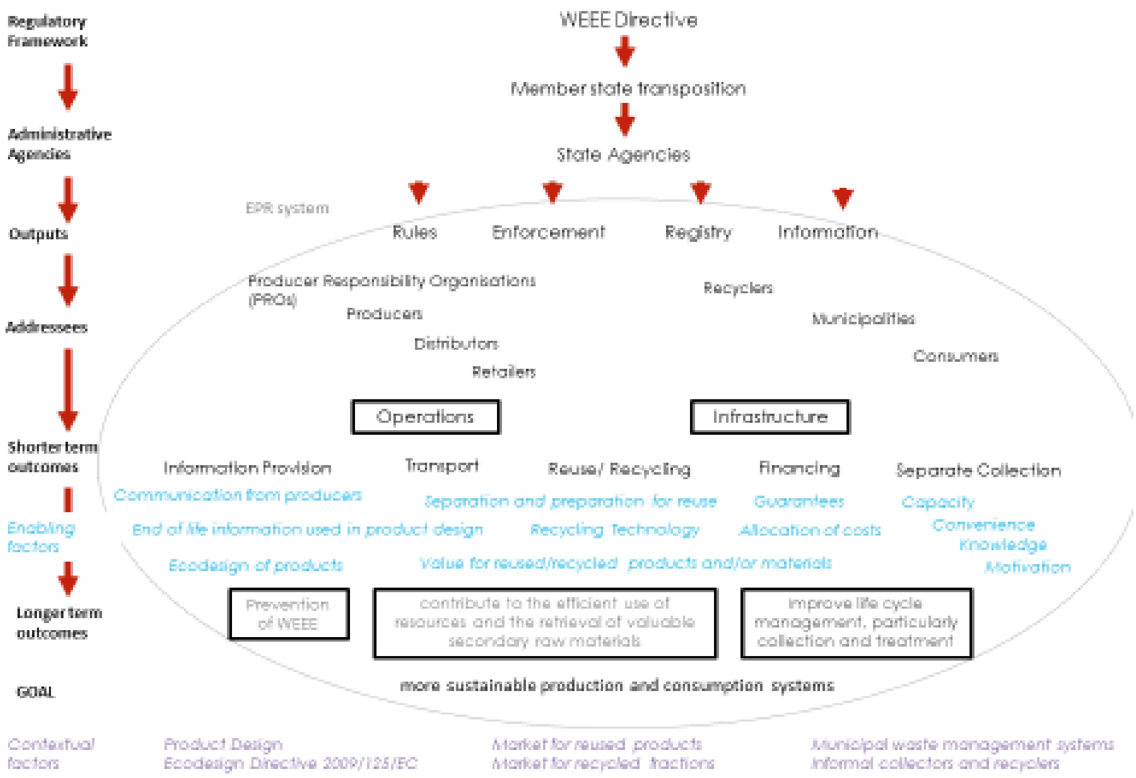

Figure 1 Simplified intervention theory for the WEEE Directive

4. Mapping Value Captured: What positive tangible and intangible value is created for each of the stakeholders? Does the stakeholder network mitigate negative outcomes?
5. Mapping Value Destroyed: What are the negative outcomes of the policy for any of the stakeholders? For each stakeholder group consider the positive and negative outcomes
6. Value Missed: How might the business or policy be missing an opportunity to capture value, or wasting or squandering value in its existing operations/implementation?

3 Value Mapping: EPR policy

The value mapping tool was the basis for a focus group discussion and workshop to which key stakeholders identified by the intervention theory were invited. This included EEE producers, PROs, recyclers, and municipal waste organisations. Mainly local (i.e. Swedish and Danish) and multi-national actors active in Sweden were invited for this first experimental workshop in order to jointly test and refine the value mapping tool.

The workshop began with the invited stakeholders giving a short presentation about the values they believed were captured by the EPR system and the values still a challenge for the EPR system to address. Then researchers presented the value mapping tool and the goal of refining it for the policy context, considering the six steps for the WEEE Directive policy.

The whole group was first presented with and discussed the unit of analysis: EPR policy for case products (phones, washing machines, lamps). The purpose in terms of increasing circularity in WEEE systems to achieve CE and EPR policy objectives was also presented and discussed. The value mapping steps, including some starting stakeholder groups was presented as well as the workshop objective of adding relevant stakeholder groups as necessary and mapping values using post-it notes (see Figure 2).

Three focus groups were formed to work with the value mapping tool for the three case products. Each focus group consisted of a mix of stakeholders and two researchers. One researcher facilitated the discussion with the tool while the other researcher took notes. These notes were then inductively coded to find themes (these are further discussed in section 4).

As public value literature suggested, we expected that a larger range of stakeholders might be relevant for the policy context than for the business context. This was indeed the case and this step turned out to be iterative as stakeholders were revealed and added throughout the value mapping process (see Figure 2).

Figure 2 Value Mapping tool for lamp case

As the purpose of the mapping tool in the business context is to allow for different dimensions of value to be discussed, the questions in steps 4-6 were also relevant for the policy context. Table 1 below outlines stakeholder values for the washing machine and mobile phone group that were agreed upon by the group and added to the value map. While there were some similar values identified between groups, it was interesting that they also recognised quite different values as well.

Table 1 Values mapped in workshop

	Washing machines	Mobile phones
Value captured	Sound management of waste products (Policymakers) Economic value (Recyclers) More tasks and better results (Recyclers) Positive stories (Recyclers) Bad products = less competition with second-hand markets (Recyclers) Reduce mining (Environment)	Better use of pre-consumer recycled materials (Producers) Enhanced material efficiency (Producers) Chemical tax (Regulators) Easily recycled metals (Recyclers) Precious metals (Recyclers) Communication enhanced (Society) Access to smartphones for poorer populations (Society)

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Value destroyed, missed, or wasted	Some measure counter-productive (Policymakers) Affordability (Users/Consumers) Time/convenience (Users/Consumers) End-of-life in Africa or other places without sophisticated recycling (Recyclers) Not all materials recycled (Recyclers/society)	Closed loop recycling over other recycling options (Producers) Rare earth metals (Recyclers) Trace materials (Recyclers) Higher power consumption (Users) Mixed materials make recycling difficult (Environment) Suboptimal recycling (Environment) Materials not collected (Society) Non-optimal recycling solutions (Society)
Value opportunities	Standardisation of plastic (Policymakers) Targets for materials (Policymakers) Collection to real treatment (Collectors) Individual Responsibility (Producers) Collaborative Projects (Producers) Incentives (Users/consumers) Prolonged life (Environment) Improved material recovery and use of materials (Society)	Direct the correct usage of recycled materials (Producers/OEMS) Know the material content (Producers) Optimised product design (Producers Requirements for consumers (Policymakers) Requirements for material recycling (Policymakers) Sorting and trading (Recyclers) Collection points (Recyclers) Chemical plastic recycling (Recyclers) Durability (End Users) Faster speed of system (End Users) Good eco-rating (Investors) Global EPR system (Environment) Recycling to close loops (Environment)

4 Discussion

Perhaps even more interesting than the values that were agreed upon was the discussion of why values were captured or not, and the discussion around values that were not agreed upon. In addition to notes taken by the researchers, each focus group presented their value map to the other groups and the main themes of their discussion were then discussed by the group as a whole. These themes are discussed in this section.

The tool promoted discussion about how some actors may be relevant to the value considerations, but are not direct stakeholders in the EPR system (e.g. mining companies may have little to do with EPR systems, but can influence materials supply and prices for secondary materials recovered from the EPR systems). Another example was phone network operators who were identified as a serious barrier to mobile phone reuse. They captured economic value outside the EPR system by only selling a service (network connection, data, etc.) but their service is tied to a product in an EPR system, i.e. mobile phones, without bearing any of the responsibilities either upstream (design) or downstream (reuse and proper recycling).

The identification of reuse markets outside the original market also raised questions about whether regional Directives can capture the value of reuse effectively or whether this requires cooperation outside the EU where reuse markets for EU goods also thrive, see e.g. [10]. However, if this is the case there needs to be a serious discussion about the true boundaries of EPR – i.e. can it be only in the EU if producer products end up outside of the EU?

There was still a tendency to talk in terms of economic value first and foremost. For example, in the case of washing machines, the group members agreed that concrete had little, if any, value. At the same time, steel was recognized as the most valuable material in washing machines. In all groups, the feasibility of increased recycling was perceived as entirely dependent on economic factors (e.g. making recycling small volumes difficult, influence of fluid material markets).

Aiming towards circularity for the producers and OEMs was equated with gaining competitive advantage, and, by extension, increased profit. Increased recovery of material was perceived as hindered by lack of economic returns for producers to invest money for developing recovery technologies (esp. for difficult materials – e.g. rare earths – which are also found in low quantities in products).

It was argued that technological developments in recycling and storage (i.e. for economies of scale) to address the costs would need to be made to make increased recycling of critical (e.g. rare earths) and harder to recycle materials (e.g. mixed plastics) feasible, but who should make them was not decided. Lacking technical processes or knowledge was also argued as the reason for much missed value opportunities for not using all materials from the recycling process.

There were several conflicts identified. For example, between maximizing financial value for the producers and reuse, which, when increased, would possibly take some value away from producers. This was debated, however, as there is a potential financial value for the second-hand user (i.e. reduced purchase price). However, the participants agreed that the market for used washing machines in Sweden is rather non-existent and this issue concerns mostly other countries – again highlighting the complex value consideration and heterogeneity of consumers.

This range of values for consumers was also discussed to be specific to the products. It was suggested that a phone might have more emotional value to a consumer than a washing machine, but less than a car. It was generally agreed that consumers with emotional attachments to products would value repair and maintenance more. Indeed, literature has suggested that emotional attachment to products varies but is key for increased circularity [11].

There is also conflict of interests between stakeholders as to who should be responsible for the environmental value. The participants agreed that it does not necessarily match the economic value, thus someone has to pay for it and there was disagreement as to which stakeholder it should be.

4.1 Value opportunities

There were places where inefficiencies in the EPR system (e.g. different systems in each member state) also resulted in costs and employee time to understand and report in all these systems. Perhaps more coordination between member states could lower these costs and instead cover costs for more ambitious targets (i.e. environmental value).

The need for governments to have vision, determination, and control over, in addition to consideration for, the business actors was also discussed. Targets for materials and not waste categories was mentioned as one opportunity to capture more value from recycling. The currently captured value was sound waste management, which was not the case before the WEEE regulations was also mentioned, but other objectives remain elusive. This has been well-noted in evaluations of the WEEE Directive [12]–[14].

It was also noted that there were many opportunities to improve information provision and sharing with the EPR system. There could be more and better quality information about products given to recyclers, for instance. Also, the data quality of data provision to Eurostat could be improved, and data made more useful to stakeholders. This has been one of the endeavours of the ProSum project [15].

Collaboration between different stakeholders was discussed, for example with research on material recovery, thus creating greater value for recyclers, society and the environment. Cross-sectoral cooperation (e.g. industrial symbiosis) might also present opportunities for recycled material to be used by another industrial sector.

5 Potential going forward

There are times in using the tool where there was confusion between discussion of the product system (i.e. product life cycle) and the EPR system. In further researching improvements to the system, analysis would benefit from complementary visualisations of complex values in a system. To this end, the value mapping tool could be part of the stakeholder discussions in methodical approaches to conceptualising, measuring and capturing complex value, e.g. the CVORR method of mapping a product system in e.g. materials flow analysis and identification of relevant stakeholders and dimension of value - see [6].

The tool was also effective in identifying both key stakeholders and their role either in the EPR system or influencing the EPR system. Based on this, a modification of the tool with the main stakeholders agreed upon by the focus groups as relevant for the EPR context is shown in Figure 3. The stakeholders are much more than those explicitly mentioned in the WEEE Directive (stakeholders in blue) or even directly involved in the EPR system implementation (stakeholders in yellow). They also include upstream stakeholders (in orange) and stakeholders who are influencing or influenced by the system (in green). The tools makes visible the complexity of EPR systems in reality and challenges stakeholders to expand their own thinking about the policy.

The mapping tool was relevant for making synergies and trade-offs more visible to stakeholders. When trying to be specific about what values captured and by whom, it becomes clear that sometimes the value for one stakeholder is also a value for another stakeholder. Just as often, however, the value is not a value to other stakeholders (e.g. design for recycling is good for the recycler but may not have much value to the producer or consumer). It was noted by the group that the areas of shared value should be the first places to look for improvement.

While many of the issues raised by the tool have been noted in literature and other discussions for EPR, the tool's main strength was in facilitating discussions about where improvements are needed, what stakeholders are benefitted or adversely affected by those improvements, and which stakeholders should be responsible for leading those improvements.

Going forward, the tool will be further tested with policymakers in workshops discussing values in EPR systems. The tool can be seen as an initial step in identifying issue areas and types of values that can then inform further analysis and selection of appropriate metrics.

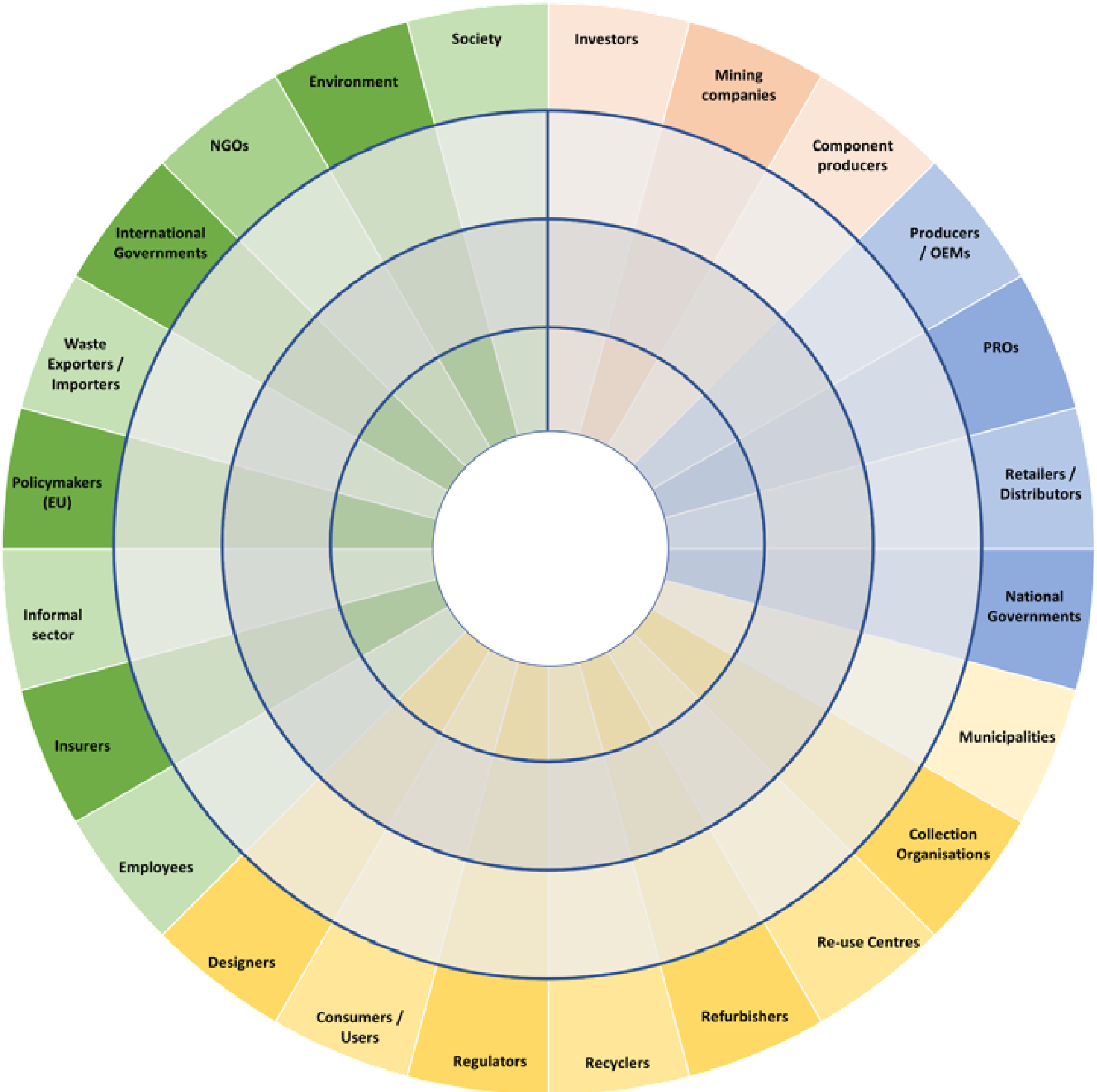

Figure 3 Modified value mapping tool for the EPR context

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D

SOCIETAL PERSPECTIVE AND COMPLIANCE

D.1

ASSESSMENT: LCA, NON-LCA AND BEYOND LCA

Modernizing a Life Cycle Eco-Impact Estimator for ICT Products

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Abstract

ICT (Information and Communications Technology) is essential to contemporary civilization, and like most any other technology, contributes to negative environmental impacts throughout its life cycle of manufacturing, use, and disposal. A key step to reduce impact is to be able to measure the impact. Life Cycle Assessment (LCA) is the well-recognized methodology to assess environmental impacts through a product's life. Carrying out an LCA for an ICT product, which is complex in parts types and materials composition, is usually done using large scale LCA software with expert resources. This is both expensive and time consuming, and in many cases a simpler approach can be employed, which can further enable adoption and environmental impact reduction action.

Presented in this paper is modernization of a simplified approach for estimating the environmental impact of ICT products. The established approach provided a means to more quickly and easily evaluate product concepts and optimize design trade-offs. It uses simplified techniques and algorithms for estimating Global Warming Potential (GWP) in terms of carbon dioxide equivalents. The approach is extensible to other environmental impact parameters as well.

Over the past decade the iNEMI industry consortium has worked on developing and improving an ICT eco-impact estimator based on this simplified approach. Work included developing a modular foundation and a viable tool. Its format progressed from a spreadsheet-based software tool to a database driven tool that was uploaded to a dedicated server within an academic institution.

LCIA data improvement within the ICT industry needs to parallel the technological advances that are rapidly evolving within this industry. Collaboration amongst industry and academic/research institutions is critical. An iNEMI project team recognized the need for updating the component categories, datasets and algorithms, and has completed a series of updates to the LCA eco-impact estimator. Attention was focused on the categories that have more significant eco-impact – bare printed wiring boards and integrated circuits. Data and algorithms were also correspondingly reviewed and updated for the other component categories such as mechanical parts, cable assemblies, and cooling components. The resulting modernization offers significant benefits in providing a combined database driven tool for enhanced use.

Keywords:
Information and communications technology, ICT, LCA, life cycle assessment, environmental impact assessment, eco-impact, global warming potential, greenhouse gas emissions, carbon footprint, electronics environmental impact measurement, LCA estimator

1 Introduction

ICT products are essential to modern society. They comprise a significant portion of the global economy, along with consuming large amounts of resources and energy during their manufacturing, use, and disposal, while contributing to environmental impact. Their inherently short life and increasing demand will worsen the scenario. Given the current climate change challenges, it is necessary for ICT manufacturers to reduce the impact.

In any successful approach to reducing impact there needs to be a means to measure it and a method to follow. Life Cycle Assessment (LCA) is the well-recognized methodology to assess environmental impacts through a product's life, from raw material extraction to end of life. Performing an LCA for ICT products is usually done using large scale LCA software with expert resources, which tends to be time consuming and expensive.

A simplified approach for estimating the environmental impact of ICT products has been developed and demonstrated by several ICT industry members through the International Electronics Manufacturing Initiative (iNEMI) organization [1]. The approach provides a means to more quickly and easily evaluate product concepts and to optimize design trade-offs. It uses simplified techniques and algorithms for estimating primarily Global Warming Potential (GWP) in terms of carbon dioxide equivalents.

Over the past decade iNEMI members endeavored to improve on the methodology and the data and formulae for estimating the environmental impact of ICT products. In support of existing LCA methodologies [2] and standards [3], there are several life cycle impact assessment (LCIA) systems, databases and tools available. They offer varying levels of information, global / regional data, industry processes, materials and flows, and mechanisms for quantifying product environmental impacts. A more simplified approach to quantifying the life cycle environmental impacts is based on the methodology framework that was developed by iNEMI [4]. This approach is intended to more easily estimate the eco-impact for different types of ICT products. It provides sufficient accuracy to meet the LCA practitioner's intended needs in assessing the important environmental impacts of a product over its life cycle stages.

2 Objective

The main project objective for iNEMI is to develop mechanisms for prioritizing and collecting relevant data from the supply chain. This is necessary to stay abreast of the rapid technological advancements within the ICT industry for the estimator to be useful to the LCA practitioner. This paper provides a most recent summary of the work being performed in an iNEMI project to further improve on the eco-impact estimator tool, and to maintain its purpose and usefulness in line with the contemporary innovation and progress of the ICT industry.

3 LCA Estimator Framework

The estimator is designed to be capable of evaluating a product consisting of individual equipment pieces. The product unit is attributed to a functional unit as defined by the product manufacturer. ICT products can be classified into distinct categories with common attributes that produce certain levels of environmental impact regarding their component makeup, assembly, usage, and design life. These classifications were then sorted into component categories comprised of similar materials and manufacturing processes. The components were then analyzed regarding their respective contributions to the environmental impacts associated with their manufacturing stages. Categorizing these ICT components offers a means of producing a concise list that can be analyzed for common environmental impacting attributes, which can then be rationalized and modeled to derive their level of impact within an LCA estimator tool.

The major component / subassembly categories for ICT products include printed wiring boards, integrated circuits, electro-mechanical assemblies such as cooling fans, metallic components, polymeric components, displays, cables, batteries, and specialized components such as optical and radio frequency devices, and disc drives. Global Warming Potential (GWP) – 100 years' time horizon is the single environmental impact currently assessed in the estimator, which is due to it being one of the most commonly evaluated environmental impact mid-point indicators.

Key parameters and metrics are then defined for assessing the environmental impact of the component categories. They represent the significant environmental impact contributors based on the analyzed datasets, available from within the ICT industry such as integrated circuits, and from other industry sectors such as bulk metals and plastics. An associated algorithm can be determined based on the LCIA data available for the key parameters of a given component category [5].

Detailed LCA analyses conducted on ICT products have shown that the component types providing the greatest contribution of environmental impact are the bare printed wiring boards and the large integrated circuits. Figure 1 shows the estimated eco-impact (GWP)

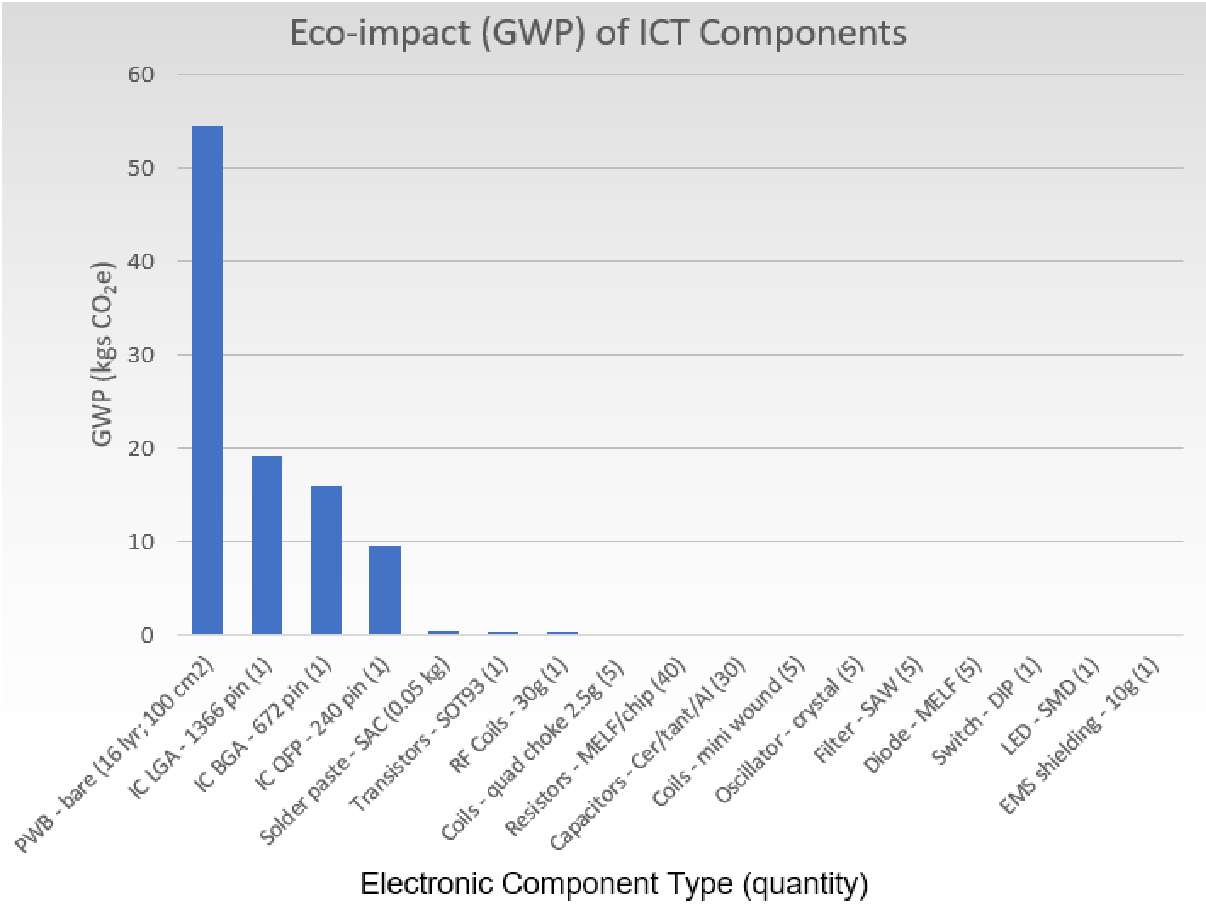

Figure 1. Eco-impact (GWP) for some ICT components within the manufacturing stage of the ICT product life cycle

for some ICT component types within the manufacturing stage of the ICT product life cycle.

There is a linear functional dependence between the GWP and the PWB unit area and its layer construct – see Figure 2. Similarly, as depicted in Figure 3, for the integrated circuits, the GWP has a linear relationship

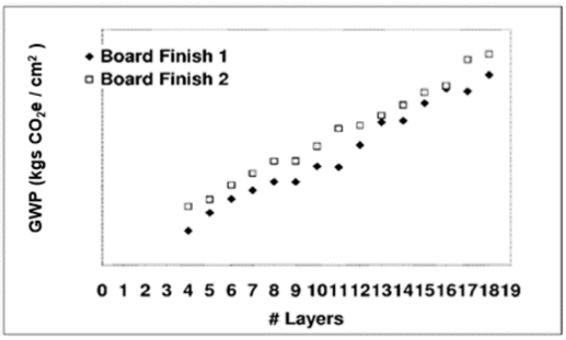

Figure 2. GWP per unit area of printed wiring board with increasing layers and two types of surface finishes

with the package type incorporating the silicon die and the number of leads (for example: pins, balls, I/O's).

A key goal in developing the algorithms is that the result should be within about 15% of the result obtained from more in-depth methods for over 90% of the circuit pack assemblies investigated [6].

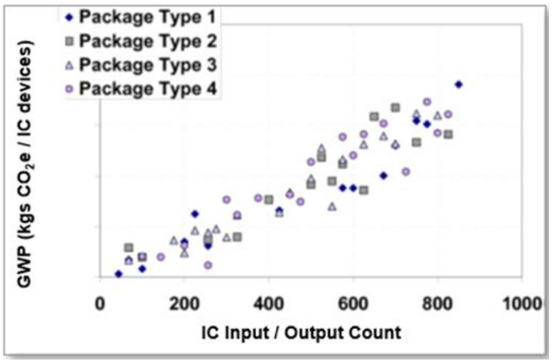

Figure 3. GWP per integrated circuit package type and with increasing input/output count

3.1 Modeling the LCA Stages

For the manufacturing stage, the LCA environmental impacts reflect the total of ICT component manufacturing, intermediate transport, final product assembly & testing, and finished product packaging. Assembly and testing include processes such as surface mounting technology, thru-hole mounting technology, mounting of ICT assets, surface treatment (e.g., painting or plating) for pre-manufactured cabinets, and testing of the ICT product. These parameters are treated as a collective summation of the total assembly and testing processes, and defined as an overall factor applied to the total impact of the product for the manufacturing LCA stage [7].

The finished product transport stage includes assessing environmental impact of the logistics – transport, distribution and installation of ICT products / assets. Parameters for this stage include location of final assembly (by region), location of product integration / warehousing (by region), location of final product installation (by region), transport mode (e.g. truck, rail, marine, air), and their associated environmental impact factors.

Use stage includes assessing environmental impact of the product's usage by parameters covering location of product usage (by region or country), power consumption per typical configuration and feature set, utilization rate per annum, and product operating life.

The end-of-life stage for ICT products are modeled by parameters that include the product's constituent materials – derived from the components' input for the manufacturing stage, and the final disposition of the product, e.g. remanufacturing, refurbishing, recycling, incineration / energy recovery, landfill.

4 LCA Estimator Improvement And Modernization

The initial environmental impact LCA estimator was developed using a spreadsheet format and made available to iNEMI members starting in 2012. Some industry members further developed the estimator and transferred it to a database format. This provided easier modularization of its component categories, a means to graphically view and configure a product's hierarchy, and easy storage / retrieval of configured products and subassemblies for further usage in other product configurations or by other designers.

In 2019, iNEMI transferred the LCA estimator in database format to Purdue University, and made it available for iNEMI members and academic researchers. This regime also provides data security and backup features. iNEMI's intention is to eventually make this openly available to the ICT industry and research institutions, thus offering a means to share the methodology and tool and provide data transparency. It also promotes easier future improvements in the estimator's methodology and in its component categories and environmental impact datasets.

As part of iNEMI's Phase 3 Project for the LCA estimator, undertaken in mid-2019, work was performed on improving the algorithms, datasets and methods for estimating environmental impact in areas including:

- Printed wiring boards (bare) – conventional and HDI type boards
- Integrated circuits - including flip chips, SOCs, stacked die arrays
- Cable assemblies, cooling systems, and mechanical parts made from metallic and polymeric materials (e.g. cabinets, chassis, racks)

4.1 Printed Wiring Board Improvements

Work in the PWBs mainly entailed inclusion of eco-impacts associated with contemporary PWB technologies, including conventional and high-density interface (HDI) PWB manufacture. The members found that the recent eco-impact assessments done by the HDPUG Group for printed wiring boards [8] - see Figure 4, of-

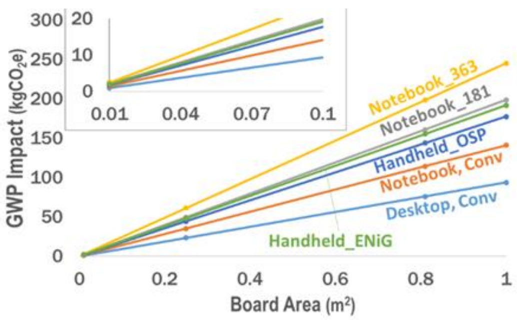

Figure 4. GWP Impact of PWBs as a function of board area for several representative designs

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fered contemporary eco-impact data for the ICT industry. This information was subsequently included in the eco-impact LCA estimator tool.

4.2 Integrated Circuit Improvements

Research on integrated circuit (IC) LCA eco-impacts have been completed over the past decade, and include publishings by Sarah Boyd et al [9], Anders Andrae et al [10][11], and Donald Kline, Jr. et al [12][13]. The work done by Kline, Jr. et al provides the energy consumption and GWP impact for a range of IC manufacturing technology nodes per square millimeter of silicon die production – see Figure 5. This data was then combined with the IC packaging eco-impacts as assessed and reported by Andrea et al, and subsequently integrated into the eco-impact LCA estimator tool.

estimation deems to be less accurate, an override feature is included in the estimator tool to allow the user to input a more precise count.

4.3 Mechanical Parts Materials Modernization

As newer materials have come into use over the past decade, the iNEMI project team researched into these materials and their associated GWP contribution for the eco-impact estimator. Here, input from iNEMI member companies provided GWP values for polymeric materials, including rigid plastics, elastomers, foams, and films. These values were compared to available data from Plastics*Europe*, Sphera GaBi LCA software, and ecoinvent, to provide a more contemporary and comprehensive eco-impact dataset.

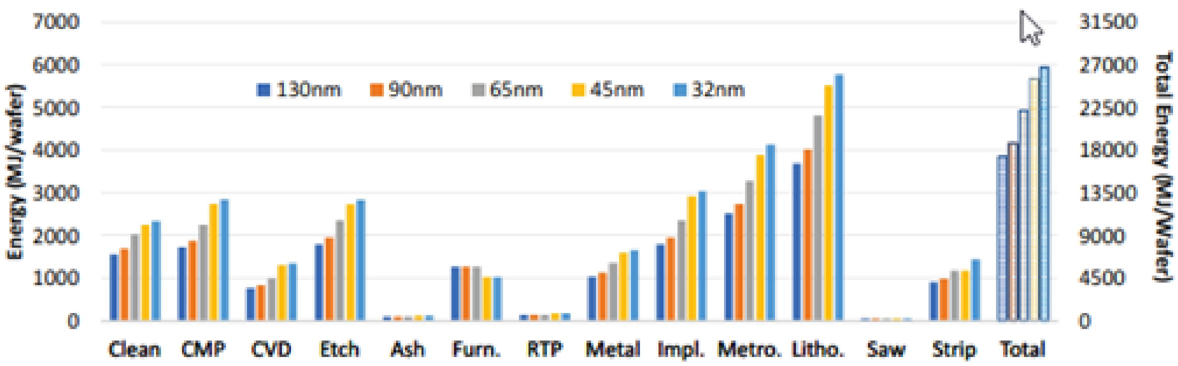

Figure 5. Energy consumption of IC manufacturing for different technology nodes

In addressing the passive components associated with the ICs, an algorithm is included that provides the GWP contribution from passive components relative to the PWB area – see Figure 6. In this regard, publishings from Bevin Etienne et al [14] provides analogies between PWB area and the total number of passive components (e.g. resistors, capacitors), such that an algorithm could account for these latter devices relative to the total PWB area. In the case where passive device

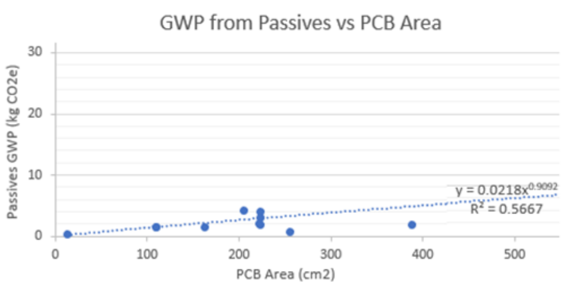

Figure 6. GWP estimation of passive devices relative to PWB area

Similar analysis and update was performed on the metallic materials and resulted in the inclusion of post-consumer recycled content mixes in the dataset.

5 LCA Estimator Database-driven Tool

The resulting updates and modernization efforts by the iNEMI team provides a robust tool that offers users quick analysis of an ICT product along with full transparency to its data sources and calculations. A view of the input/output screen for the PWB component module is shown in Figure 7. This modernization effort offers significant benefits in providing a combined database driven tool for enhanced use. A longer-term goal is to continue to evaluate newly available data for ICT

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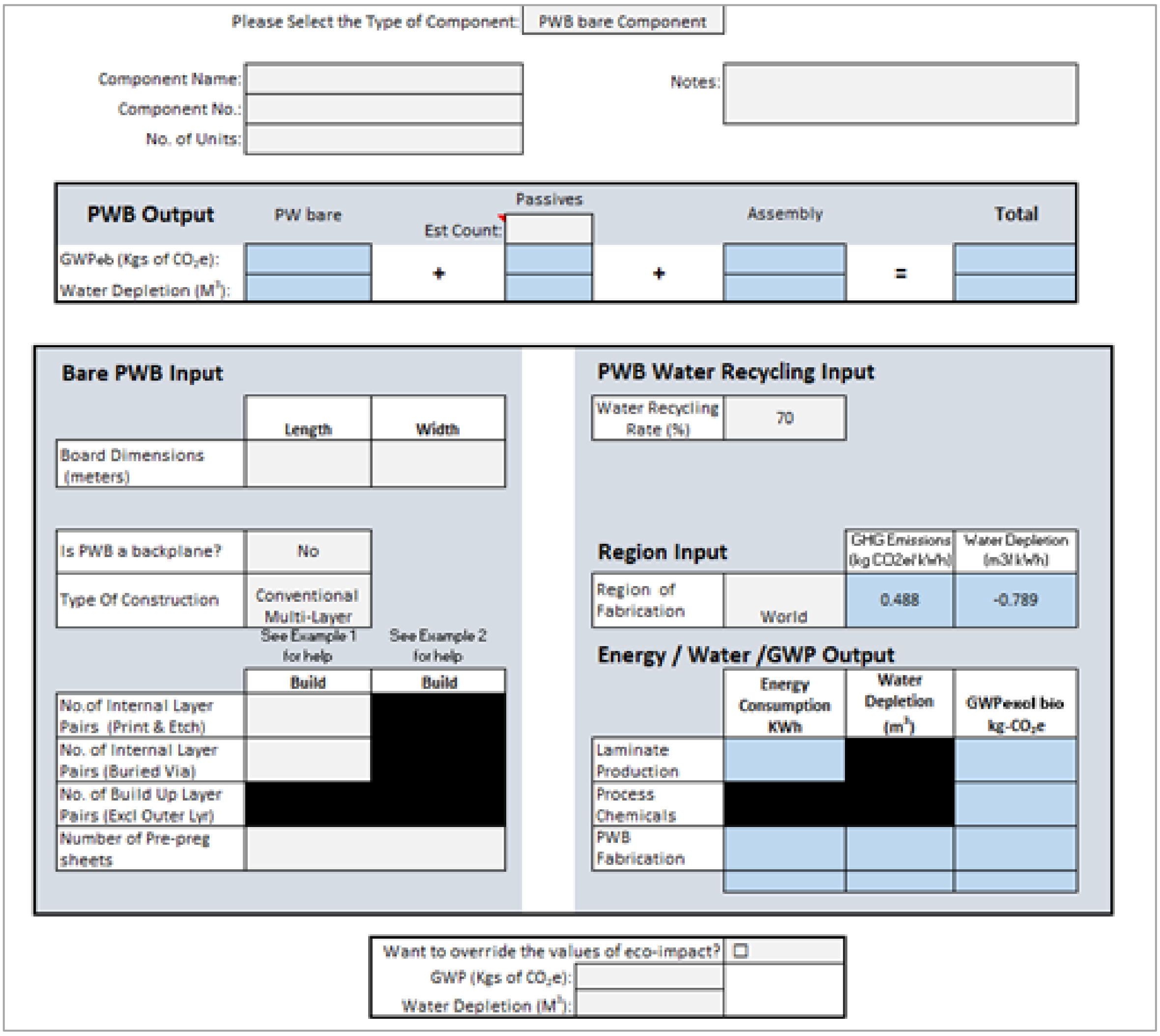

Figure 7. Input/output screen for the PWB component module of the iNEMI LCA Eco-impact Estimator Tool

components manufacturing techniques as they become available.

6 Summary

The iNEMI LCA eco-impact estimator offers a means for product designers and environmental specialists to more easily assess the GWP of ICT products over their full life cycle – manufacturing, transport, use, and end-of-life treatment.

In an effort by iNEMI members to improve the existing estimator, the members worked on collecting, assessing and integrating more contemporary information and data into the estimator. The resulting modernization of the tool and its information, data and resulting GWP eco-impact estimation will offer an enhanced means of measuring ICT product eco-impact that better parallels the technological advances that are rapidly evolving within this industry. By having this modernized tool available in database format via a hosting organization (Purdue University), it is hoped that the LCA estimator offers more open availability to its members and academic researchers. Additional eco-impact aspects, such as water usage, are relevant to the ICT industry, and may be included in the estimator tool as LCIA modeling for such eco-impact advances. Future endeavors may include opening the database formatted estimator to further ICT industry utilization as well as continued usability enhancements and dataset updates.

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Reaching Carbon Neutrality with Role-Based Access to LCA Information of materials, parts, and components

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Abstract

Brands have started to set ambitious carbon reduction targets, partly intending to become carbon neutral or even carbon negative e.g. by 2030. This leads to manufacturing companies in different sectors facing the demand for carbon transparency and evolving environmental standards, including their supply chains. However, sustainability data sharing and data management can be considered as one of the important bottle necks. The digital transformation of manufacturers offers environmental solutions, that are investigated through the InnoEnergy financed innovation project Live LCA. The starting point was to link a comprehensive Life Cycle Assessment (LCA) software with a new application for high-level access to parametrized calculation results. A flexible configuration environment enables experts to establish LCA models, that provide an adaptable interface for Non-LCA Experts from different departments with further analysis, e.g. monitoring Key Performance Indicators and share the information. Requirements towards software features are examined and refined by means of four different cases.

1 Introduction

Pure efficiency measures are no longer sufficient to achieve sustainability goals like Carbon Neutrality by 20xx, increase Circularity of all products to 80 - 90%, or remove toxic and hazardous substances from the overall portfolio. Companies must deal with evolving and more ambitious environmental standards; their customers want to see them setting and achieving environmental targets taking the supply chain into consideration. Getting a deeper insight into the interrelation of the entire product life cycle and assessing life cycles of organisations and policies becomes widespread. The European Commission identified LCA as the best available "framework for assessing the potential environmental impacts of products" and therefore created the European Platform on Life Cycle Assessment [1].

For selected product categories or materials in the EU, Life Cycle Assessment (LCA) may become mandatory through new legislation. For example, to significantly decrease greenhouse gas emissions in the EU the European Parliament recently suggested that "full life-cycle

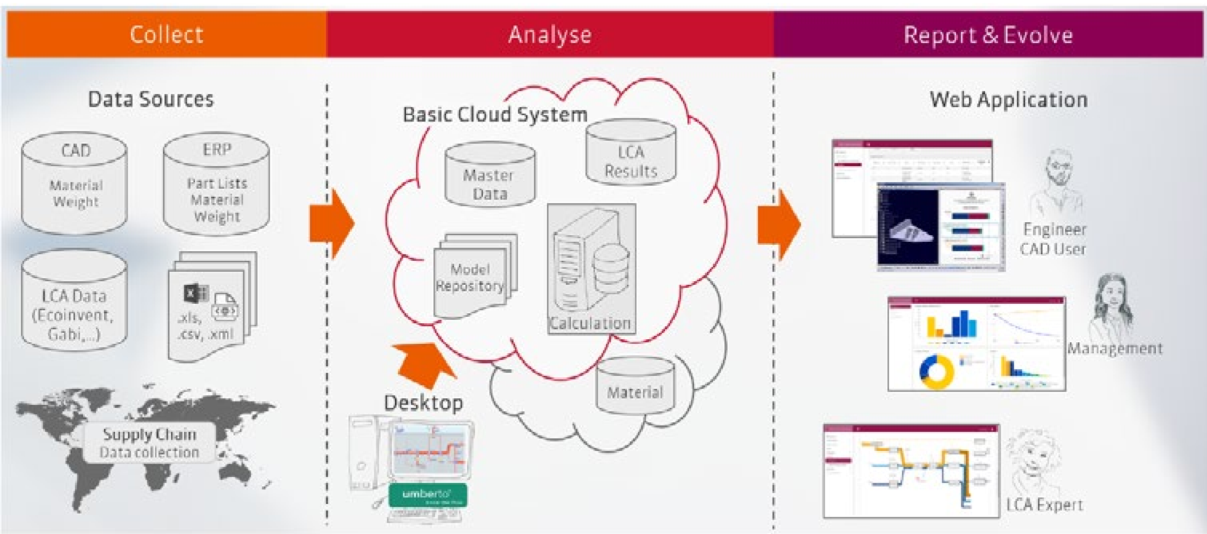

Figure 1: Overview on Live LCA

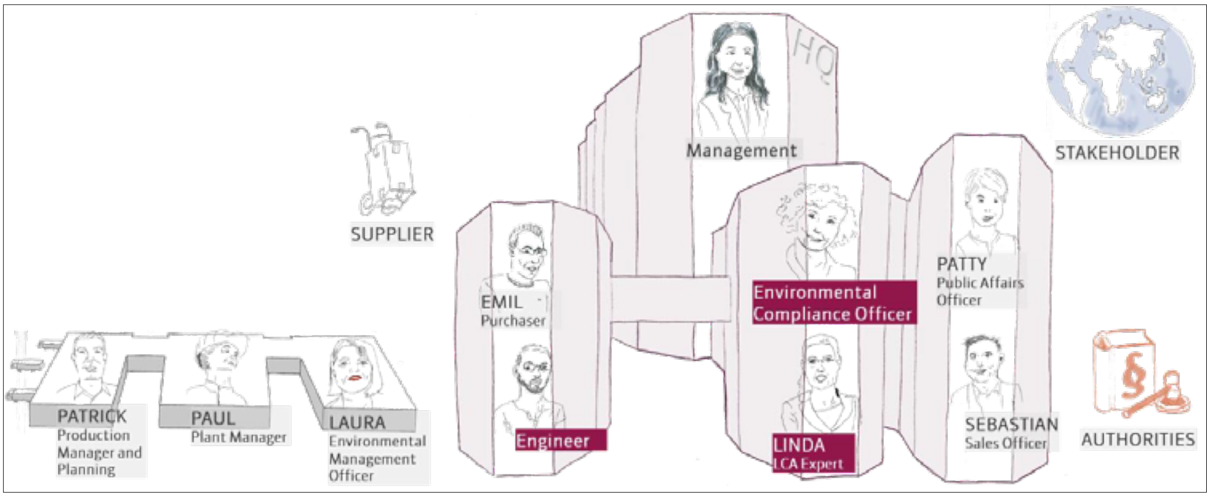

Figure 2: Identified (fictive) stereotype persons, their roles, and relations

of emissions from cars should be assessed at EU level" [2]. The Circular Economy Action Plan states, that the Product Environmental Footprint approach is further supported and even "mandatory requirements to increase the sustainability not only of goods, but also of services" are considered [3].

In parallel, manufacturers and their suppliers are about to start setting up the structures to handle their life cycle data management and to report the companies` sustainability performance on a regular basis.

However, sustainability data management is identified as a severe bottle neck. The first reason is, that such data is hard to access as it is highly dispersed in companies. Secondly, processing, and interpreting life cycle information for developing representative environmental impact assessments is a resource-intensive expert task. Typically, such LCAs require at least an effort of 1-2-person month - depending on the complexity of the product or/and the scenarios assessed, also much more.

The digital transformation of the manufacturing industry offers new opportunities to overcome these difficulties. The innovation project Live LCA leverages these potentials.

2 Live LCA

The project "Live LCA" aims to create a cloud-based Software-as-a-Service (SaaS) solution for semi-automized environmental impact evaluation used by many departments. Providing environmental information will become more transparent throughout the supply chain, and internal decisions (e.g. in product design) can be based not only on economic but also on environmental performance indicators. A fusion of the existing and newly adapted LCA software Umberto and a new Application for high-level access to the parameterized LCA models including their calculation results is the basic architecture. It is an InnoEnergy financed project conducted by the iPoint Group in cooperation with TU Brunswick and the industry partner Dormakaba (producer among others of electronic building access and data systems).

Figure 1 gives an overview on the operating principles of the software. At first, data is collected in a semi-automized way through an interface with ERP-systems, energy monitoring systems, production planning systems, material management systems etc. (Collect). Data of the supply chain is connected as well through a central data management, which is then managed in a cloud-based SaaS, including a browser application and an LCA calculation engine (Umberto). Versatile analysis options (methods based on ISO standards) help to view every aspect of the environmental performance of the company's products comprehensively (Analysis). After the LCA is conducted it is made available for the Non-experts of the company (Report&Evolve).

2.1 Industry Requirements towards a Sustainability Software

When examining the needs and pains of the customers by requirements management workshops with industry participants from the electronics, automotive and construction industries, hypotheses on the stereotype future user were verified. A better understanding was gained of the roles and organisational structures companies have in terms of achieving sustainability goals and managing environmental data. An overview on the developed roles in their departments is shown in Figure 2. Also, it was an aim to understand which data sources in companies need to relate to the SaaS. High level information such as department structures, as well as operational information, e.g. day-to-day data decisions and digital/analogue data sources were documented. As result, a generic overview of the departments and persons involved in the process was determined.

A clear demand was identified: Sustainability data needs to be accessible beyond a group of LCA experts. Different roles in a company have different requirements. All departments and roles have demands to operationalize the use of sustainability information in their business process. Data silos between departments need to be identified and replaced by data exchange and data sharing approaches.

2.2 Role-based access

Operational work with sustainability information in the respective departments is made possible with Non-LCA Expert user profiles. These profiles are curated by an admin, i.e. adapted to the role of the person in the company (design, management, sustainability, etc.). Every role can access an adaptable view on specific LCA results, including the necessary analysis options. On the one hand it covers comparing material options for one product, and on the other hand varying pre-defined LCA parameters. The access configured for Environmental Experts provides more profound insights into the underlying LCA, i.e. the Sankey mode of Umberto models, but does not include options for changing the underlying LCA model(s). In short: Experts establish highly flexible generic LCA models and all other custom roles benefit from accessing results appropriate for their specific use case.

2.3 Use Cases

Based on the requirements management, iPoint created four main Use Cases, including persons with specific pains and needs:

- Engineering
- Product Stewardship
- Packaging Design
- LCA Expert

After submiting them to potential users for evaluation, they were refined. The first use case is about a typical engineering department. In general, the engineering department, including the designer, is responsible for product construction decisions. The identified demand is that engineers want to use LCA data in an early stage of product design for specifically comparing the materials impact with each other or for other investigations that lead to design decisions. The Engineering users' vision is to integrate sustainability knowledge into CAD (or other construction design software). This

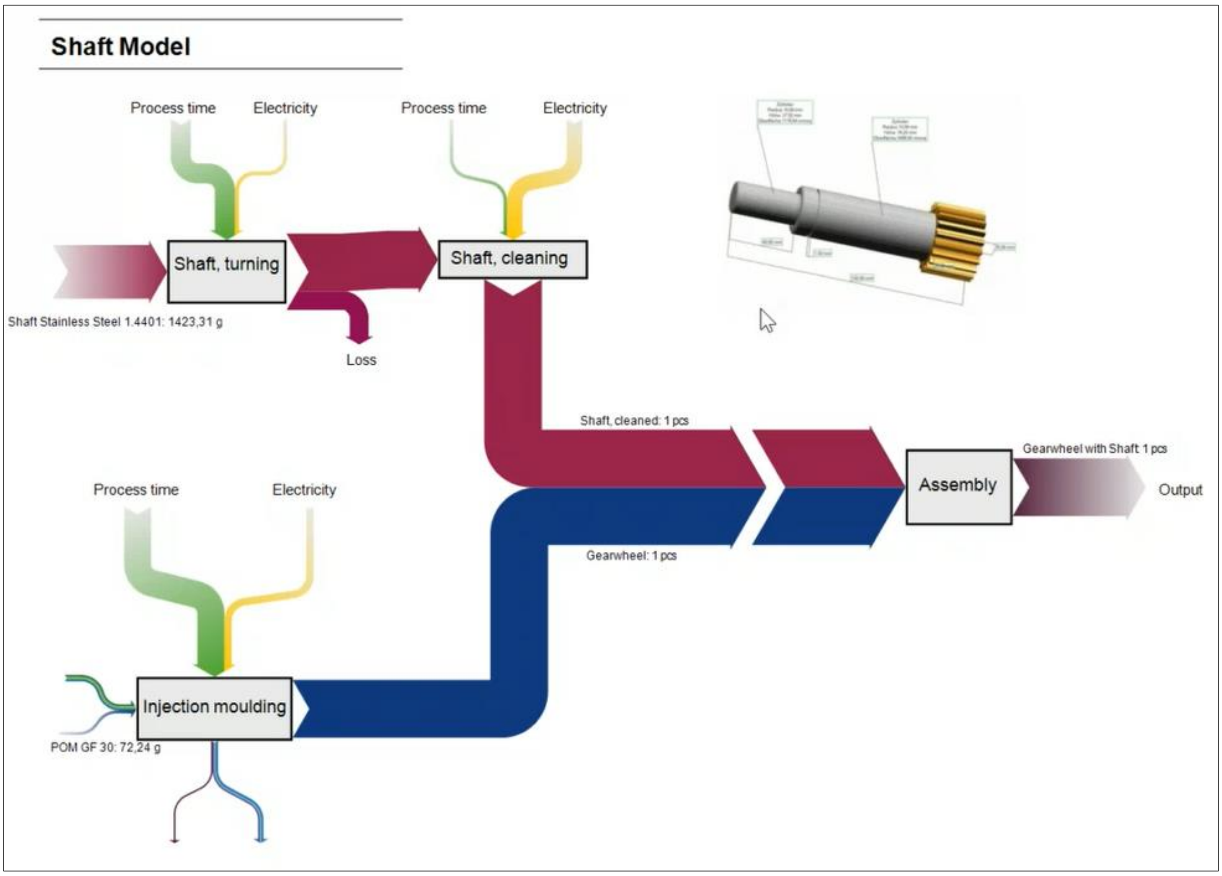

Figure 3: Example of an Umberto Model, facilitating an LCA: Shaft Model

requirement was refined in the way that designers shall not only decide for the most economic construction (based on experience) as also for the one with the lowest environmental impact. In Industrial Interest Group workshops, it was found that - to date - such data is highly dispersed in companies' analogue and digital systems. Therefore, there is a need gathering data in one Application.

Secondly, a Product Stewardship use case covers the requirements of a sustainability expert responsible for the environmental product performance. It is assumed that such a person needs a software to calculate e.g. carbon footprints for many different products. To minimize the efforts, this person is demanding semi-automated calculations of the Global Warming Potential. To use the data already available in the company, bills of material (BOMs) can be retrieved from the ERP and linked to LCA data. This procedure is based on a generic model that can be used for all products of one or a group of product categories. This allows results to be achieved based on existing data without specific modelling. Another need is the function to create product scenarios for versatile materials and compounds, creating comparisons, calculating common impact categories e.g. ozone layer depletion, land use etc. Visualisations like bar charts, showing a reference value in relation to the compared options, enable the prompt understanding. The results need to be archived to be available also after years.

A third use case focuses on sustainable packaging design. It is assumed that a user wants to upload a BOM, in which he/she can then change various properties of the individual BOM components and other parameters (e.g. used energy mix) online. Comparisons between materials or components should be possible; for a better understanding the results are visualized in various ways. When an LCA Expert has created a model with different parameters, users can access this LCA model using the web application and calculate different options by varying the parameters, e.g. shifting the energy demand upwards. Another need of the packaging use case is (as in other cases) to exchange results with colleagues from other departments. This is fulfilled by a shared memory to which all users have access.

Finally, the fourth use case is the prerequisite for the other cases. This Expert Use Case reflects the needs of an LCA Expert. The LCA Expert uses the desktop LCA software (Umberto) extensively to build parameterized models, with a pre-selection of the relevant impact categories. As an example, a shaft model is shown in Figure 3. The LCA Expert ensures both robustness of the model calculation as well as flexibility regarding parameter variations and scenario settings. Parameters are e.g. energy use of a specific production step; content of recycled material; transport. LCA models ready to import and directly analyse BOMs are supporting the examination in early design phases. An export option enables the transfer to the cloud application, facilitating the high-level analysis by the other roles. The LCA Expert is enabled to deliver his or her work to colleagues within the company.

These four cases show that Live LCA integrates a role-based approach, with profiles that can be adapted to the user's needs. Several other features aim to reduce the effort to select and examine data, calculate, and share sustainability information within a company. An example is the storage of product and component specific information in a central material and substance database. The advantage of managing data centrally is that even Life Cycle Information saved in other iPoint solutions can be used in the LCA-specific sustainability solution, and vice versa.

3 Outlook

Soon another feature will be added: the plant manager-adapted profile. This profile is based on a real case: the Horizon2020 project iCAREPLAST [4]. The aim of iCAREPLAST is to provide a cost and energy-efficient alternative to recycle and valorise yet non-recycled plastic waste in a pilot plant producing virgin-quality polymers that serve as raw materials for other industries. Near real-time computer algorithms will control and propose actions based on process information. The controller is as well combined with LCA information to suggest the process parameters resulting in the products with the lowest environmental impact of production. A plant manager will work with varying the parameter according to the LCA results that he/she can analyse in the software Live LCA.

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Leading a global supply chain to clean energy

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Abstract

In 2018, Apple reached its goal of generating or sourcing 100 percent renewable electricity for its global facilities. Apple achieved this in 44 countries around the world, with 83 percent of the renewable energy coming from Apple-created projects. Apple's work to address climate change also extends to its supply chain. Manufacturing makes up more than 70 percent of Apple's carbon footprint, and most of those emissions are from the electricity used to make the parts in Apple's products. Therefore, in 2015, the Supplier Clean Energy Program was established to transition suppliers to 100 percent renewable electricity for Apple production. As of June 2020, over 70 suppliers have committed to using 100 percent renewable electricity for Apple production. As of July 2020, the Supplier Clean Energy Program has obtained nearly 8 GW in renewable energy commitments. This momentum has led to Apple's most ambitious goal yet: the electricity used across its entire manufacturing supply chain—including material extraction, component manufacturing, and final product assembly will be from 100 percent renewable sources by 2030. This transition is part of Apple's broader goal to be carbon neutral across its entire footprint by 2030. Apple supports its suppliers' transition to clean energy by working with them to advocate for policy change in key markets, by connecting suppliers with high-quality clean energy projects and developers, and by educating them on how they can take full advantage of the benefits of clean energy. Progress made by Apple and its supply chain, including innovative solutions created to overcome hurdles is shared here to promote corporate action that will help decarbonize electricity grids around the world.

1 Introduction

According to CDP, "The private sector has huge potential to drive environmental action. However, with supply chain emissions on average 5.5 times greater than operational emissions, it's clear that to take meaningful action, companies must leverage their purchasing power, and collaborate with their supply chains" [1]. In the urgent years ahead, companies will need to think differently and act urgently. Apple is committed to doing its part and creating pathways others in its industry and beyond can follow and join.

Manufacturing makes up more than 70 percent of Apple's carbon footprint. And most of those emissions are from the electricity used to make the parts in Apple's products. So, in 2015, Apple established the Supplier Clean Energy Program to transition suppliers to 100 percent renewable electricity for Apple production and lay the groundwork for an even more ambitious initiative.

2 Committing to carbon neutrality

In July 2020, Apple committed to achieving carbon neutrality by 2030. This commitment covers Apple's entire end-to-end footprint and Scope 3 emissions, which includes the shipping that moves its products around the world, and the energy used to power its customers' devices. As part of this plan to reach carbon neutrality, Apple committed to transition the electricity used across its entire manufacturing supply chain—including material extraction, component manufacturing, and final product assembly—to 100 percent renewable sources by 2030.

This commitment builds upon years of work focused on reducing its environmental footprint. Apple is already carbon neutral for its corporate emissions, including corporate travel - resulting from its use of 100 percent renewable electricity for its facilities and investing in high quality projects that protect and restore forests, wetlands and grasslands. In fiscal year 2019, Apple reduced its comprehensive carbon footprint for the fourth consecutive year—down 35 percent compared to 2015, when Apple's carbon

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emissions peaked, even as net revenue increased by 11 percent over that same period (see figure 1).

3 Renewable energy history

Apple began its work driving its scope 2 emissions from electricity to zero in 2011. Today, Apple occupies over a thousand offices, retail stores, data centers, and distribution centers across 44 countries—all powered by 100 percent renewable electricity since January 2018.

Apple strives to select projects with the greatest potential for impact and projects with a clear carbon, ecological, and social benefit. In most cases, wind and solar solutions meet its criteria. For some energy projects, such as biomass and hydroelectric generation, Apple reviews the individual project to ensure that it delivers positive impact while minimizing harm. Apple also upholds stringent accountability standards to ensure that all clean energy can be verified.

As of January 2020, 83 percent of the renewable energy Apple sources comes from projects that Apple created, for a total of 1.2 gigawatts operational and another 350 megawatts under contract. And the company aims to cover its entire electricity load with Apple-created projects.

4 A focus on supply chain

Apple uses a life cycle–based approach to measuring its comprehensive carbon footprint, which is verified annually by a third party. Apple utilizes as much Apple-specific data as possible, falling back on industry averages where original data isn't available. Emissions from manufacturing make up about three quarters of Apple's overall carbon footprint (see Figure 2). And around 70 percent of those emissions are from the electricity used to make its products. It was clear from the analysis that Apple would need to extend beyond its corporate renewable energy work.

In October 2015, Apple launched the Supplier Clean Energy Program to advance clean energy through its manufacturing supply chain. Upon launch, executive leadership including Apple's CEO, Tim Cook, and VP of Environment, Policy and Social Initiatives, Lisa Jackson (former Administrator of the US Environmental Protection Agency), publicly supported the program and committed to bringing 4 GWs of renewable energy online by 2020. Apple also launched the Supplier Energy Efficiency Program in 2015, which aims to educate suppliers, identify opportunities to reduce energy use, and create programs to help suppliers take advantage of those identified opportunities. In the launch of both programs, Apple prioritized supporting suppliers in becoming more energy efficient, and moving them to clean, renewable energy sources.

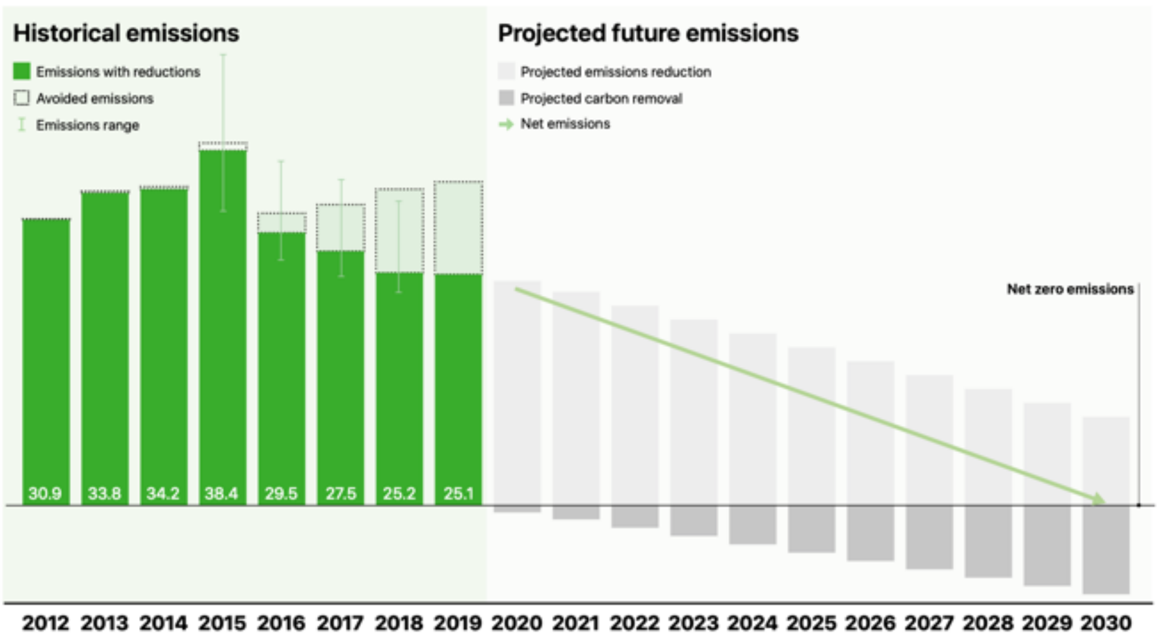

Figure 1: Apple's Carbon Footprint 2012-2020

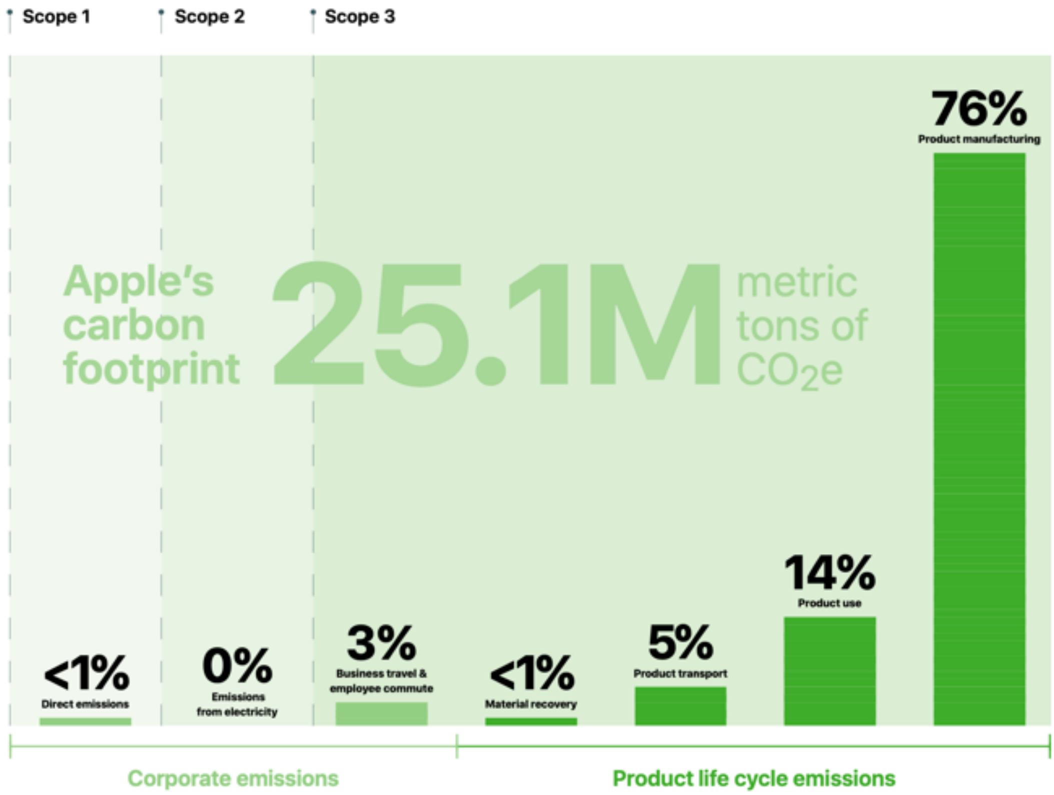

Figure 2: Apple's 2019 Carbon Footprint

The WRI Greenhouse Gas Protocol defines the methodology for calculating carbon emissions.

5 Supplier clean energy program methods

The Supplier Clean Energy Program is integral to reducing Apple's overall emissions. Apple has publicly stated its commitment to carbon neutrality means working with partners who share in its mission.

To track progress, Apple suppliers report annually on its greenhouse gas emissions, which includes its electricity use for Apple production and sources of electricity. When a supplier joins Apple's Supplier Clean Energy Program, the supplier is making a commitment to power 100 percent of its Apple-related electricity load with renewable energy that meets Apple's rigorous specifications. Through the Supplier Clean Energy Program, Apple has helped dozens of Apple suppliers transition to using clean energy. This gives suppliers a powerful new competitive advantage that will set them apart in the years ahead and enables a broader transition to renewable energy—creating a meaningful impact far broader than Apple's own carbon footprint.

5.1 Demonstrating leadership in suppliers' markets

The transition to renewable energy can require complicated deal structures across many regions, each with diverse market designs and regulatory requirements.

Apple seeks to break down that complexity for its suppliers by sharing learnings from its own investments in renewable energy—often in challenging markets. For example, the first step that Apple took upon launch of the program was to help develop nearly 500 megawatts of solar and wind projects in China and Japan to address upstream emissions in its supply chain. These direct investments provided important learnings about both markets that Apple was able to share with its suppliers.

5.2 Connecting suppliers to high-quality projects

Apple developed new tools for its suppliers to help accomplish its renewable energy goals. Apple also connects suppliers with opportunities to buy renewable energy directly from project developers and utilities as those models emerge around the globe.

Access to capital often presents a significant barrier to suppliers seeking to implement the energy efficiency improvements identified in energy audits. In 2019, Apple collaborated with the U.S.-China Green Fund to accelerate engagement with the manufacturing sector through the creation of a special fund to initiate the investment of $100 million in supplier projects.

The U.S.-China Green Fund employs an innovative approach that provides both solution design and up-front capital investment for efficiency upgrade solutions. As savings are realized, the investment is recouped. This reduces the investment barrier for suppliers, while allowing them to realize energy savings achieved through upgraded equipment and management systems.

In many markets where Apple operates, companies have limited options to access cost-effective clean energy. To break down that barrier, Apple created a first-of-its-kind investment fund in China, the China Clean Energy Fund, which enables Apple and its suppliers to invest in clean energy projects totaling more than 1 gigawatt of renewable energy in China. The fund, which will include nearly $300 million from 10 initial suppliers and Apple, will invest in and develop clean energy projects totaling more than 1 gigawatt of renewable electricity in China and will enable suppliers to meet its renewable electricity commitments.

By virtue of its size and scale, the China Clean Energy Fund gives its participants the advantage of greater purchasing power and the ability to attain more attractive and diverse clean energy solutions. The China Clean Energy Fund will be managed through a third party, DWS Group, which specializes in sustainable investments and will also invest in the fund.

In September 2019, the China Clean Energy Fund announced its first renewable energy investments: two 48-megawatt wind farms in Hunan province and a 38-megawatt wind farm in Hubei province. These massive wind turbines will help to displace polluting fossil fuels, helping to clean the air, and provide a timely solution for suppliers seeking to cut emissions and fight climate change.

The wind farms in Hunan and Hubei provinces also support their local economies and governments, helping each province reach mandated renewable energy goals. In Dao County, which is classified a state poverty county, the revenues from the construction and running of Concord Jing Tang and Concord Shen Zhang Tang farms also provide important sources of local income.

The China Clean Energy Fund offers a timely solution for suppliers seeking to act now and make a material contribution to the climate crisis. However, the need for such a fund underscores the importance of strong climate policies that enable a diverse set of cost-effective solutions for anyone to choose from, like direct renewable energy procurement.

5.3 Building clean energy champions

Apple leverages its own experience and brings in world-leading experts to help its supplier partners plot their transitions to renewable energy. In 2017, Apple developed the Clean Energy Portal, an online platform which offers training and tools to help suppliers identify commercially viable renewable energy solutions in regions around the world. Portal content includes policy guidance and financial analysis tools, intended to make adoption of clean energy in key markets even easier. As of 2019, over 100 suppliers had registered for the site.

Building on the success of the Supplier Clean Energy Portal, in 2019, Apple hosted its first in-person training for over 30 suppliers in China. The intensive, two-day training equipped suppliers with the market insights, policy analysis, and tools needed to drive renewable energy solutions—within Apple's supply chain and beyond.

5.4 Advocating for strong policy

Apple has spoken clearly and unambiguously across different forums, in public statements and closed-door discussions, and through its actions. Whether making known its support for the United States upholding its obligations under the 2015 Paris Agreement or backing a price on carbon, Apple is pursuing strong policies that promote decarbonizing our economy. And in November 2019, Apple issued about USD$2.2 billion in green bonds dedicated to meeting its 2030 climate goal. Apple remains the largest corporate issuer of green bonds, underscoring its strong commitment to the environment.

Apple also lent its voice to make an immediate impact on policy. In the United States, Apple submitted comments urging the Federal Energy Regulatory Commission not to finalize a rule that would subsidize fossil fuels, which would limit the ability of renewables to compete in the electricity market.

Suppliers often face regulatory barriers to cost-effective renewable energy options. Clean energy technology offers tremendous benefits to companies, electricity grids, and countries. When policymakers fully value these benefits, clean energy becomes more cost competitive than fossil fuel energy.

Apple actively supports policies that create cost-effective renewable energy markets and works closely with suppliers and other climate-leading companies to engage local, regional and national governments. This encourages the development of country-specific policies that support scalable renewable energy solutions, with impact far beyond Apple's supply chain.

In Korea and Vietnam, Apple engaged with policymakers to advocate for energy market reform, including allowing businesses to purchase power directly from renewable power plants. Apple has held roundtables with companies and NGOs to identify possible solutions to some of the challenges for creating renewable energy projects in Korea, Singapore, and Taiwan. And Apple has undertaken similar efforts in Japan, where it joined other companies to formally encourage the Japanese government to promote corporate renewable energy use.

6 Supplier clean energy program progress

Apple has made strong progress toward its initial goal to bring online 4 gigawatts of new clean energy by 2020 (See Figure 3).

As of July 2020, 71 manufacturing partners in 17 countries have committed to 100 percent renewable energy for Apple production. Apple itself has invested directly in renewable energy projects to cover a portion of upstream emissions. The Supplier Clean Energy Program now has 7.8 gigawatts of clean energy commitments. Once completed, these commitments will avoid over 14.3 million metric tons of CO2e annually—the equivalent of taking over 3 million cars off the road each year.

Apple and its suppliers are implementing clean energy solutions using a variety of contracting mechanisms—with renewable power purchases and direct project investments representing 55 and 42 percent, respectively, of all solutions identified or implemented to date (See Figure 4).

7 Conclusion

Apple envisions a world where renewable energy is cost-effective, reliable, and widely available to all. The Supplier Clean Energy Program is helping to meet Apple's 2030 carbon neutrality goal by reducing product-related carbon emissions, creating a more resilient supply chain, and contributing to healthier communities—while also paving the way for others to follow.

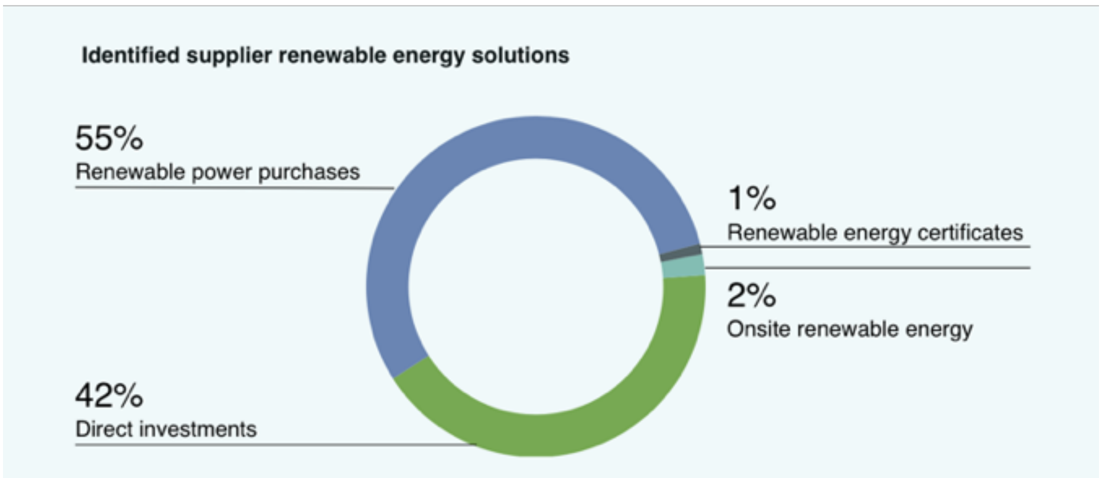

Figure 3: Supply chain clean energy progress

The data above reflects only those projects that meet Apple's strict standards and include only clean energy generated or sourced since Apple's engagement. Operational data is based on Apple's annual supplier energy survey for fiscal year 2019. Commitments are current as of April 2020.

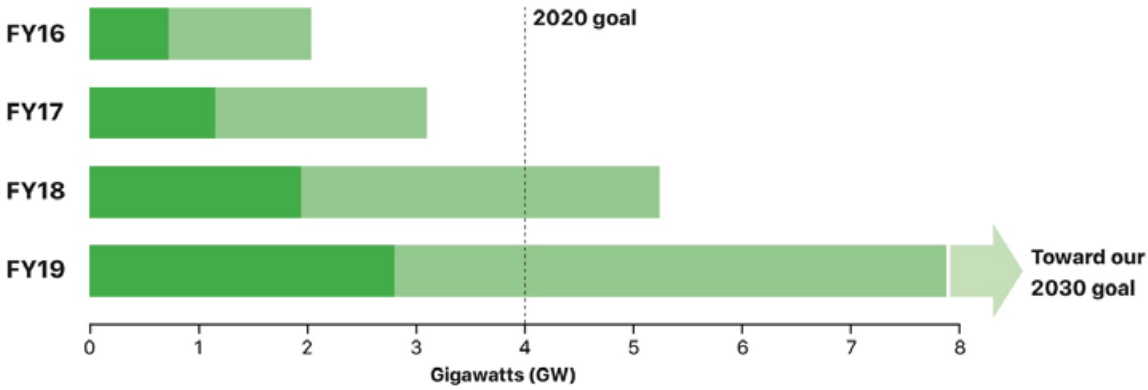

Figure 4: Identified supplier renewable energy solutions

Apple and its suppliers are implementing clean energy solutions using a variety of contracting mechanisms – with renewable power purchases and direct project investments representing 55 and 42 percent, respectively, of all solutions identified or implemented to date.

8 Literature

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Creating win-win-situations for data exchange – how to handle the trade-off between data security and benefits from artificial intelligence approaches

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Abstract

Many enterprises currently see big opportunities in applying or providing digital services. Regularly, effective solutions require a sound data basis, sometimes from different enterprises. For example, sharing of free capacities in production involves reliable data regarding the actual free capacities. Usually at least parts of the provided data are sensitive, since it enables conclusions on information that is interesting for competitors but also for customers or suppliers when it comes to contractual negotiations. To avoid that opportunities for digital services are rejected prematurely because of concerns regarding data security it has to be transparent for the enterprises why particular data is required, how the data is processed and what is done with the obtained results. The objective of this paper is to present an approach that supports an effort/risk-benefit-analysis regarding the provision of data and data access and enable corresponding conscious decisions and supporting business models.

1 Opportunities for digital services

Digital transformation is a topic that caught a lot of attention in the last years [1], [2]. Enterprises expect great opportunities related to it, in particular new revenues and lower costs. In many cases the new revenues should come from new digital services. This is also an approach of producers of physical products. They offer these services in combination with their physical products as a Product Service System (PSS). But there are also many enterprises that act as pure service providers.

Special types of services are based on Artificial Intelligence (AI). The Cambridge Dictionary [https://dictionary.cambridge.org] gives following definition: "*The use of computer programs that have some of the qualities of the human mind, such as the ability to understand language, recognize pictures, and learn from experience*".

The number of applications for AI is growing [3]. Well established applications are for example [4]:

- Optical detection, e.g. recognition of biometric data for authentication.
- Speech recognition / Natural language processing, e.g. to control smartphone functions.
- Data analysis / data mining, e.g. identification of anomalies for predictive maintenance.
- Chat bots, e.g. on customers support platforms.

In particular consumers are sometimes enthusiastic about the new opportunities. They make use of speech recognition in their cars, let their iris be scanned to unlock their smartphone and use e.g. Amazon's Alexa to control their entertainment devices at home and order things.

Enterprise in business also recognise the great opportunities related to AI. According to a study of McKinsey [2] the global market for services, software, and hardware based on AI could grow up to 15 to 25% each year and reach US$ 130 billion till 2025.

Digital transformation and the application of AI can provide various benefits. The following list shows a summary of typical benefits that can be found in a similar way in different publications able [5]:

- Improved efficiency of processes, e.g. through a more effective automation, a better adaptation to recognised surrounding conditions, reduction of traveling through online solution or route optimisation.
- Flexibility due to highly adaptable/self-adaptable processes, e.g. for more customer orientation with customised products.
- Acceleration of processes based on automation and on decisions or decision support through AI, e.g. faster validation/verification of documents.

- Better insights to systems like machines, equipment and plants, e.g. to save energy and resources or to enable a more effective maintenance.
- Comfort and Convenience in particular when it comes to communication with or the control of a digital system, e.g. natural language processing or optical recognition of face, fingerprints, iris or gestures.

However, many enterprises also recognise the corresponding challenges, in particular when it comes to the provision of data.

Generally, digital services require data from the customer of the service. This can be a very limited input, e.g. the considered location for a weather forecast and the IP-address of the customer, so that the forecast can be transmitted. But it can also be a continuous provision of larger amounts of data, e.g. for telematic solutions in cars. In particular most AI solutions based an artificial neuronal network require a huge amount of data to be trained (see e.g. [1]).

The transmitted data has a value. This becomes obvious in the fact that several service providers do not charge their customers for some of their services, e.g. a search query on Google does not cost money. In most of these cases the "payment" is the data transmitted by the customers that is then used for advertisement [6].

Some consumers are very open to provide their data or they act at least very open. Other consumers and most enterprises are more critical when it comes to the provision of data to external partners. Research on this topic shows that trust, transparency and security are important aspects to ensure acceptance as a basis for economic success of such digital services [6], [7].

Therefore, there is a general need for structured trade-off between the benefits provided by the digital services and the efforts and potential risks of data provision. Research offers several examples of benefits of AI and other digital services as well as corresponding business models. There is also some work done on data classification and security. However, there is still a lack of methods to do the described effort-benefit-analysis.

The objective of this paper is to contribute to fill this gap. The considerations are based on literature research and the work in the research project LongLife that is aiming at the prognosis of the remaining service life of technical components and corresponding business models to improve sustainability and avoid waste of resources.

2 Sensitivity of sharing data

When an enterprise considers the consequences of improper handling of data it can ask following questions:

1. What happens if the data falls into the hands of unauthorised persons or organisations?
2. What happens if there are unauthorised manipulations of the data?
3. What happens if the data is no longer accessible for the enterprise, e.g. because the storage medium gets damaged and there was no back-up yet?

Since this paper considers the potential provision of data to partners it will focus on the first question. Potential answers to that questions are:

- Loss of competitiveness by providing unwanted insights to competitors.
  - Disclosure of sensitive technical product know-how.
  - Disclosure of sensitive process-know how.
- Loss of negotiation power by providing unwanted insights to customers and suppliers but also by competitors that fight for the same customer.
  - Disclosure of sensitive economic parameters like cost structures, capacity utilisation rate etc.
- Breach of contractual obligations.
  - E.g. violation of non-disclosure agreements.
- Violation of laws, executive orders, or other compulsory regulations [8].
  - E.g. regulation regarding the protection of individual-related data.
- Damaging the image/integrity of the enterprise.
  - Insights to certain internal affairs/issues could damage the reputation from the viewpoint of externals.
- Distress or embarrassment to externals.
  - E.g. if externals got the impression that they were rated unfavourable or unfair.
  - Insights to certain affairs/issues of these external that could damage their reputation.
- Mislead externals to wrong actions and decisions.
  - In particular if the enterprise could be held liable for caused damage.

It is important to note that these effects do not necessarily have to be caused directly by the data. It could also happen that the combination of data that is not sensitive for itself enables conclusions regarding other sensible information.

A classification of data according to its sensitivity depends on how strong these negative effects are and on how likely they are. Examples for classification schemes can be obtained from the public sector, where this was issue already before electronic data handling. Following structure can be derived for the data provision related to digital service from those examples [9].

- Public/unclassified.
  This data can be provided to anyone internal and external without negative effects for the enterprise.
- Restricted.
  This data should just be provided internally or to reliable partner for common purposes/processes, since disclosure to unauthorised person or organisations could be disadvantageous to the enterprise or its partners.
- Confidential.
  The data must only be provided to specially authorised persons from the enterprise or its partners since unauthorised disclosure could cause significant harm.

Established methods to reduce the sensitivity of data are anonymisation and pseudonymisation [10]. Both methods lead to a de-identification of data. For anonymisation the relation (e.g. the ID or the name) of the particular data subject/object is deleted and cannot be restored afterwards. If it is necessary to remain the information that some data belongs to the same data subject/object pseudonymisation is the appropriate method. In the case the identifier is not deleted but replaced by replaced with artificial identifiers or pseudonyms. A further approach is Differential Privacy [11] that should ensure that sensitive information in a database can be used for analysis without exposing the original data.

The described aspects of potentials risks and the options for countermeasure provide a structure to assess potential negative effects that then have to be multiplied with the likelihood of their occurrence.

3 Assessing the effort-benefit-relation of data provision

Enterprises that consider the effort-benefit-relation of providing data for digital services can do that from two perspectives:

- Is the enterprise itself willing to provide data to external partners?
- Can the enterprise's customers be convinced to provide data for the service?

Although these perspectives should not be mixed up, the steps for the suggested effort-benefit-analysis are generally the same. An overview of the corresponding process is given in Figure 2.

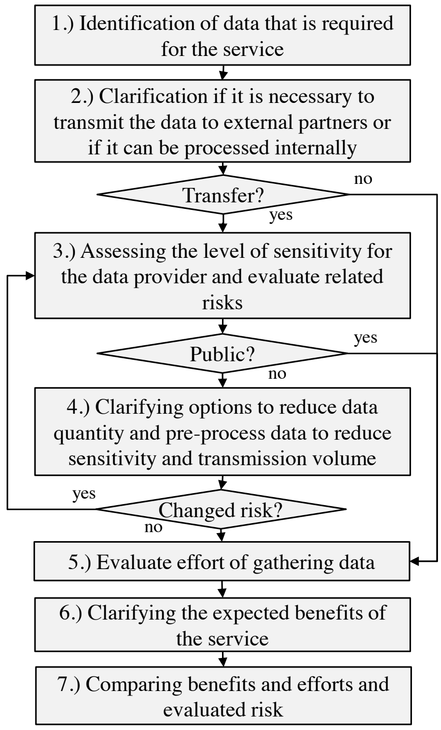

Figure 1: Process of effort-benefit-analysis

The identification of required data (1) is a technical task. It has to be analysed how the input required for the planned or existing service can be provided by the enterprise from which data-sources. In particular services that comprise pattern recognition usually require a broad and large data basis. The same applies when prognosis models have to be generated. However, to work with the ready models requires usually significantly less data.

In a second step (2) it has to be clarified where the data is processed. If it is possible that the enterprise is doing it within its own systems and it is decided to do so, then there is no need to provide data to external partners.

In this place it has also be considered how the data will be gathered and where it will be stored (see Figure 2). If the enterprise does it on its own it has full control of the data. If the gathering is done by the service provider these options for control will be limited. This is in particular relevant if the data gathering is done without the explicit consent of the enterprise, e.g. if components of a machine are equipped with data loggers by default. There are also different options for storing the data: Internally, on the device, or on databases of the service provider. If the data is stored on external databases to which the enterprise has no access this reduces the transparency for the enterprise.

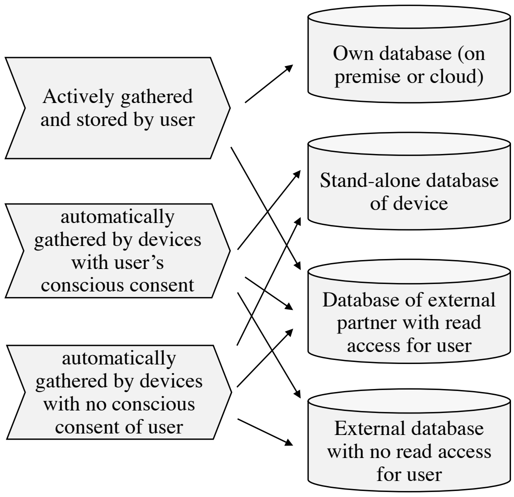

Figure 2: Process of effort-benefit-analysis

An example for low impact on the data can be found in the telematic solutions of modern cars. The car communicates permanently with the system of the producer without transparency or control. That's why one lawyer has chosen to keep his old car for meetings where he does not want to be localised.

The assessment of the sensitivity (3) of the data for the data provider (the enterprise or the potential customer) can be done according to the questions given above in paragraph 2. The actual risk is the result of the potential effects and the likelihood of their occurrence.

In the subsequent step (4) it is analysed if and how the data can be processed to reduce the quantity and the sensitivity of the transmitted data. Potential methods are anonymisation and pseudonymisation that were described above. This can be applied to generally all fields of the dataset. If, for example, it should not be recognisable which work shift is affected, the time stamps can be deleted or transposed.

Another approach to reduce the amount of data and to limit the insights that enable conclusion regarding the actual situation, e.g. the actual order volume or capacity utilisation rate, is to gather data not continuously but only for a certain period of time.

These measures could/should have an impact on the risks assessed before in step (3). Therefore, it could be necessary to adapt these assessments.

The effort of gathering and handling of data (5) depends strongly on the degree of automation and on the possibility to use data that is already available. If very huge amounts of data have to be handled the effort for transmission and storage of data could become significant. To obtain an accurate evaluation it is important to differentiate between data gathering that is needed to develop the service and gathering for its operational application. The first one has to be regarded as an investment with a corresponding rate of depreciation. The second one is regarded as operational expenditures.

A sound description and assessment of potential benefits of the service (6) is an essential task that also provide the basis for the later business models. It has to be clarified what added value is provided to which customers/stakeholders and how the benefit is perceived by them ("would they be willing to pay for it?"). It is important to note that there could be different stakeholders on the side of the customer, e.g. the production manager, the machine operator and the internal technical service in enterprise that should apply the service offered for a machine. The objective is to obtain quantified benefits, if necessary, based on assumptions and estimations.

The final step (7) is the comparison between effort, risks and benefits. In most cases it is not possible to do an exact calculation (quantified benefits minus quantified effort and effects emerging from risks). So, comparison has to be done in a qualitative way. To do so, the quantified benefits are placed on one side of the table as illustrated in Figure 4. On the other side all required data-types are listed and for each data-type the expected gathering effort and potential effects emerging from risks are outlined. Then decision makers have to discuss and evaluate the overall relation and decide if the service is assessed as favourable, ambivalent or unfavourable. In this way does not automatically produce a result but helps to structure the considerations and to ensure that the relevant issues are covered.

4 Business Models to support data provision

The basic motivation for an enterprise to provide data to external partners is an expected added value [5], [6]. Some typical types of added values were given above. For enterprises the added value is often process improvement, facilitation and acceleration and making better use of their resources. On the other hand, this added value is generally not for free. They have to pay for it in some way. The relation of provided added values, the revenues in return, and the involved roles are described in business models (see e.g. [12]). There are different conceivable settings for the relation of an enterprise, its customers, and the service provider. A simple one (see A in Figure 3) is that the enterprise receives a service directly from the service provider, provides the required data, and pays for the service, either transactional or as a lump sum/flat rate. In this case the value of the service has to justify the data provision and the price of the service. A little more complex is a case where the enterprise does not provide its own data but data from its customers that is related to the products or services it supplies (setting B). The service provider is still payed by the enterprise. The enterprise receives the service from the service provider and uses it to provide added value to its products or services for its customers. In the example customers do not have to pay extra money for the added value, so they just have to decide if it justifies the data provision and the related effort and risks. The benefit for the enterprise could be an own internal use of data and/or an improved competitiveness and customer loyalty. In a comparable way the enterprise could apply services that are "for" free because they are "sponsored" by others (setting C). In this case the enterprise has to assess the related efforts and risks of data provision.

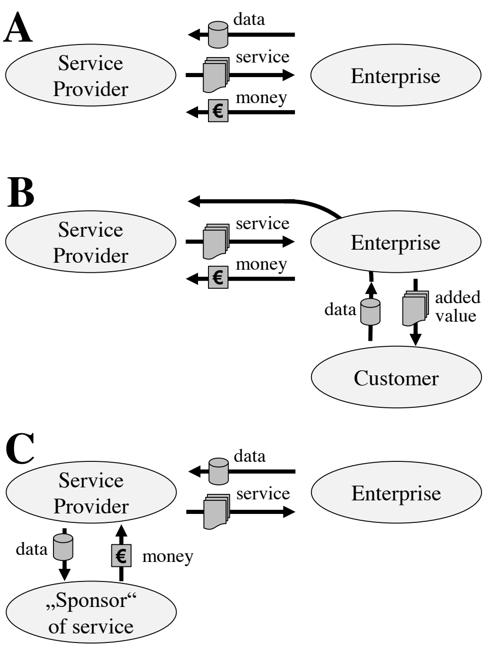

Figure 3: Business Model settings for digital services

It has to be considered that there could be different stakeholders within an enterprise that could benefit from a service, e.g. product manager, production manager, service technicians, and others. To obtain a better understanding of the potential added value two questions can be asked [12]:

- Who has which problems that can be solved or mitigated by the service?
- Whose job can be facilitated and improved by the service?

There could be different business models for the provision of data that is required during the development of a service, e.g. the development and training of AI algorithm, and the data that is required as input to obtain results from the service. Usually there are extra benefits for partners that contribute to the development phase, e.g. free use of the new and other services.

If the customer can decide if the data input to the service a kept as an addition to the knowledge base of the service this will require an appropriate incentive too.

These aspects should be considered when the added value is considered as benefit in the effort-benefit analysis.

5 Practical application

As mentioned above the general motivation for effort-benefit-analysis evolved from the research project LongLife that is aiming at a prognosis for remaining service life of technical components. The prognosis requires a corresponding prognosis model and a broad data-basis to develop it. In the practical application the prognosis should be based on data that is gathered with a mobile test bed / measuring device. So, the LongLife approach requires the provision of data for model development and later to provide the service of prognosis. Since some enterprises are reluctant regarding the provision of data a further objective on LongLife is offer reference business model to reduce this reluctance.

One applications scenario considers bearings in a module that is critical for the functionality of a machine.

First step was to brainstorm parameters that can be measured on the module or in its surrounding and might enable conclusions regarding that actual state and the remaining service life of the component.

Some of the parameters, e.g. sound and temperature, were regarded as non-sensitive. However, during the discussion it was worked out that some customers (machine operators) want to keep information regarding their current number of working shifts internal. It could be also critical to share data that enables conclusions regarding the productivity of the person that operates the machine. Hence, such data should be anonymised as far as possible.

The manufacturer of the machine has already a sound data-basis for the machines that was gathered from other digital services and a service platform. Unfortunately, the data regarding the considered module that was brainstormed for the prognosis was not measured yet. Therefore, the data should be gathered in a first step internally on a test machine and from measuring modules that were replaced due to regular maintenance interval or because they have shown defects. Later on, this can be completed by measurements at selected customers that are interested in the planned prognosis. Parts of anonymised data will be shared with Partners in the LongLife consortium that contribute to the development of the service and have signed a common Non-Disclosure Agreement.

The manufacturer sees no risk, if this data is provided to partners in the LongLife project that develop the prognosis model.

Since the risk is very limited the effort-benefit analysis will concentrate on the effort of gathering the data. Some data can be gathered automatically along with other testing on the test machine. But this will not be sufficient. There have to be extra tests on the machine and extra measurements on the returned modules. The corresponding effort has to be calculated with hourly rates for personnel and equipment. Since this effort is related development of the prognosis service it is regarded as an investment with a rate of depreciation. (For the overall assessment of the effort it has to be considered that development is part of a research project and partly funded.)

The effort to gather data that is required for the later application of the developed service depends on the technical realisation of the measuring device. The effort can be low, if the device and the sensors are already integrated in the system and can be accessed automatically. But the measurement can also require activities by personnel for installation of the test bed and the actual measurement. This has to be evaluated for the particular case.

The main sources of benefits and the corresponding recipients that have been preliminarily identified are:

- Avoidance of unplanned downtimes that are caused by breakdowns of the module or late availability of spare parts. => Benefit for the enterprise that operates the machine.
- Input for a further optimisation of the machines to increase customer satisfaction and competitiveness. => Benefit for the manufacturer.

This can be accompanied by environmental relief. On the one hand, resources are saved by extending the service life of components and on the other hand e.g. by reducing scrap.

Benefits	Evaluation	Required data	Effort	Risks
Reduction of un-planned downtime/ year by 25% => … €	favourable	Maximum Operation cylcles per day	Already gathered => no extra effort	Conclusion on current production volume …
		Data B	Extra manual measurement => ... €/year	…
		Data C	…	
Benefit XXX				

Figure 4: Example for effort-benefit-analysis

The manufacturer is considering to include the service in the already existing maintenance service package without extra charging. This should increase the attractiveness for the customers.

A first effort-benefit-analyses was done according to the structure suggested above. Figure 4 shows an extract of the considerations.

The suggested evaluation of new digital service should contribute to foster acceptance for those services. Many of them also provide opportunities to include the aspect of increased sustainability in the business model. This was also one of the essential objectives of the LongLife project and gets more important for many enterprises today.

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Analysis of impact of ICT services on lifestyles and CO_2 emissions considering users' regions and ages

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Abstract

As climate change has become more serious, lifestyle changes have become required to reduce environmental load. In addition to environmental problems, Japan faces various social problems such as aging and depopulation of rural areas. These problems can potentially be solved by Information and Communications Technology (ICT) services. However, ICT services and their impact on the environment may vary depending on the attributes of users such as region and age. In this study, as a case study of environmental impact estimation of ICT service considering users' regions and age, CO_2 emission changes by Mobility as a Service (MaaS) utilisation for the working-age and elderly populations in urban and suburban areas were estimated by Life Cycle Assessment on the basis of time usage patterns. The estimation results suggested that the main factors influencing the effect of CO_2 reduction by MaaS were the degree of car dependence, necessity of pickup services in daily life, travel time, and usage of the time saved.

1 Introduction

As climate change is seriously impacting environments, economies, and societies worldwide, reduction of greenhouse gas (GHG) is an urgent task. Many studies have warned that existing consumption patterns may induce increasingly large damage [1].

The household sector accounts for about 20% of GHG emissions in Japan. Japan's Intended Nationally Determined Contributions approved in 2015 calls for a significant GHG reduction (39% compared to 2013) [2] in the household sector as well as the commercial sector, but GHG emissions have not been sufficiently reduced at the present time. The main GHG emission factors of Japanese households are mobility and food, so lifestyle changes in these aspects are required [3].

In addition to environmental problems, Japan faces various social problems such as aging and depopulation of rural areas. Information and Communications Technology (ICT) services have potential to solve these problems as shown in Society 5.0. Society 5.0 was proposed in the government of Japan's 5th Science and Technology Basic Plan as a future society to which Japan should aspire. It is defined as "A human centred society that balances economic advancement with the resolution of social problems by a system that highly integrates cyberspace and physical space [4]." In Society 5.0, penetration of ICT services will solve social problems as well as improving the energy-efficiency and convenience of people's lives. In the case of mobility, utilising data such as sensor information, weather, and traffic data will enable comfortable mobility without congestion or accidents, smoother movement by combinations of public transportation, and movement support for the elderly, as well as reduce GHG emissions generated through mobility [5].

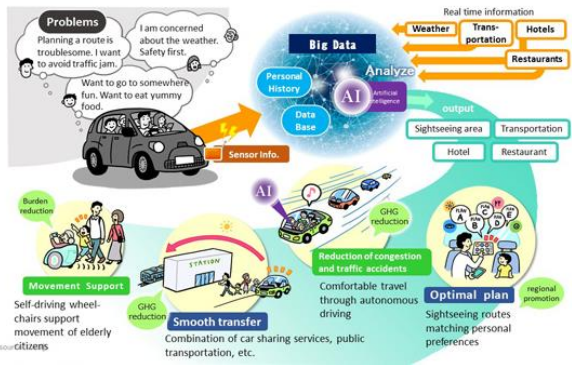

Figure 1: Future lifestyle changes in terms of mobility [5]

Thus, penetration of ICT services will further change people's lifestyles and affect environmental impacts. However, changes in people's lifestyles through penetration of ICT services and their impact on the environment may vary depending on the attributes of users such as region and age. For example, the effects of reduced mobility due to telework seem to differ between regions in which people mainly commute by car and regions in which people mainly commute by public transportation. The purposes and trends of ICT service utilisation differ in accordance with age [6]. However, few existing studies have estimated such effects of ICT services considering users' regions and ages.

2 Previous Studies

The effects of people's lifestyle changes due to ICT services and their impacts on the environment have been studied. The European Commission estimated that reduction of transportation and goods consumption by using ICT services such as telework, online shopping, and e-books would result in reducing GHG emissions by 0.5-1% [8]. The Global e-Sustainability Initiative estimated that the use of connected private transportation, e-banking, e-learning, and e-work would reduce transportation and GHG by approximately 1.5Gt-CO_2 worldwide by 2030 [8].

Furthermore, although time and cost will be saved by using ICT services, environmental load will be generated by additional activities on which the saved time or cost is spent. These effects, called rebound effects or induced effects, may cancel out the effects of CO_2 emission by 1-200% [9] [10]. For example, NTT examined additional activities on which time and cost saved by business-to-customer (B2C) ICT service use were spent and estimated CO_2 emissions generated by the additional activities as the "first–order rebound effect." Although CO_2 emissions could be reduced through reduction in transportation and goods consumption due to use of various ICT services, the first-order rebound effects were estimated to cancel out the effect of CO_2 reduction by 1-70% [11]. These studies estimated reduction of CO_2/GHG emission in the macro level such as country or world without considering users' regions or ages.

Therefore, in this study, the effects of lifestyle changes such as those shown in Society 5.0 on CO_2 emission are analysed by considering users' regions and ages.

3 Method

3.1 Overview of estimation method

Daily CO_2 emissions per person were estimated by Life Cycle Assessment (LCA) on the basis of patterns of time use and compared before and after introducing ICT services. Activities shown in Table 1 were classified on the basis of results of a "Survey on time use and leisure activities" conducted by the Ministry of Internal Affairs and Communications.

$$Cb = \Sigma E_i \times T_i \quad \text{(eq. 1)}$$

$$Ca = \Sigma E_i \times T_i + \Sigma E_i \times Tg_i + S \quad \text{(eq. 2)}$$

Cb: CO_2 emissions before introducing ICT services (g-CO_2/person/day)

Ca: CO_2 emissions after introducing ICT services (g-CO_2/person/day)

E_i: CO_2 emissions intensity of activity i (g-CO_2/min)

T_i: Duration of activity i per person per day (min)

Tg_i: Duration of activity i as part of saved time per person per day (min)

S: CO_2 emissions from ICT devices (g-CO_2)

Primary activity	Sleep
	Personal errands
	Meals
Secondary activity	Commuting
	Work
	Study
	Household chores
	Nursing and elderly care
	Child care
	Shopping
Third activity	Transportation other than commuting
	Watching TV, listening to radio, reading newspapers or magazines
	Rest and relaxation
	Learning, self-development, and training
	Hobbies and entertainment
	Sports
	Volunteering or social participation activities
	Personal relationships
	Medical examinations and treatments
	Other activities

Table 1: Classification of activity

The second term of eq. 2 represents CO_2 emissions due to saved time generated by using ICT services. This is defined as a first-order rebound effect as in previous studies. The saved time was calculated by subtracting the time spent on the use of ICT devices and the time spent on the activities after introducing

ICT services from the time spent on the activities before the introduction of ICT services.

The effect of introducing ICT services was reflected in CO_2 emission intensity (E_i) and duration of activity (T_i). The saved time generated by using ICT services was allocated to each activity on the basis of results of a questionnaire carried out in our previous study [13].

3.2 Targeted ICT services and users

3.2.1 Targeted ICT services

The effect of mobility changes on CO_2 emission was analysed because mobility will greatly impact CO_2 emissions as shown in Society 5.0. Lifestyle changes in mobility by introducing Mobility as a Service (MaaS) were selected as targets of analysis. In MaaS, all means of transportation are integrated for one-stop reservation, payment, and utilisation as shown in Figure 2. Though each means of transportation has been accessed independently until now, MaaS enables multiple means of transportation to be used optimally as if they were one service, and this contributes to shorten travel time. Since the convenience of public transportation will be improved, MaaS is expected to contribute to the reduction of private cars. The concept of MaaS includes various ICT services for transportation. Route research and taxi allocation services, which are major services in MaaS, were selected as target services. The effect of introducing each service was shown in follows.

(1) A route research service

- Reduction in utilisation rate of private cars
- Generation of the first-order rebound effect because of reduction in transportation time

(2) A taxi allocation service

- Increase in taxi utilisation as a means of transportation from stations or bus stops to one's home

3.2.2 Targeted users

Two areas with extensive public transportation were selected as target areas. Tokyo, where car utilisation is low, was selected as the target urban area, and Chiba Prefecture, where car utilisation is high despite having many railway stations, was selected as the target suburban area. Since traffic behaviour is expected to change in accordance with age, the target users were further divided into working-age people between 25-35 and elderly people 65 or older.

3.3 Usage scenario

The functional unit was the conventional travel time per person per day. Transportation and the behaviour during the saved time were set as the scope of LCA. Travel time included the time to commute and other travel as shown in Table 1. Figure 2 shows users' behaviour before and after introducing MaaS. Assumptions about the impact on each user are shown in Table 2. Statistical data from the survey on time use and leisure activities [12] and a national survey on urban traffic characteristics [14] were used for the travel time and the rate of car use of each user. The reduction rate of car utilisation was uniform at 50% [15]. Travel time was shortened by about 20% by increasing the efficiency of transportation [16]. According to the urban traffic survey, people regard a station as close if it is within a 15-minute walk. Thus, assuming that people other than car and bicycle users who live more than 1 km from a station and more than 500 m from a bus stop would use the taxi allocation service, the utilisation rate of the taxi allocation service was estimated from statistical data [17]. The frequency of taxi utilisation was assumed to be twice a week and every time for working-age and elderly people, respectively. Figure 3 shows the use of the saved time for each user. The saved time due to introducing MaaS was allocated to each activity according to this pattern as first-order rebound effect.

The CO_2 emission intensity of transportation was made from the value in Embodied Energy and Emission Intensity Data for Japan Using Input-Output Tables (3EID) [18] and the database of Green Value Chain Platform [19]. CO_2 emission intensity of activities other than transportation was made from literature values [20] and the survey on time use and leisure activities [12]. CO_2 emissions from ICT devices were calculated in the same way as in a previous study [21].

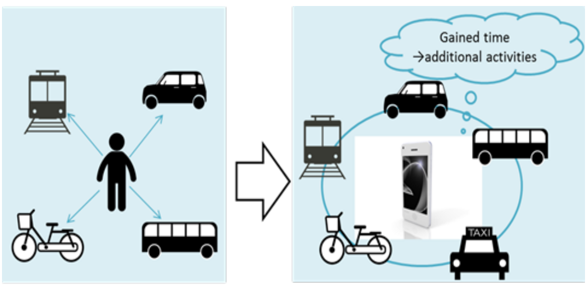

Figure 2: Users behaviour before and after introducing MaaS

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		Urban area	Suburban area
Reduction rate of private car	working-age	50%	50%
	elderly		
Rate of car utilisation	working-age	8.0%	32.3%
	elderly	11.1%	39.1%
Rate and frequency of taxi utilisation	working-age	1.1%, twice a week	10%, twice a week
	elderly	1.9%, every time	23.8%, every time
Travel time	working-age	87 min	98 min
	elderly	48 min	41 min
Saved time due to introducing MaaS	working-age	16 min	18 min
	elderly	7 min	7 min

Table 2: Usage scenario

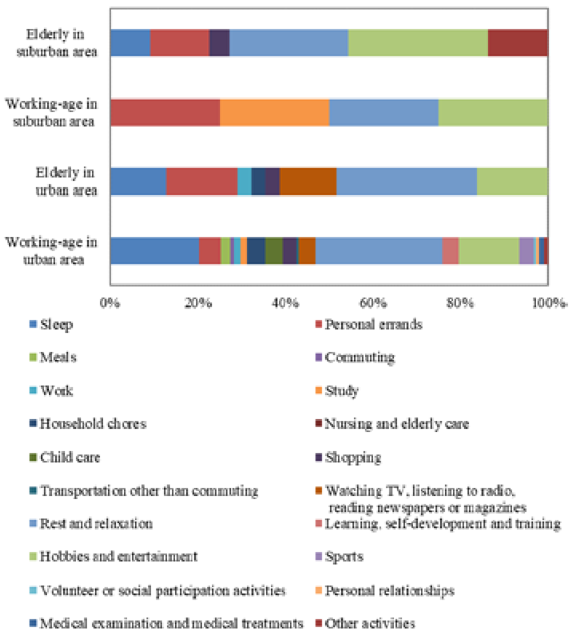

Figure 3: Usage patterns of saved time for each user

4 Result and Discussion

Figures 4 and 5 show each user's CO_2 emission before and after introducing MaaS. Blue and red bars show CO_2 emissions from transportation and the first-order rebound effect, respectively. CO_2 emissions from smartphones are included in the blue bar. CO_2 emissions were reduced by 140-970 g-CO_2/person/day. Though the proportion of the car use was higher for the elderly than for the working-age, the CO_2 reduction was larger in the working-age, because their travel time was about twice as long. When the calculated CO_2 reduction per capita was multiplied by the population to obtain the total reduction in each region and age, the suburban working-age had the largest total reduction. Through the population is larger in the urban area, the CO_2 reduction effect of the suburban working-age would surpass the difference in the population.

The rate of CO_2 reduction by introducing MaaS is shown in Figure 6. The CO_2 reduction effect achieved by transportation reduction was canceled out by 12-28% due to first-order rebound effect. The CO_2 reduction effect achieved by transportation reduction tended to be larger than the first-order rebound effect.

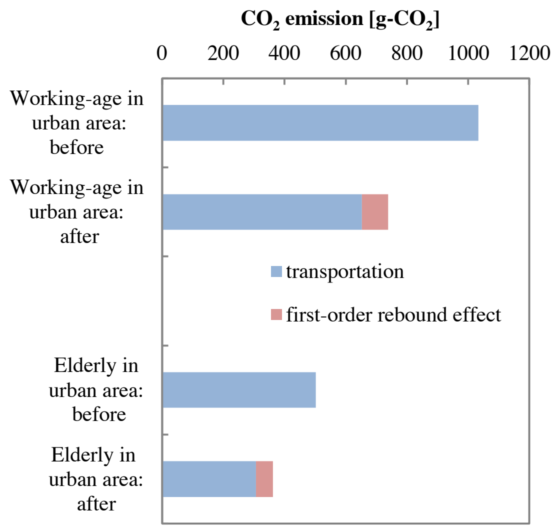

Figure 4：CO_2 emissions per person per day in urban area before and after introducing MaaS

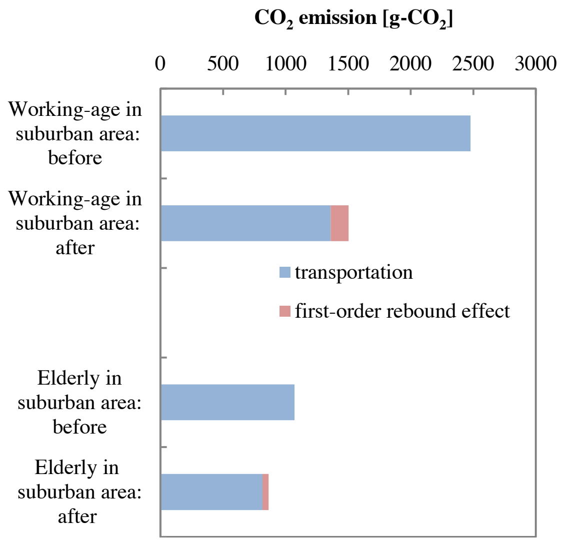

Figure 5: CO_2 emissions per person per day in suburban area before and after introducing MaaS

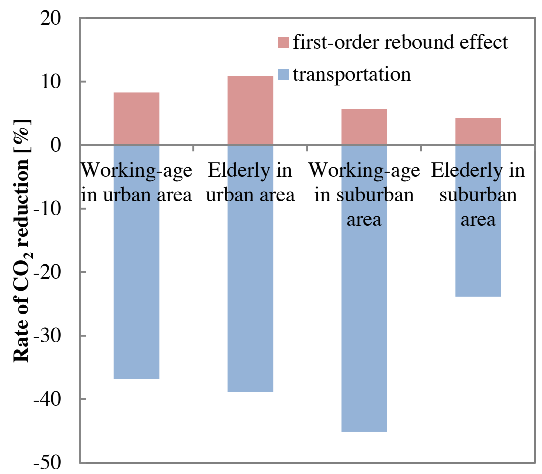

Figure 6: Rate of CO_2 reduction per person per day by introducing MaaS

In the urban area, the rate of CO_2 reduction related to transportation was higher for the elderly, but the reduction rate including the first-order rebound effect were higher for the working-age. It is considered that the rate of CO_2 reduction related to transportation was higher because the rate of car utilisation was higher for the elderly. On the other hand, the elderly were more likely than the working-age to spend the saved time on activities using water and utilities such as personal errands, resulting in an increase in CO_2 emissions due to the first-order rebound effect.

In the suburban area, both the rate of CO_2 reduction related to transportation and the reduction rate including the first-order rebound effect were higher for the working-age, though the car dependence of the elderly was especially strong. This suggested that CO_2 emissions from vehicles such as taxis may be induced by lifestyle changes of the elderly, because the elderly who do not live within walking distance of stations or bus stops may shift to depending on pickup services as an alternative if they give up driving their own cars. Such lifestyle changes may be the reason the rate of CO_2 reduction was lower for the suburban elderly than for the urban eldely. Though the taxi allocation service was expected to be an useful means of transportation for the elderly who no longer drive, it may cause CO_2 emissions to increase if it is used frequently.

These results indicate that the main factors influencing the effect of CO_2 reduction by MaaS were the degree of the car dependence, necessity of pickup services in daily life, travel time, and usage of the saved time. It is considered that CO_2 emissions can be effectively reduced through MaaS by switching from lifestyle a dependent on cars to a lifestyle dependant on public transportation, walking, and cycling. In addition, to minimize the first-order rebound effect, the time saved due to efficiency improvement of transportation can be allocated to activities with comparatively small environmental load such as hobbies and entertainment, sports, and volunteering and social participation.

5 Conclusion

In this study, as a case study for evaluating the environmental impact of ICT services considering users' region and age, CO_2 emission change through introducing Mobility as a Service (MaaS) was estimated for working-age and elderly people in urban and suburban areas. A route search service and a taxi allocation service were focused on as major service of MaaS. Overall, the effect of CO_2 reduction related to transportation tended to be larger than the first-order rebound effect. The estimation results suggested that the main factors influencing the effect of CO_2 reduction by MaaS were the degree of the car dependence, necessity of a pickup service in daily life, travel time, and usage of the saved time. CO_2 emissions could be effectively reduced by switching from a lifestyle dependant on cars to the lifestyle dependant on public transportation, walking, and cycling. In addition, to minimize the first-order rebound effect, the time saved due to efficiency improvement of transportation can be allocated to activities with comparatively small environmental load such as hobbies and entertainment, sports, and volunteering and social participation.

In the future, the effective usage of ICT services and lifestyle changes they enable will be further studied to solve social and environmental problems, while the secondary effects such as increases in outing opportunities for the elderly will be also considered.

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Reviewing environmental opportunities and pressures of digital transformation – Results of a meta study on non-energy and non-greenhouse gas environmental impacts

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Abstract

There is a general belief that digital transformation contributes to a better quality of life for citizens and fosters sustainable development. While the effects on energy consumption and climate change have been analysed widely, the consumption of resources has not yet been systematically explored so far. Based on a literature review, this paper provides an overview of the currently available knowledge on the effects on abiotic resources, water consumption, land use, and waste, as a result of digital transformation. The analysis distinguishes three levels of environmental effects of digitalisation (direct, indirect and systemic effects). The literature reviewed encompasses life cycle assessments as well as studies on material flow analysis and electronic waste statistics. We conclude that current knowledge about the resource-related effects of the digital transformation is still incomprehensible and inconclusive. Hence, one cannot assume that digitalisation will automatically lead to benefits in terms of resource, water and environmental aspects.

1 Introduction

Digitalisation is expected to have profound ('transformative') effects on the economy, society and politics as well as on the planet itself. There are many positive expectations and viewpoints that digital transformation and innovation could and should contribute to a better life for humans, while facilitating sustainable development at the same time.

In recent years, many research studies on assessing direct and indirect effects related to the digitalization have been conducted, however mainly focusing on climate change and energy aspect. For instance, not exhausted, [1] investigated the direct and indirect greenhouse gas (GHG) emissions of digitalisation in Switzerland. [2] broadly reviewed literature estimating energy consumption impacts covering four ICT services: e-commerce, e-materialisation, telework and monitoring and controls. The extensive review by [3] identified 54 studies assessing indirect environmental effects of ICT covering 15 different methodological approaches. Within the 16 studies using the LCA (life cycle assessment) approach, only one LCA study by [4] investigated other environmental impacts apart from GHG/Energy.

Digital transformation requires an enormous amount of electronic hardware devices in form of information and communication technologies (ICT). Digital equipment encompasses not only end-user devices such as computers, smartphones, sensors and actuators. Over and above, digital services require data centres, data transmission networks and accompanying infrastructures (e.g. cooling, uninterrupted power supply, etc.) as well as software. All these facilities are made up of sophisticated hardware which consists of a wide range of technical materials, many of which are scarce and resource intensive. Thus, digitalisation entails an increasing demand for raw materials, chemicals, and cooling water as well as space. It also affects natural eco-systems such as rain forests or the deep sea, which in some cases can be attributed to the mining of critical raw materials and the construction of cable networks. Throughout their life cycles, digital devices are linked to biodiversity damage and human health impacts caused by resource acquisition and electronic waste processing and disposal.

Despite the existence of many studies dealing with environmental impacts that go beyond GHG and energy aspects, there seems to be a lack of systematic knowledge about the overall dimension of resource, water and land use impacts of digitisation. In particular, the high expectations about the presumed resource efficiency potential of digital transformation often seem to be based more on anecdotal assumptions than on generalizable evidence. What is missing is an overall picture of the balance between resource-related opportunities and risks of the innovation trend.

Against this background, the DG Environment of the European Commission commissioned us in September 2019 to gather evidence on the areas where digital applications have already been shown to offer environmental opportunities and where resource-related environmental pressures exist.

The aim of the study was to gather up-to-date quantitative evidence on positive and negative environmental effects of the digital transformation with the focus of non-GHG and non-energy environmental impacts. Particular attention is paid to impacts on abiotic resources depletion, water consumption, and land use.

2 Methodological approach

Three levels of environmental impacts in the interaction of ICTs and the natural environment – direct, indirect and systemic impacts – have already reached consensus and are widely accepted, although taxonomy and degree of details differ one from another, as described in [2]. Following the definitions by [5, 6], we relied on the following taxonomy:

- ‘First order’ effects (direct impact) include the use of natural resources and emissions into the environment that are caused by the production, use, and disposal of ICT products.
- ‘Second-order’ effects (indirect impacts) arise from ICT applications and enable other product systems more resource or energy efficient. Second order effects may have positive or negative environmental impacts.
- ‘Third-order’ effects (systemic impacts) involve consumer behavioural and economic changes as well as the interaction among them due to the medium- or long-term adaptation of digital applications.

The classification of these effects is helpful for understanding the hierarchy of the mechanism of effects relating to the influence of ICTs on our society. In addition, the classification also facilitates the development of political instruments for shaping digital transformation from a sustainability perspective. The literature review focused on identifying scientific evidence that can be attributed to these three levels of effects of digital transformation. The following criteria were taken as basis:

- This paper focuses on the three main environmental categories of resource depletion, water consumption and land use.
- Studies investigating quantitative results of environmental impacts based on a life cycle perspective are firstly considered. The Life Cycle Assessment (LCA) approach as a holistic assessment method with the consideration of the full life cycle while avoiding burden shifting from one life stage to other stages. Additionally, the holistic assessment avoids favouring one certain environmental impact. If studies with a life cycle perspective are not available, other relevant quantitative assessment studies related to resource, water and land use, e.g. on material flow analysis, will also be considered to obtain the magnitudes. In this paper, we do not differentiate between various types of LCAs (e.g. attributional, consequential LCAs), which has already been discussed by [7].
- As regards the temporal scope, we have limited the literature screening largely to studies published after 2010: given the rapid pace of technological progress in the ICT area, older studies may have become obsolete.

This meta study is not intended to compare the results of various studies but provides an overall picture on the evidence of resource-related opportunities and pressures of the digital innovation trend. It cannot be fully guaranteed that all available publications have been taken into account.

3 Evidence I: First Order Effect (environmental pressures)

3.1 Hardware I: Final ICT Equipment

The final ICT Equipment we have reviewed not only includes classic devices such as desktops, laptops, smartphones, tablets and routers but also the innovative ICT devices tested or applied mostly in business sectors, such as drones (Unmanned Aerial Vehicles) used in logistics services.

3.1.1 Resource depletion

Life cycle assessments of mobile devices such notebooks [8, 9], smartphones [10, 11] and tablets [12] show that the production phase, including the acquisition of raw materials for the manufacturing of final ICT goods, dominates the resource depletion impact (more than 85% of the results) throughout the products’ whole life cycle (including distribution, use, end-of-life). These mobile devices are particularly relevant for the resource depletion due to 1) a high content of critical raw materials and metals 2) a large number of global shipments, and 3) quite a short use time [13]. As for stationary computers, the use phase is the most significant in terms of abiotic resource depletion [14] due to the relative long lifetime assumed. The components with the most significant resource depletion impact in the production of ICT equipment are; ICs (integrated circuits, especially CPU and memory chips); display; PWB (printed wiring boards); battery and power supply. [13] revealed indicatively that cobalt and palladium contained in smartphones and tablets each contribute to about 9% of the world primary production. [15] conducted an LCA on drones using Li-ion batteries in an online shopping system. The production stage dominates (accounting for more than 90%), contributing to all 11 impact categories investigated including abiotic resource depletion. The main contributors to abiotic resources are copper (20.47%), silver (17.67%), lithium (15.72%), and lead (15.37%). The LCA study of virtual reality (VR) headset [16] revealed that the silicon wafer processing and final assembly of integrated circuits (ICs) have the highest relevance for the overall environmental impact of VR headsets. To our best knowledge, a life cycle assessment considering the multiple environmental impacts for a home router is not yet available, which also corresponds to the finding of [17].

3.1.2 Water consumption

Environmental impact assessments of ICT barely address water consumption or water scarcity. The LCA study of a smartphone by [10] shows that water consumption is dominated (more than 80%) by the production stage. The absolute value varies between 3m^3 to 50m^3 of a smartphone used over three years depending on the secondary datasets used. Generally, the significant water user of ICT equipment derives from 1) mining processes and 2) semiconductor industry. [18] compiled a database of 8314 data points from 359 mining company reports. The results show that water use referring to the water inputs to mining processes varies between 340 and 6,270 litres per tonne ore processed. The semiconductors demand is driven by the increased ICT products. The semiconductor industry uses vast amounts of water, especially purified water, for cleaning the silicon wafers at different stages in the fabrication processes and for cooling various tools. Besides, a large number of fabrication plants are located in water-stress regions such as Singapore, Taiwan, and parts of China mainland and the United States. The intensity of water demand is strongly related to the types of microchips associated with the corresponding process complexity, for instance, fabrication of logic microchips requires more water than memory microchips [19]. The total annual water use (fabs feedwater and water for electricity) by semiconductor manufacturers in 2016 was 21,785 billion liters according to estimations by [20], without considering the water scarcity weighting factor.

3.1.3 Land use

At present, there is no consensus on best practices for quantifying land use in LCAs in general (x). The latest method using a soil quality index based on the LANCA model [21] was suggested by the ILCD handbook, developed by the European Commission's science and knowledge service "Joint Research Centre (JRC)". The calculation of land use impacts caused by ICT is very difficult due to a lack of data, and also for methodological reasons. A screening LCA study of a laptop used in Poland by [9] quantified that the production phase accounts for 97% of the impacts on land use. The LCA study on a laptop by [8] mentioned that deforestation, soil erosion, and land use are connected to mining activities, however, without providing any quantitative assessment.

3.2 Hardware II: data transmission networks

According to the Cisco VNI™ (Visual Networking Index), global digital data traffic is rising at an exponential rate [22].

Generally, the more data we create, the more ecologically important data centres and networks become.

3.2.1 Resource depletion

Data transmission network is a complex system encompassing fixed networks and mobile networks. The transmission network is divided into different hierarchy levels, which can be roughly divided into the three network levels *access network*, *aggregation network* and *backbone network*. As for fixed network, no comprehensive LCA studies on resource depletion are publicly available at present. The enormous number of devices (copper cables, optical fibre cables, DSLAM, switches, routers, cooling systems etc.) require energy, metals and mineral raw materials, use chemicals and release pollutants during their production. Furthermore, the maintenance they require, and the way in which they are treated at the end of their life are straightforwardly linked with an environmental burden. The knowledge gap regarding these aspects should be closed.

Concerning mobile networks, [23] investigated the environmental impacts of the core network for mobile telecommunications based on the LCA methodology. Raw materials acquisition has the highest contribution to abiotic resource depletion, accounting for 95% of the total life cycle. The main contributors are silver with 54% of the total abiotic resource depletion potential of the raw materials phase, followed by gold contributing 18% and antimony 17%. [24] estimated roughly the material balance of components of the 2G und 3G mobile network in Germany, however, on the basis of a very limited data basis. 136,000 tons of metals (mainly steel, aluminium, copper, and electronics) and other materials are bound in the German mobile network. [25] conducted an interesting case study of environmental assessment on a city-scale wireless sensor network (WSN) applied in a monitoring system for municipal glass waste containers. The production of hardware (sensors, repeaters and gateways) and the operation phase each contribute to 50% of the resource depletion based on a ten-year operation. Sensors (production and operation) account for a share of 83% with regard to raw material depletion through the life cycle.

In considering underwater cable, it is found that nearly 1,207,005 km of cable already connect the continents to support internet connectivity [26]. One LCA study on cable system by [27] is publicly available, however, this study dates back to 2009. Although it is out of the period of time covered, it has been taken into account since it is the only publicly available LCA on undersea cables to our best knowledge. The results based on the 13-year use and maintenance of the cable show that the use & maintenance phase dominates the abiotic resource depletion with 70%, followed by installation with 8%, the production phase with 10%, and end-of-life with 12%.

3.2.2 Water consumption

Few LCA studies investigated water consumption of networks. The LCA study on core networks for mobile telecommunications by [23] shows that the production stage which includes raw materials acquisition, production, transport and assembly, dominates water consumption, accounting for 87% of the total life cycle. This is mainly due to the applied Chinese electricity mix corresponding to the location of most suppliers in the modelling. The results of the sensitivity analysis show that a reduction of the microchips area by 30% can lead to a reduction of the overall impact of production activities by an average of 11%.

3.2.3 Land use

There is less data on land use and land use change associated with data transmission networks. Eurostat land use statistics indicate that land uses related to transport, communication networks, storage and protective works account for 2.5% of the EU-28's territory in 2015. A further breakdown only referring to communication networks is not possible due to a lack of data. Generally, land is needed to accommodate infrastructure for data transmission networks including mobile towers, masts, antennas, ducts, tunnels, cable lines, base stations and so on.

3.3 Hardware III: data centres

Data centres encompass:

- ICT equipment such as servers, networking devices and data storage systems
- Infrastructure equipment such as heating, ventilation and air conditioning (HVAC), uninterruptable power supply (UPS), lighting, etc.

3.3.1 Resource depletion

The JRC LCA study [28] of severs concluded that the manufacturing phase dominated the impact in terms of abiotic resource depletion. The key relevant components are the main board with 28%, CPU 26%, memory cards with 12%, HDD with 10%, and expansion cards with 7%. The recycling of the server, especially higher recovery rates of gold, palladium and silver, can help reduce abiotic resource depletion ranging between 20% and 60%.

The LCA case studies of three German data centres by [29] indicate that the production phase of IT equipment (servers, networking equipment, storage) and uninterruptible power supply dominates the impact category of abiotic resource depletion, contributing with 45% to 65% to the impact of the whole life cycle. An LCA study on a UK data centre over a 60-year lifetime by [30] concluded that the production phase accounts for 15% of the total life cycle regarding resource depletion. The share can be increased as a result of a shorter lifetime or more frequent replacements of servers [30].
Generally, servers are the mostly thoroughly investigated hardware in data centres. Resource depletion impacts on other networking equipment like switches and routers have hardly been investigated under the life cycle perspective.

3.3.2 Water consumption

Water consumption in data centres encompasses the direct water usage in data centres for cooling the system and indirect water usage mainly referring to the electricity generation. Due to the very high energy use in DCs [31], the indirect water footprint greatly exceeds the direct water footprint. [32] reported that data centres that have 15 MW of IT capacity consume between 300 - 500 million litres annually, which almost corresponds to 0.8 - 1.3 million litres per day.

3.3.3 Land use

Few LCA studies investigated the land use of data centres so far. The LCA results on land use by [30] show that the operation phase is principally (92%) responsible for the land use of the entire life cycle of a UK data centre, followed by the manufacturing phase accounting for 7%. The worldwide land coverage for data centres is expected to increase continuously along with the increasing data flow. Additionally, the upstream processes such as mining and disposal of tailings result in intensive land use.

3.4 Software

Investigation of the holistic environmental assessment of software is still in the beginning phase. To the best of our knowledge, there are currently no publicly available comprehensive LCA studies covering the whole life cycle of software.
But the importance of software has been increasingly acknowledged. Hardware and software are interlinked very closely; – one cannot function without the other.

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In the context of the German "blue angel" ecolabel for software, two comparable text processing software products running on the same hardware have been tested regarding the energy consumption. The results show that the energy consumption of program 1 is 4 times higher than the energy consumption of program 2 [33].

[34] concluded that software solutions for dynamic predictive load management in data centres promise energy saving potentials of 25% to 30%. Improving the average capacity utilization also means improving materials efficiency of the hardware. Furthermore, it is worth noting that software-induced hardware obsolescence is becoming more relevant for analysing the environmental impacts of hardware [33]. Hardware could very quickly become obsolescent, if the update of software demands faster processors or larger memory capacity.

4 Evidence II: Second order effect (opportunities or pressures?)

This section compiles the key findings of case studies that qualitatively evaluate direct and indirect environmental impacts in terms of resource depletion, water consumption and land use. The case studies were chosen on the basis of available LCA studies which might illustrate the broad digital innovation solutions discussed.

The LCA results of **e-book readers versus paper books** by [4] show that for abiotic resource depletion, the break-even point in this study is around 30 books. That means that, from the perspective of these impact categories, e-book readers will only be justified after more than 30 books. The break-even points will change if other environmental impact categories are considered. Authors summarized that there is no simple answer as to which book is better from an environmental perspective. Many factors can have an influence on the impacts, e.g. read times, lifetime of the devices, more readers, the proper disposal of devices.

[35] conducted a comparative analysis of environmental impacts of **drone-based** pizza delivery services versus motorcycle services in Korea. The scope is limited to the operation stage. The production stage of drones and motorcycle is excluded from the scope of the assessment. The limited results show that the gasoline motorcycle delivery was about 2.4 times higher than drone delivery in terms of abiotic resource depletion,

Smart farming is widely expected to generate benefits for the environment in terms of reducing energy and GHG emissions, saving water withdrawal, reducing chemical use and remotely monitoring and diagnosing the status of crops. There are investigations on quantifying the site-specific environmental benefit of smart farming mostly in the context of trial tests or pilot projects which present evidence on reductions in water use, pesticide use and N_2O emissions [36]. But few studies take into account the holistic environmental assessment method. Smart farming requires additional efforts, an increased demand for hardware and infrastructure accompanying data transmission, which in turn entail increased resource demands and e-waste. The number of agricultural devices for gathering data worldwide was estimated at 30 million in 2015 and is expected to rise to 75 million by 2020 [36]. If each tractor was equipped with a camera and uploaded its data to the cloud, 1.7 Exabyte would be generated each year for Germany and 8.7 Exabyte for the EU [37].

The probably first LCA study on **connected automated vehicle** (CAV) sensing and computing subsystems by [38] assessed energy and GHG emissions only. The authors pointed out that no other impacts could be considered due to limited data. Each fully automated car will be generating around 4000 GB (or 4 Terabytes) per day according to Intel [39]. The processing of this significant amount of data requires a powerful sensory and computing system and a 5G wireless infrastructure, which in turn entails an additional resource demand.

5 Evidence III: Third order - Rebound effect (opportunities or pressures?)

The fundamental mechanism of third order effects including rebound effects and systemic transformation has been well described and discussed by many authors [3, 40,]. An assessment of the third order effects involves taking account of economics factor, consumer behaviour, life style and value system, social practices, technical systems, dynamic implication of change and the interaction between the different influencing factors. The most-discussed effects are rebound effect. A typical example is the optimisation of logistics, which has dramatically changed the consumer online shopping behaviour, e.g resulting in an increased order return rate in online shopping [3]. [40] presented examples such as teleworking, E-commerce and self-driving cars to discuss some of their possible rebound effects, and provided interesting digital services with little or no rebound effects.

To our best knowledge, comprehensive publicly available studies quantifying the non-GHG impacts in terms of resource depletion, water consumption or land use for third order effects, or which estimate the net decreased/increased resource depletion related to the direct and higher-order effects, do not exist. Concerning GHG, certain efforts have been made in order to obtain an estimation. For instance, [41] pointed to several estimations ("SMARTer 2030" study, GHG enablement factors of different telecommunication network operators, IPTS study) on the net GHG emissions which yield diverging results, due to the differences in the approaches applied. Authors identified methodological challenges that have an influence on the overall GHG net effects.

The net decreased GHG results could be overestimated, if the focus would only be on the indirect enabling effect such as substitution or efficiency, and simplify the direct effect. To fairly assess whether a digital application induces more environmental benefits than risks, evaluating direct effects associated with the required ICT equipment is the first fundamental step.

Besides, a holistic approach based on LCA is needed to properly understand the impacts, avoid trade-offs between impacts, and get robust results on the digital services. As described in section 3, the manufacturing stage of ICT equipment is often a main driver for resource depletion, in contrast to GHG where the use stage is the main contributor in the entire life cycle in terms of energy consumption. Focusing solely on the use stage creates the risk of receiving biased results.

Beyond the methodological challenges [41, 42], data gaps still exist. Data centres, data transmission networks and emerging innovation technologies such as blockchain, 5G, sensory technology, semiconductor industry or edge computing have not yet been sufficiently explored from an environmental perspective, especially regarding non-energy aspects.

6 Discussion: How can digitalisation contribute to resource efficiency?

The purpose of quantifying the net resource-related environmental aspects is to identify sectors or applications in which digitalisation can be expected to induce environmental benefits in terms of resource or material efficiency rather than risks, and furthermore to introduce strategies which incentivise greater resource efficiency.

The evidence gathered, however, is not such as to allow to make a clear statement whether there is a net decrease or an increase of resource depletion in quantitative terms. However, we provide "entry points" as below for designing and managing the digital transformation in a way that minimises resource depletion threats and increases resource efficiency.

- E-wastes

Discarded ICT equipment contains valuable materials as well as hazardous substances. Although 66% of the world's population is subject to e-waste legislation, and despite the fact that precious materials contained within e-waste are worth an estimated 55 billion euros, only 15% - 20% are recycled through appropriate methods [43]. Much of the rest goes to informal disassembly in developing countries, primarily in Africa and Asia. This has already led to severe water and air pollution, soil contamination, and adverse health impacts for workers and the local population. [44] estimated that the WEEE volume is expected to further increase to 52.2 million metric tons by 2021. In addition, ICT equipment arising from the technological innovation trend, e.g. sensors used in a wide variety of applications, smart textiles-embedded circuit boards and electronic components, drones with batteries, will in all probability further exacerbate this problem, because these products should not only be small and inexpensive, but are also often combined with other short-lived consumer goods. The short lifespan entails an increased need for resources to manufacture new products. The environmental benefits (reduce the need for primary resource depletion and further environmental impacts related to mining) resulting from the reuse, refurbishing and recycling of ICT equipment have been proven by many researchers [45,46,47]. The concentrations of scarce metals are considered to be high compared to ore grades; there is, for example, 100 times more gold in a tonne of mobile phones than in a tonne of gold ore [49]. The recovery rates of scarce metals are still very low. For instance, gallium (41% of virgin gallium used in integrated circuits), germanium (often used as a semiconductor) or rare earth elements (notably permanent magnet scrap, batteries) which are the relevant critical raw materials (CRMs) for the EU, are only recycled to a share of less than 1% in their end-of-life stage [49].

Digitalisation and the advancement in technology could have a positive impact on mitigating the negative effects caused by e-waste. For instance, an e-waste recycling app ("Baidu Recycle App") connects all relevant stakeholders (consumers, manufactures and recyclers) on one platform and facilitates the take-back activity, which has resulted in 152.74 million of pieces collected in China annually [50]. Greentec Robots employed a robotic cell to dismantle hard disc drivers in the end-of-life treatment in order to increase the recovery of valuable components [51]. Most importantly, the technological advancement plays a role in better collection and subsequent recycling of electronic waste and the reuse of the materials used.

- Critical raw materials (CRMs)

It is necessary to increase the remanufacturers` awareness and knowledge on embedded CRMs to facilitate informed planning for the recovery of CRMs on component level, for instance, declaring the information on the CRMs within the products and sharing it across the value chain by applying digital technology. It could firstly support remanufacturers and recyclers in making informed decisions on component or product treatment; and secondly support policymakers in monitoring the use of CRMs. Blockchain technologies, for instance, could be one option for the tracking and tracing of raw materials. However, the environmental impacts of the blockchain technologies should be further assessed in order to avoid a shift of problems.

- Secondary materials and components

Digital solutions like online trading platforms may help to improve information sharing on well-functioning secondary materials and components. In this context, quality standards, the exchange of information on material characteristics, deliverable quantities, impurities, costs, etc. play an important role for a healthy secondary market.

7 Conclusions and Outlook

The aim of this paper was to gather up-to-date quantitative evidence on positive and negative environmental effects of the digital transformation with the focus on abiotic resources depletion, water consumption, and land use.

It became obvious that several investigations focusing on resource depletion under the life cycle perspective have been conducted on ICT equipment, such as classic end ICT devices and servers in data centres. However, there are only few comprehensive LCA studies on data transmission networks and networking equipment such as switches and routers. This could be explained by the complexity of the network topology and therefore the limited availability of inventory data. Hardware associated with frontier technologies such as drones, sensors, robots, mining machines for blockchain technology or AI-enabled hardware have hardly been explored from the life cycle perspective. In the relevant studies that have investigated the three relevant impact categories, resource depletion was examined more frequently than water consumption and land use. Little evidence on resource-related environmental impacts is available for the higher-order effects.

Our review concluded that the interactions between the digital transformation and the environmental crisis have not been thoroughly investigated. Resource efficiency through the digital transformation could not be ascertained on a scientific basis in the LCAs. We cannot confirm the presumed resource efficiency potential of digital transformation in general.

Although this paper only addresses the environmental impacts beyond energy consumption and global warming, there is no doubt that energy and GHG are nevertheless important issues to reach global climate and energy targets. Yet, the time has come to pay more attention to the investigated resource-related environmental impacts assessment. Understanding other environmental impacts beyond GHG and energy issues is a precondition to identify the environmental opportunities of digital transformation and thus to enhance environmental friendliness in the field of digitalisation. Digital transformation is straightforwardly linked with an enormous amount of electronic hardware devices, data centres, data transmission networks and accompanying infrastructures, which entails an increasing demand for raw materials, metals, chemicals, and cooling water as well as space throughout the products' life cycles which will end up as e-wastes after their useful service life.

In a nutshell, it is imperative to apply a holistic assessment approach (i.e. broadening impact categories beyond GHG and energy; including entire life cycle; assessing first and second order effects). Policy makers should encourage more case studies for third order effects, in order to gain more experience on the practical implementation and to contribute to the ongoing development of the methodology, such as [52].

Digital transformation cannot be sustainable if it is not regulated in a way that mitigates its negative environmental effects. The European Commission as well as individual member states are intensively promoting digital transformation. Recently, the related support measures have been significantly intensified in order to cushion the economic slump caused by the corona pandemic, and to provide new growth impulses. For example, the German government's economic stimulus package includes a number of measures to promote digitalisation: Improving mobile phone reception in trains (€150 million), research in the field of network technologies (€2 billion), developing a concept for a digital identification system for citizens (€300 million), strengthening the range of digital administrative services (€3 billion), the Smart City Programme (€500 million) and research and development in the field of artificial intelligence (AI) (€4 billion) [53]. It would be desirable if these measures also promoted intensive accompanying research to ensure that environmental requirements are taken into account from the outset during implementation, and are furthermore considered in the design of technologies and business models. In this context, future research should first and foremost identify the sectors or applications in which digital transformation will most likely not only contribute to GHG abatement but also to resource efficiency.

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Case study based on quantitative assessment of ICT solutions in GHG emission reduction (2)

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Abstract

In 2017, NTT Group formulated the Eco Strategy 2030, which includes the commitment of contributing to society's CO_2 emission reduction by at least 10 times more than the NTT Group's own emissions. To achieve this commitment, NTT Group has been promoting a Type II environmental labelling initiative named NTT Group Environmental Labelling System for Solutions to indicate its contribution to reduction of greenhouse gas (GHG) emissions by means of ICT solutions. The candidate ICT solutions for the labelling have been selected focusing on their business prospects as well as their reduction of Scope 3 and external GHG emissions. This paper will describe two examples of labelled ICT solutions using cloud servers, because they are emerging businesses and their environmental burden is controversial, especially for datacentres.

1 Introduction

Climate change is one of the greatest challenges facing humanity, as seen in the sustainable development goals (SDGs) adopted at the United Nations summit in 2015 and in the Paris Agreement that was reached in December 2015. Global e-Sustainability Initiative (GeSI) estimated that the information and communication technology (ICT) sector's emissions of GHG would reach 1.27 Gt, representing 2.3% of global GHG emissions, in 2020, and 1.25 Gt, representing 1.97% of global GHG emissions, in 2030. Meanwhile, they also found that by rolling out identified ICT solutions across the global economy, total global GHG emissions could be cut by 12 Gt by 2030, nearly 10 times higher than ICT's expected footprint in 2030 [1]. In line with this approach, NTT Group formulated the Eco Strategy 2030 in 2017, which includes the commitment of contributing to society's CO_2 emission reduction by at least 10 times more than the NTT Group's own emissions. In addition, NTT Group has been implementing an environmental labelling initiative formulated in fiscal 2010 named Environmental Labelling System for Solutions to facilitate our customers' understanding of our environmental contribution efforts using ICT, as well as to promote environmental endeavours. To qualify for labelling, the ICT solution needs to achieve a reduction rate of more than 15% compared to conventional solutions when the amount of reduction in CO_2 emissions is quantitatively evaluated.

GeSI also analysed that the switch to more energy efficient end-user devices is particularly important in the context of a rapid increase in the adoption of devices like tablets and smartphones, as well as services like cloud computing, broad band networks and data centres, as nearly half of the sector's emissions come from end-user devices, rather than from networks or data centres [1]. In line with these findings, candidate ICT solutions for labelling have been selected focusing on their business prospects as well as their reduction of Scope 3 and external GHG emissions.

2 Method

We selected two ICT solutions using cloud servers because they were expected to reduce the number of end-user devices. Although the methodology for ICT-related environmental life cycle assessment (LCA) is standardised [2][3], there are few case studies for ICT solutions because of the difficulties in setting functional units, system boundaries, and modelling, as well as in consideration of other indirect options such as rebound effects and changes in use cases [4][5][6][7].

In this paper, we conducted examinations in partial compliance with ITU-T L.1410 on two ICT solutions to quantitatively assess each ICT solution's potential for reducing GHG emissions. The objective of each assessment was to quantify the contribution of each ICT

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solution toward GHG emission reduction by comparing a scenario where the ICT solution was employed with a scenario using the conventional method where the ICT solution was not employed.

The overall purpose of these assessments was to estimate the GHG emissions avoided by adopting each ICT solution. For this purpose, the scope of the assessments in this paper was to quantitatively estimate the level of GHG emission reduction by the ICT solution as compared to the conventional method. Rebound effects were included in the conditions of modelling if they affected the use cases.

2.1 Case study 1: Certificate Issuance Service

Under current circumstances, in which universities are promoting digital transformation and preventing infection, they have been reducing their internal services such as sending of transcripts or other verifications. The new way of life also means that students and alumni have been avoiding travelling to receive documents at the university office. To meet these needs, NTT West has been offering a document service named Certificate Issuance Service, which enables online requests, online PayPal payment or cash payment in convenience stores, and receipt of documents printed from copy machines in convenience stores using cloud servers.

Figure 1 and Figure 2 show the modelling and system boundaries of conventional document services and Certificate Issuance Service, respectively. Compared to the conventional document services, Certificate Issuance Service was expected to reduce travel by students and alumni to request and receive documents, and also decrease database servers in university offices. These

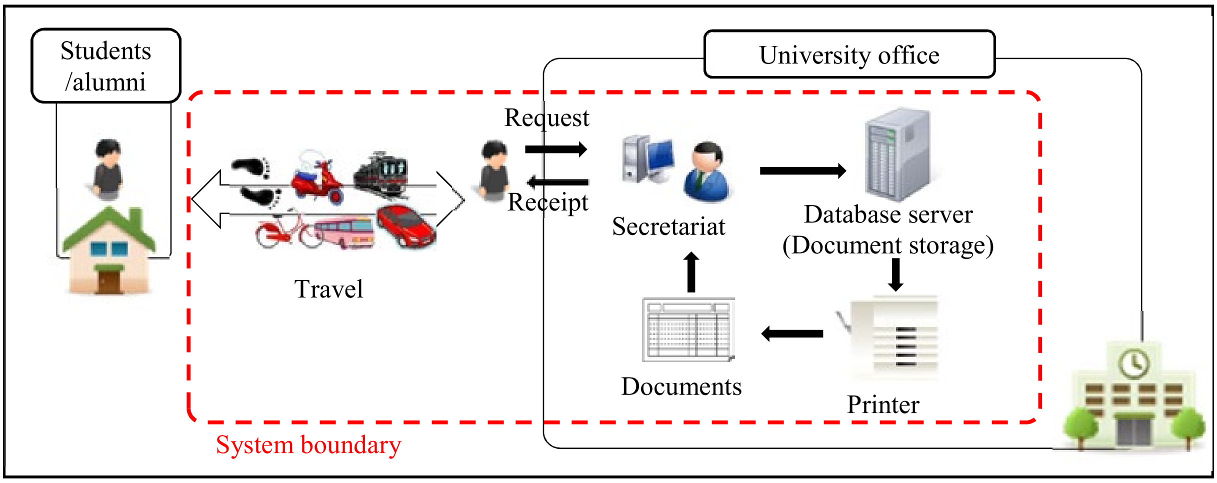

Figure 1: Modelling and system boundary of conventional document services

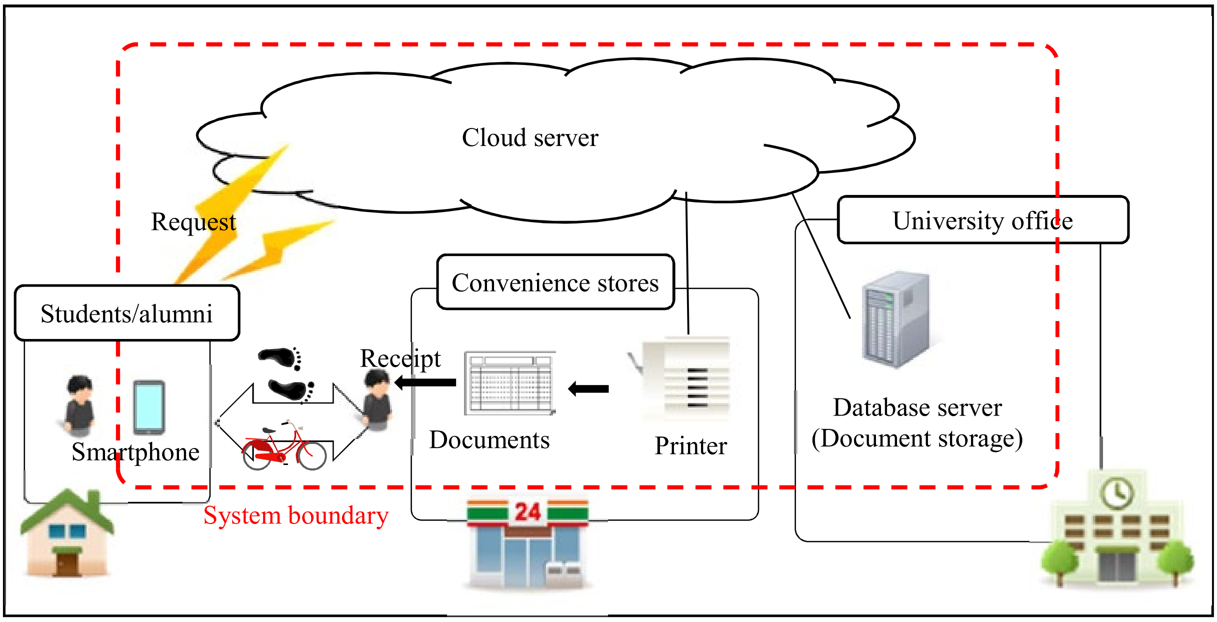

Figure 2: Modelling and system boundary of Certificate Issuance Service

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changes in behaviour would lead to reduction in GHG emissions.

The functional unit of the assessment was 26,000 students' submissions of requests for documents twice per year. Table 1 shows details of items within the system boundaries that were considered for the assessment. We did not consider any increase of requests for documents caused by employing Certificate Issuance Service in this case study.

Table 1: The items considered for assessment of document services

8 checklist items	Conventional services	Certificate Issuance Service
ICT hardware	Servers, printers	Servers, smartphones, printers
Site infrastructure	—	Network lines
ICT software	—	Transcripts/ verification service
Travel (movement of people)	Travel of students from home to university office	Travel of students from home to convenience stores
Transport (movement of goods)	—	—
Consumption of goods and energy	Paper (documents)	Paper (documents)
Storage of goods	—	—
Office work	Handling of requests, printing of documents	—

2.2 Case study 2: Cloud UTM

Network security has been one of the most significant issues within working environments. Unified Threat Management (UTM) is a network security system which unifies two or more security functions. While on-premises UTM requires operation and maintenance of hardware by users, typical cloud UTM services require operation and maintenance not by users, but by data centres. Adding to the high security and freedom from maintenance for users, Cloud UTM is also expected to reduce the GHG emissions of user equipment because cloud-based service enables consolidation of end-users' equipment.

Figure 4 and Figure 3 show the modelling and system boundaries of an on-premises security system and

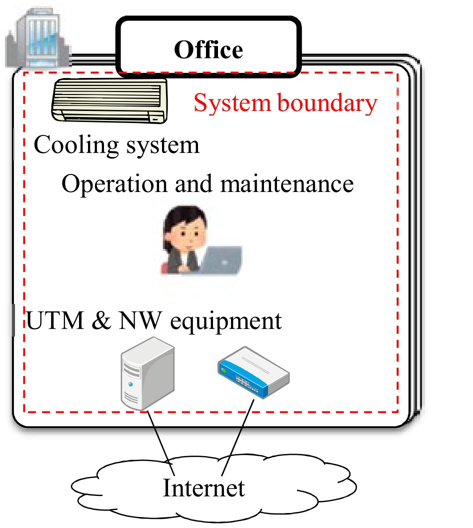

Figure 4: Modelling and system boundary of an on-premises security system

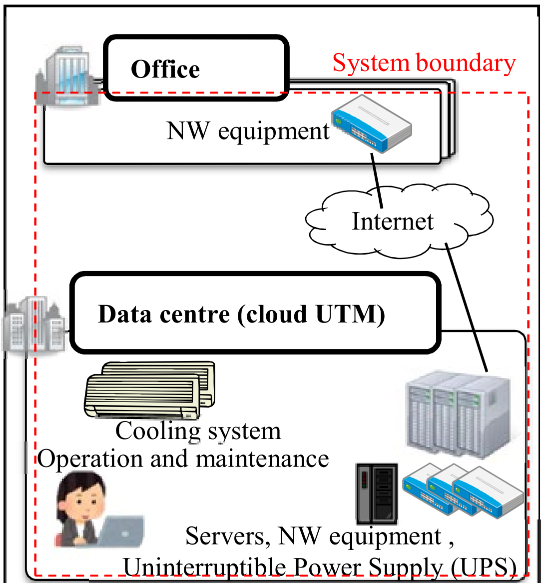

Figure 3: Modelling and system boundary of Cloud UTM

Cloud UTM, respectively. Compared to the on-premises security system, Cloud UTM was expected to reduce the need for cooling systems, UTM equipment, and network (NW) equipment in users' offices. Cloud UTM also seemed to consolidate operation and maintenance.

The functional unit of the assessment was operation and maintenance of network security for 44 offices per year. Table 2 Table 1shows details of items within the system boundaries that were considered for the assessment. We did not consider any increases of offices or subscriptions in this case study.

Table 2: The items considered for assessment of security systems

8 checklist items	On-premises security system	Cloud UTM
ICT hardware	Office: UTM equipment, NW equipment	Data centre: Servers, storage, NW equipment, UPS, cooling system Office: NW equipment
Site infrastructure	—	Network lines
ICT software	—	Cloud UTM system
Travel (movement of people)	Office: Travel for operation and maintenance	Data centre: Travel for operation and maintenance
Transport (movement of goods)	—	—
Consumption of goods and energy	—	—
Storage of goods	—	—

Office work	Office: Operation and maintenance	Data centre: Operation and maintenance

3 Results and discussion

The GHG emission reduction potential of two ICT solutions using cloud servers was quantitatively assessed based on LCA.

3.1 Case study 1: Certificate Issuance Service

Figure 5 shows the LCA results for document services. Whereas Certificate Issuance Service increased GHG emissions from use of network lines and ICT software, it reduced GHG emissions from students' travel and university office work. The GHG emissions avoided were estimated to be up to 7.1 $t\text{-}CO_{2e}$ (34%) per year compared to conventional document services.

3.2 Case study 2: Cloud UTM

Figure 6 shows the LCA results for security systems. Whereas Cloud UTM increased GHG emissions from use of network lines and cloud UTM systems, it reduced GHG emissions from UTM equipment and operation and maintenance in each office. The GHG emissions avoided were estimated to be up to 27.2 t-

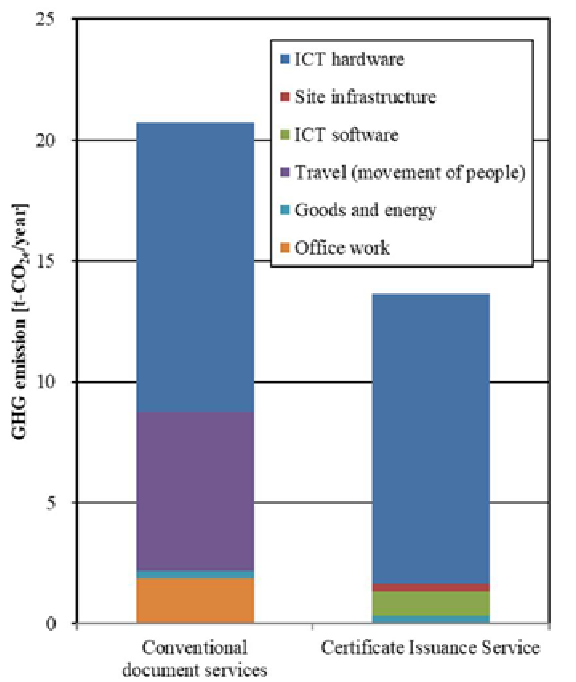

Figure 5: Assessment results for document services

CO_{2e} (42%) per year compared to an on-premises security system.

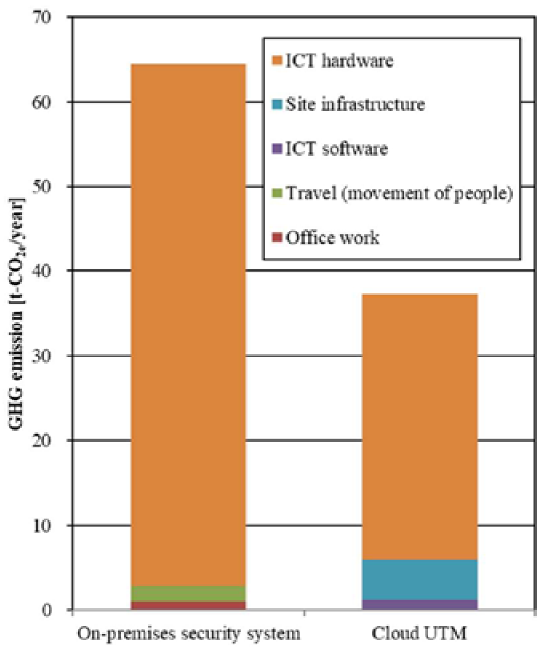

Figure 6: Assessment results for security systems

4 Conclusion

The GHG reduction potential of two ICT solutions using cloud servers, Certificate Issuance Service and Cloud UTM, was assessed quantitatively. Because cloud solutions can decrease the number of end-user devices, these cloud solutions showed reductions in GHG emissions compared to the conventional solutions of 34% and 42%, respectively. In addition, these two solutions did not seem to have any direct or indirect rebound effect.

Furthermore, quantitative environmental assessment methodologies for ICT solutions with rebound effects are expected, especially for cloud-based solutions. In further studies, feedback on the assessment results and labelling from service design and sales personnel, as well as customers, could contribute to promotion of green ICT.

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Assessing the Different Aspects of Circular Economy: Pathway to a Method for ICT Equipment

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Abstract

In 2016 Orange launched a broad scope stakeholder dialogue on Circular Economy with its manufacturers, customers, NGOs, and public authorities. This program helped the operator to obtain a better understanding of which type of equipment (e.g., smartphones, home networks, and networks) and on which phase/action (e.g., reparability, reuse, remanufacturing) it should focus. For network equipment, the question of how to challenge the manufacturers on aspects such as reparability or remanufacturing was raised. From 2018 to 2020, several methods were developed, first internally with relative success, and then through the ITU-T telecommunication standardization body with the help of manufacturers and other operators. This article is a walkthrough of the trials, errors, and success of these past years to reach an assessment system adaptable on a large variety of ICT equipment for the several aspects of Circular Economy.

1 Introduction

Circular Economy encompasses several concepts such as designing equipment with improved reparability, setting-up alternative business models to achieve higher reuse and refurbishment rate, or finding new partners to recycle materials that use to be considered as waste. Global telecommunications operator as Orange sell, rent and operate hundreds, if not thousands, of different type of sophisticated electronic equipment, which are supplied by dozens of manufacturers. This aggregation of different concepts, types of equipment, and partners along the value chain makes it difficult for an operator to challenge the manufacturers efficiently and set-up internal goals.

2 Orange and Circular Economy

In 2018 Orange started working on a Circular Economy scoring system, which will be introduced in network equipment requests for information or proposals (RFI or RFP). The method had to be flexible enough to adapt to different equipment typologies, from small ONTs (optical network termination) to large core network routers, and to be able to cover the multiple aspects of Circular Economy at the design level. The different drafts for the CEN-CENELEC JTC 10 (Material Efficiency Aspects for Eco-design working group) were used as a basis. Therefore, the main goal of the proposed method was to use the same topics (i.e., durability, reparability) with tailored questions for each type of equipment. Each topic was assessed on one or several criteria as follows. The awarded points are indicated in bold.

1. Durability

- Assessment of the three most critical failure modes at the equipment level, according to FMEA (Failure mode and effects analysis). **Assessment available: 2 points; not available: 0 point**
- MTBF (mean time between failures) assessment at the equipment level. **Assessment available: 2 points; not available: 0 point**

2. Reparability

- Type of fasteners used on electronic boards (e.g., are the heatsinks fastened with an acrylic thermal conductive adhesive which might damage the board during the disassembly process). **The fastener can be reused after repair: 4 points; not reusable fastener which can be removed without damage or problematic residue: 2 points; non-removable fastener: 0 point**
- Tools required for disassembly. **Available for purchase by the general public: 4 points; available to authorized third-party repairers: 2 points; manufacturer proprietary tools: 0 point**
- Spare part availability. **Will still be available after equipment end-of-life: 4 points; available as long as the equipment is on catalog: 2 points; not available: 0 point**

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3. Upgradability

- Ability to upgrade the equipment key components (e.g., CPU, HDD, and RAM for a server). **Key components upgradable: 2 points; key components not upgradable: 0 point**

4. Remanufacturability

- Certified second-hand electronic components or sub-assemblies used for remanufacture operation. **Second-hand components used: 2 points; not used: 0 point**
- Remanufacturing time for field-serviceable components. **Less than 15 minutes: 4 points; between 15 and 30 minutes: 2 points; more than 30 minutes: 0 point**

5. Recyclability

- Post-consumer recycled material intentionally used for large metal parts (e.g., heatsinks or cabinet). **More than average recycled content (i.e., a fraction of secondary scrap metal in the total metal input to metal production) defined in UNEP report [1] for the given metal: 2 points; less than this value: 0 point**
- Equipment design-for-recyclability regarding critical raw materials [2]. **Designed-for-recyclability: 2 point; not designed-for-recyclability: 0 point**

6. Critical Raw Material (CRM) Content

- Information on CRM content provided by the manufacturer. **Yes: 2 points; no: 0 point**
- Information provided by the manufacturer on CRM substitutability. **Yes: 2 points; no: 0 point**

As it was carried out in the Orange 2018 CRM assessment method, the second step is to aggregate each criterion to create a single indicator for circularity. This can be achieved by various means:

- **Add the points awarded for the items of the different criteria.** The overall circularity indicator will thus be between 0 and 32. With this additive method, a manufacturer can still achieve a decent mark even if it was not able to score any point for one item.
- **Multiply points awarded for the items of the different criteria.** This multiplicative method is very punitive for manufacturers as a single 0 points answer leads to a null score for the overall circularity indicator. Knowing that some of the questions are quite challenging (e.g., critical raw materials content, which requires third-party suppliers' collaboration), many manufacturers might obtain 0 on first trials.

On top of this additive/multiplicative method, it is also possible to weight the different criteria, for example, according to their importance regarding Orange circular economy strategy or the expected reliability of manufacturer answers. Table X below displays an example of weighting to achieve a maximum score of 100, with a focus on reparability and remanufacturability.

Working ahead of standardization proved a difficult task, as it was not possible to directly use the CEN/CENELEC methods in preparation. For instance, for the recycled content in the equipment, it was not possible to simply ask the manufacturers to provide the amount per material according to the standard. To circumvent the problem on such aspects, the questions to the manufacturers were tailored to a certain extent, depending on the type of material expected to be encountered in the equipment and the possibility to include recycled content. Heatsinks made of copper or aluminum could be targeted, as well as thermoplastics for housing parts. This method was systematically implemented in RFQs, covering large equipment such as servers, as well as customer premises equipment (CPE, i.e., ONT). The feedback from the manufacturers was excellent and helped Orange to leverage the Circular Economy aspects to reduce the equipment's environmental footprint during their lifespan. However, as the method was unique to Orange, the entire process was time-consuming, with the customization of the questions, exchanges with the manufacturers to ensure they understood how to answer and finally on Orange side to determine the score consistently according to these very different answers.

3 Move to the ITU

Based on this evidence, Orange joined the standardization effort at ITU-T Question 7/5 work item L.CE2 as soon as it was launched in May 2019. Note that as end of June 2020 the document drafted by the working group is currently identified as ITU-T draft recommendation L.1023 and is in its final stage of approval process. This working group, which also includes manufacturers as Huawei, Nokia, Cisco, or Apple, started to analyze an already existing three steps methodology to identify a product's circularity in six dimensions [3]. The original method is based on a three-step methodology to identify the design guidelines that need to be incorporated into an existing design to improve equipment circularity and is derived from a publication in the Journal of Environmental Management [3]. The method covers 33 criteria, and for each one to two metrics, R for Relevance and MI for Margin of Improvement, has to be assessed on a 1 to 3 performance scale.

R represents the relevance to the customer of incorporating a given criterion. For instance, for servers, the criterion "Adopt modular designs" is an important one to be able to swap the CPUs or to add a more powerful power supply unit. MI is the margin of improvement comparing the current design and an optimal one. For example, on a server, the capability to "Be able to identify disassembly joints quickly" varies a lot. Some manufacturers add markings (e.g., latches colored in blue to notice them quickly) while some tend to put screws on hidden places.

The Circularity Improvement Score (CIS) is calculated for each criterion using Equation 1. The 33 criteria are grouped into six categories ("Circular design guidelines group" - CDGG), and a single score can also be assessed by calculating the average score of the 6 CDGG.

$$CIS = R * MI \tag{1}$$

The method was tested at Orange on a blade server to check if it can be applied to network equipment. Two major issues were identified during the assessment. First, as the different criteria are not defined precisely, and a glossary is missing, the method leaves much margin for interpretation. For instance, assessing the level of performance R and MI for the criterion "Timeless design" is a subjective question if no guidelines are provided. Secondly, as R and MI are assessed on a 1 to 3 scale, the analyst might often choose the middle ground performance level (i.e., 2) to reflect a design that is neither bad nor top-notch.

Contributions were submitted to the ITU-T working group in June 2019 to solve these issues. They included, among other improvement proposals, several formulas proposals to replace Equation 1. Hence, the new Equation 2 mainly focusses on obtaining a better distribution for the CIS score (i.e., achieve acceptable scores with medium to high MI and R scores) and on expressing the CIS in percentage (better score = 100%).

$$CIS = \left[\frac{(MI + R)}{MI * R} - \frac{1}{2}\right] * \left(66 + \frac{2}{3}\right) \tag{2}$$

When submitted to the ITU-T working group during a technical meeting the significant remark on Equation 2 was that the best score (100%) must be attributed to the combination [MI=1; R=4] (that reflects the fact that there is no more improvement possible and the criterion is very relevant for the customer), while the combination [MI=1; R=1] should have a lower score. Indeed, manufacturers should focus their attention on the relevant topic considering their customer's standpoint.

This remark was addressed by working on a value allocation method directly in the CIS table and on a new equation. Figure 1 shows how the priority levels were first attributed to the different R and MI combinations, to allocate A for [MI=1; R=4] and E for [MI=4; R=4] combinations. The mathematics to obtain the different scores was explained in a previous paper published by Huawei and Orange [4].

		R			
		1	2	3	4
MI	1	C	B	A	A
	2	C	B	B	A
	3	C	D	D	E
	4	D	D	E	E

⇨

		R			
		1	2	3	4
MI	1	55	75	90	100
	2	50	60	70	80
	3	40	35	30	15
	4	25	20	10	0

Figure 1: Left: CIS table completed with priority levels (A = highest) for R and MI. Right: CIS table with priority levels translated in scores (with the best score for [MI=1; R=4])

$$CIS = \left(\left(\frac{1}{3} * MI^3 - 2,5 * MI^2 + \frac{25}{6} * MI\right) * R^2 + \frac{47.188}{MI} + 20,203\right) * 1,006 \tag{3}$$

As the design of the equipment differs massively, and the business model (operated, sold, or rent goods) may also influence, a lot of the initial criteria might not always be relevant. On the other hand, criteria might be missing to depict the design or the business model applied to the device (e.g., design-for-refurbishment for equipment used for a product-service system).

4 Challenges to Find Criteria Suitable for Everybody

To address this problem, the ITU-T workgroup reviewed several contributions. For Orange's Home Network equipment, the (R) values are strongly influenced by the applied business-model. As these devices are rented out to the customer, they are the operator's property during all their lifespan. The operator is, directly or through subcontractors, in charge of collection, repair, and refurbishment operation. This gives a strong incentive for the operator to design equipment that can be disassembled easily (maximum R-value for criteria such as "Use joints that can be disassembled rather than fixed joints") and quickly (maximum R-value for criteria such as "Use screws with the same metrics"). Following this disassembly step, the different parts of the equipment are tested and checked for any aesthetic defaults (e.g., casing plastic parts with scratches or white color that turned yellow due to UV). The faulty parts and the ones that do not match the "as-good-as-new" aesthetics requirements are replaced. At the other end of the spectrum as Gateways and Set-Top boxes are often custom-designed for the operator the use of standardized components such as socketed CPUs or DIMM memory (Dual Inline Memory Module) is not as relevant as it would be for equipment as servers.

This first round of proposals from the different parties ended with a list of 36 criteria, and among them, 14 had examples to define the MI levels. For two of these criteria, Table 1 below shows the MI definitions.

Criteria	MI level definitions
SR: Use materials with good Scratch Resistance for housing parts	MI = 1 - Plastic scratch resistance **equal or greater than 2H** regarding ASTM D3363 - 05(2011)e2 standard
	MI = 2 - Plastic scratch resistance **equal or greater than H** regarding ASTM D3363 - 05(2011)e2 standard
	MI = 3 - Plastic scratch resistance **equal or greater than HB** regarding ASTM D3363 - 05(2011)e2 standard
	MI = 4 - Plastic scratch resistance **lower or equal to B** regarding ASTM D3363 - 05(2011)e2 standard
RC: Promote design that allows to Re-use Components to supply the refurbishment process	MI = 1 - Housing mechanical parts reuse rate **higher than 90 %** after the first year of use if refurbished
	MI = 2 - Housing mechanical parts reuse rate **higher than 70 %** after the first year of use if refurbished
	MI = 3 - Housing mechanical parts reuse rate **higher than 50 %** after the first year of use if refurbished
	MI = 4 - Housing mechanical parts reuse rate **lower than 50 %** after the first year of use if refurbished

Table 1: MI Level Definition for SR and RC (adapted from proposals as part of ITU-T recommendation L.1023 study)

At this stage, we can already notice a difference in how the MI levels are defined. For the criterion SR, an already existing standard was used to set up the levels and allow anybody, with the adequate testing tools, to carry out the assessment. On the contrary, for the criterion RC, the levels were defined according to data collection at the refurbishment center operated by Orange's third-party partner. At the same time, it was an easy task to collect this data for Orange. It would have been challenging, if not impossible, for companies that are not yet involved in the refurbishment process.

At this point, the working group started to see how to make the best use of the CEN/CENELEC standards, such as EN 45554, to define the MI performance levels; while still trying to include additional innovative criteria. Table 2 below displays a further iteration of the method with a new criteria proposal. At this stage, the total number of criteria was reduced to 24, mainly by removing those too complicated to assess. For instance, the criterion on Adaptability (explained as "From a functional point of view (e.g., Wi-Fi and Ethernet capabilities) the product covers the requirement of at least X % of the customers") was removed as it was deemed impossible to define consistent customer requirements at the global level.

Criteria	MI level definitions
ASP: Availability of Spare Parts to different categories of persons/organizations	MI = 1 - Spare parts are publicly available or available to independent repair service providers (**Class A and Class B**, as defined in EN 45554)
	MI = 2 - Spare parts are available to manufacturer-authorized repair service providers (**Class C**, as defined in EN 45554)
	MI = 3 - Spare parts are available to the manufacturer only (**Class D**, as defined in EN 45554)
	MI = 4 - Spare parts are not available (**Class E**, as defined in EN 45554)
TRP: Time necessary to Reach Parts subject to repair	MI = 1 - Disassembly time to reach all the essential components for repair operations is **less than 45 seconds**
	MI = 2 - Disassembly time to reach all the essential components for repair operations is **less than 90 seconds**
	MI = 3 - Disassembly time to reach all the essential components for repair operations is **less than 3 minutes**
	MI = 4 - Disassembly time to reach all the essential components for repair operations is **more than 3 minutes**

Table 2: MI Level Definition for ASP and TRP (adapted from proposals as part of ITU-T recommendation L.1023 study)

The criterion ASP in Table 2 is somehow a direct adaptation of the EN 45554 standards, with a contribution from the ITU working group members to define which levels of availability have to be achieved to obtain the best MI score (i.e., at least an availability for independent repair service providers). The criterion TRP is also derived from already existing articles, and the example provided here is valid for Home Network equipment (e.g., gateways, set-top boxes, Wi-Fi repeaters). However, even if reference time values for standard disassembly tasks based on the MOST and eDIM methods were to be used (e.g., 1.4 seconds for a tool change) members of the working group argued that in real conditions a disassembly time was a combination of factors such as type of tools, type of fasteners, accessibility, skills or working environment. Hence, there would be significant differences in disassembly time measurements for complex operations involving dozens of steps. Thus, the criterion TRP was removed from the method.

To involve the other telecommunication operators, the method was also presented by the working group at the Joint Audit Cooperation (JAC). The operators brought proposals for new criteria, such as the one on environmental footprint assessment (see Table 3 below).

Criteria	MI level definitions
EAK: Environmental footprint Assessment Knowledge available to improve the equipment material efficiency	MI = 1 – An ISO 14040/14044 and ITU-T L.1410 compliant life cycle assessment has been carried out on the equipment, and the results have been used to improve the equipment material efficiency
	MI = 2 – A simplified environmental footprint assessment (e.g., screening life cycle assessment, environmental footprint assessment on one environmental indicator such as carbon footprint) has been carried out on the equipment, and the results have been used to improve the equipment material efficiency
	MI = 3 – An environmental footprint assessment on a similar type of equipment has been studied, and the results have been used to improve the equipment material efficiency
	MI = 4 – Neither an environmental footprint assessment has been done on the equipment, nor an environmental footprint assessment on a similar type of equipment has been studied, to improve its material efficiency

Table 3: MI Level Definition for EAK (adapted from proposals as part of ITU-T recommendation L.1023 study)

This criterion was slightly modified by the working group to introduce a notion a published and publically available data to enhance transparency.

5 Walkthrough of the Final Methodology

During the workshop of May 2020, the method and list of criteria was approved at several levels (up to Study Group 5) and entered a one month revision period. The list of criteria was reduced to 21 (see Table below) to reach a consensus among the different parties. However, as the method offers the possibility to remove or add criteria, this list is only the example extracted from the recommendation. The following section will be discussed how the assessment was done on a real product (set-top box operated by Orange on its French market).

For each criterion, the scoring is determined as follows:

5.1 Scoring for Relevance

To assess the R values several factors are taken into account. Such as the type of equipment (e.g. a set-top box), how the product life cycle is handled by its operator/owner (e.g. sold or rented), the key factors for its environmental footprint (e.g. according to LCA energy consumption during use phase and electronics manufacturing) or total cost of ownership.

For the studied product, a set-top box and for the French market the life cycle will always include some refurbishment operation (Orange is the owner of these devices and they are rented to the customers). To optimize the refurbishment efficiency the disassembly depth of the device will be a crucial factor. Thus the relevance of the criteria 3RUe4: Disassembly depth will be maximum, i.e. R = 4.

The criteria 3RUm2 on Spare parts distribution will be found at the other end of the spectrum. Indeed, as Orange owns the devices the spare parts distribution is only meaningful for the third-party company mandated by Orange to handle the refurbishment and repair operations. So, for this criteria R = 1.

The studied equipment does not contain any battery, be it primary or secondary. Thus, the criteria PD5 on battery longevity is not relevant at all. As such it's removed from the list of criteria for this example.

5.2 Scoring for Margin of Improvement

In the ITU-T recommendation the assessment for the Margin of Improvement is defined by the *Table 4. Guidance for identification of MI level for each CCPD* [5]. This table provides for 4 levels of performance for each criteria in order to help the scoring process.

For example, for the criteria on disassembly depth (3RUe4) one proposal was submitted by Orange, based on studies on its Home Network equipment. The Table 4 below shows the levels of performance defined for this type of equipment, which are rather simple to disassemble. Note that these performance levels (i.e. number of steps required to access essential components) are only valid for Home Network equipment. The number of steps could be much higher for larger network equipment as servers or base stations.

3RUe4: Disassembly depth	
Number of steps necessary to reach priority parts	MI = 1 - All the essential components for repair operations are accessible after one or two disassembly steps
	MI = 2 - All the essential components for repair operations are accessible after three or four disassembly steps.
	MI = 3 - All the essential components for repair operations are accessible after five or six disassembly steps.
	MI = 4 - All the essential components for repair operations are accessible after more than six disassembly steps.

Table 4: Adapted from proposals as part of ITU-T recommendation L.1023 study to define criteria 3RUe4

In this example the studied set-top box is based on a quite old design, not ideal for disassembly. The top and bottom casing, as well as the fan, display subassembly and motherboard have to be separated in order to carry out the repair operations. This requires the following steps:

1. Remove the screws which fasten the top enclosure to the bottom enclosure.
2. Remove the top enclosure.
3. Remove the screws which fasten the display sub-assembly to the top enclosure
4. Remove the display sub-assembly
5. Remove the screws which fasten the fan to the bottom enclosure
6. Remove the fan
7. Remove the screws which fasten the printed circuit board assembly on the bottom enclosure
8. Remove the printed circuit board assembly

According to Table 4, this performance level is equal to MI = 4. Note that this design is one of the most difficult to disassemble for this type of product, usually 2 steps are enough (remove 4 screws and separate top/bottom/printed circuit board assembly). In a similar way for the criteria PD4 on Robustness the Table 5 below shows a proposal of performance rating.

PD4: Robustness	
- Wear and damage resistance- MIL-STD-810H) - NEMA Ratings for Enclosures - IP Class - IEC 60068-2-32 free fall standard - ITU-T K21 Recommendation (last version) for 'Enhanced' levels	MI = 1 - The product's design features better characteristics than the average ones for its product type for NEMA and IP Class. When applicable, it is also compliant with MIL-STD-810H, IEC 60068-2-32, and ITU-T K21 Recommendation (last version) for 'Enhanced' levels.
	MI = 2 - The product's design features average characteristics for NEMA and IP Class regarding the product type. It does comply with MIL-STD-810H, IEC 60068-2-32, or ITU-T K21 Recommendation (last version) for 'Enhanced' levels.
	MI = 3 - The product's design features worse characteristics than the average ones for its product type for NEMA and IP Class. It does not comply with MIL-STD-810H, IEC 60068-2-32, or ITU-T K21 Recommendation (last version) for 'Enhanced' levels.
	MI = 4 - The product's design features the lowest possible NEMA or IP Class. It does not comply with MIL-STD-810H, IEC 60068-2-32, or ITU-T K21 Recommendation (last version) for 'Enhanced' levels.

Table 5: Adapted from proposals as part of ITU-T recommendation L.1023 study to define criteria PD4

For the studied gateway, the NEMA and IP Class were averaged regarding its product type, and it does comply with ITU-T K21 Recommendation for the "Enhanced" level. Thus according to Table 5 this performance level is equal to MI = 2.

Other criteria are calculated likewise to obtain the completed Table 6.

Note that the criterion PD5: Battery is no longer mentioned in this Table as this criterion is irrelevant for the studied product (R = 0).

Equipment: Set-box Gen X		
Criteria	**R**	**MI**
Product Durability		
PD1: Software and data support	4	1
PD2: Scratch resistance	4	3
PD3: Maintenance support	2	2
PD4: Robustness	3	2
PD5: Battery	0	0
PD6: Data security	2	2
Ability to Recycle, Repair, Reuse, upgrade: equipment level		
3RUe1: Fasteners and connectors	3	1
3RUe2: Diagnostic support	4	3
3RUe3: Material recycling compatibility	3	2
3RUe4: Disassembly depth	4	4
3RUe5: Recycled/renewable plastics	2	4
3RUe6: Material identification	2	3
3RUe7: Hazardous substances	3	2
3RUe8: Critical Raw Materials	2	4
3RUe9: Packaging recycling	2	2
Ability to Recycle, Repair, Reuse, upgrade: manufacturer level		
3RUm1: Service offered by the manufacturer	4	1
3RUm2: Spare parts distribution	1	2
3RUm3: Spare parts availability	4	1
3RUm4: Disassembly information	1	3
3RUm5: Collection and recycling programs	2	2
3RUm6: Environmental footprint assessment knowledge publically available	3	4

Table 6: Completed Table with R and MI scores for the Set-top box example

The matrix from Figure 1 is then used to combine the R and MI results for all the different criteria in order to obtain the results for the Circularity Score. In the section 5.1 and 5.2 the criterion 3RUe4 was reviewed and scored as follows: R = 4 and MI = 4. According to the matrix in Figure 1 this gives a Circularity Score of 0. It's the worst possible case, a very relevant criteria which has a very bad performance level. This is entirely due to the non-refurbishment optimized design choice on this example of set-top box. Current products will usually have a much better score for this criterion, such as R = 4 and MI = 3 or 4, thus a Circularity Score equal to 80 or 100 for the 3RUe4 criterion.

Table 7 shows the results of the calculations for all the other criteria.

Equipment: Set-box Gen X	
Circularity Score	Criteria
100	PD1: Software and data support
15	PD2: Scratch resistance
60	PD3: Maintenance support
70	PD4: Robustness
60	PD6: Data security
90	3RUe1: Fasteners and connectors
15	3RUe2: Diagnostic support
30	3RUe3: Material recycling compatibility
0	3RUe4: Disassembly depth
20	3RUe5: Recycled/renewable plastics
60	3RUe6: Material identification
70	3RUe7: Hazardous substances
20	3RUe8: Critical Raw Materials
60	3RUe9: Packaging recycling
100	3RUm1: Service offered by manufacturer
50	3RUm2: Spare parts distribution
100	3RUm3: Spare parts availability
40	3RUm4: Disassembly information
60	3RUm5: Collection and recycling programs
10	3RUm6: Environmental footprint assessment knowledge publically available

Table 7: Circularity Score results for all criteria

The method includes also an additional step, which consist in calculating the Circularity Score at the Circular Design Guidelines Group (CDGG) level. The results for this example of set-top box are displayed in the Table 8.

Equipment: Set-box Gen X	
Circularity Score	Circular Design Guidelines Group (CDGG)
61	**Product Durability**
41	**Ability to Recycle, Repair, Reuse, upgrade: Equipment level**
60	**Ability to Recycle, Repair, Reuse, upgrade: Manufacturer level**

Table 8: Circularity Score results for all CDGG

For instance, the Product Durability contains six criteria, but only five are relevant for the studied equipment. According to Table 7, their scores are PD1: 100, PD2: 15, PD3: 60, PD4: 70, and PD6: 60. Thus the Circularity Score for Product Durability is equal to

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61, as the average of the five criteria. For the Ability to Recycle, Repair, Reuse, upgrade: Equipment level CDGG the equipment studied in this example score is rather low. Indeed, it was not planned with the "Design-for-Refurbishment" approach in mind. Current products will score around 60 to 70 for this CDGG, thanks to many improvement, for example regarding the depth of disassembly.

Note the criterion PD5 on battery longevity is not taken into account in the calculation. Likewise, the Circularity Scores for the other CDGG are calculated. Table 8 below shows the final result for the studied device.

6 Discussions on Future Implementations

On the Orange side, the primary implementation will be to include the ITU set of criteria, or at least a very close adaptation, systematically for every network equipment purchase process (request for information or proposals, i.e., RFI or RFP) for network equipment. This process will be introduced progressively during the second half of 2020. The first trials will, for example, have to cover the question of the understanding of the ITU recommendation by the manufacturers. For other types of goods (e.g., small devices like battery-powered Wi-Fi hotspots), Orange will probably investigate the relevance of the method within the following months.

As other operators (e.g., members of the Joint Audit Cooperation) were involved in setting up the method, a future implementation option could also be internal tests on their side. More extensive use of the method would reduce the manufacturers' workload as the Circular Economy question would be tackled by several actors.

7 Conclusion

The development of a method to cover Circular Economy's multiples facets is a challenging task, especially for equipment as diverse as the ones required by the ICT sector. The length of the supply chain, from dozens of material producers to the equipment supplier, makes it difficult to obtain information at the primary level, such as recycled content for all materials. The CEN/CENELEC EN4555X series will provide an excellent toolbox to tackle these issues. With, for instance, multiple ways to assess parameters such as type of tools, skills, or working environment for the question of reparability. The ITU-T method will bring an additional overlay with a selection of parameters (e.g., fasteners types and disassembly depth for reparability) and proposals of performance levels compatible with multiple types of ICT equipment. As the technology involved in these equipment evolves quickly, and new business models related to circular Economy will surely modify the landscape of stakeholders, this method will have to be updated frequently to keep a sharp edge.

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What to expect from data-driven sustainable product management? Insights from industry cases and PLM solution providers

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Abstract

The information and communication technology architecture of a firm and its rapid adjustments to new technological developments are of importance to the accomplishment of a sustainable Circular Economy. However, it is not yet explicit, how and which data could and should be collected, shared and managed along the product lifecycle. This research deficit is addressed by adopting a mixed-methods approach combining (1) a systematic literature review of 375 articles and reviews with (2) a cross-disciplinary expert focus group and (3) the analysis of 85 product lifecycle management solution providers including six semi-structured interviews. Preliminary results portend a low state of implementation of new technologies in sustainable product management (both from the product lifecycle management provider and user side), as basic compliance management is dominating over more sophisticated and comprehensive sustainable product management approaches (e.g., LCA, circularity assessments, …), which are mostly constrained to traditional ways of information collection.

1 Introduction

Considerable alterations of how product information is collected, exchanged, and managed throughout the physical product life cycle will be essential to facilitate a sustainable circularity of materials [1]. Thus, the information and communication technology (ICT) architecture of an organization and its dynamic adaptation to digital technological advancements are of relevance to implement a sustainable Circular Economy (CE) [2]. While new technological developments such as Internet of Things (IoT), artificial intelligence (AI), Big Data, or blockchain technology hold significant potentials for fostering sustainable product management [3], it is, however, not yet clear how and which data should be collected and shared along the product life cycle. Therefore, the following research questions are addressed in this study:

(1) What are existing applications for digital technologies along a product life cycle for sustainable product management?

(2) What are relevant data sources for actors along a circular (automotive) value cain?

(3) Which role and potential do commercial product lifecycle management systems have in data-driven circular product design?

The overarching goal is the exploitation of the full potential of digital technologies (DTs) for sustainable product management (SPM) along the whole life cycle of a product in a CE.

The term SPM comprises practices such as sustainable/green supply chain management (SCM), sustainable product development or sustainability/circularity assessment. SPM practices share a comprehensive life cycle perspective and the inherent dependency of exchange of material and product-related information. Product lifecycle management (PLM) systems are ICT supported applications in which product information is shared along different lifecycle stages among different organizations and processes to support the enterprise information management. With the connectedness of knowledge PLM solutions seek to provide "the right information, at the right time, in the right context" [4]. Especially in early stages of product development the availability of the right information at the right time and place is key to enable data- and evidence-driven product design contributing to a sustainable CE.

A life cycle perspective is generally indicated by a set of phases that can be considered as independent phases to be followed by a product and can be summarized under three main stages [5], [6]:

- Beginning-of-life (BOL): including the plant-, process-, and product design activities as well as manufacturing and internal logistics,

- Middle-of-life (MOL): including logistics (external distribution), use-phase, and support (e.g. repair and maintenance activities),
- End-of-life (EOL): where products retire and are either recollected by the manufacturing company itself (reverse logistics) or disassembled, refurbished, recycled, reassembled, remanufactured, reused, disposed.

The product and material information flow at the BOL stage is already quite complete as various information systems such as computer-aided design (CAD) or product data management (PDM) are already in place. After the BOL the product and material related information become more vague and insufficiently managed [7]. However, for the implementation of a sustainable CE a closed-loop flow of product and material information is imperative.

With DTs, we refer to the (digital) technologies mentioned above, that have encouraged a paradigm shift for industrial activities and manufacturing. This paradigm shift is frequently subsumed under the term "Industry 4.0" [3] and refers to a radical change in the conception of production processes where smart personalized products are built through smart procedures [2], [8]. Of these DTs that are of concern in this study, the IoT concept describes the increasing interconnectedness of objects and the formation of new networks of information. As identified by Atzori, Lera, & Morabito [9], the IoT can be realized in three paradigms: internet-oriented (middleware), things oriented (sensors) and semantic-oriented (knowledge), and their alignment is central for the usefulness of the IoT [10]. Artificial intelligence (AI) generally refers to technologies that are capable of carrying out certain tasks equally good or better than humans [11], such as machine learning and deep learning [12]. Big data analytics refers to the strategy of analysing large quantities of data that can be distinguished by their volume, variety, velocity, veracity, variability, and value [13]. The most recent of these DTs is blockchain technology, which is described as a chain of time-stamped, cryptographically secured, immutable blocks of consensus-validated digital data. Any correct information stored in a blockchain can, therefore, be seen as appropriate and valid information; thus, blockchains have a substantial potential to enable smart-contracted verifications of sustainability-related data allowing the development of new and sustainable business models [14]. From the angle of SPM, these DTs can be seen as crucial facilitator for a wider adoption of and an accelerated transition to sustainable and circular business practices [3].

2 Method

The above described research gap is addressed by adopting a mixed-methods approach combining (1) a systematic literature review of 375 publications with (2) a cross-disciplinary-expert focus group (3) the analysis of 85 PLM solution providers including six semi structured interviews.

First, a systematic literature review [15], [16] was conducted in March 2019 which focussed on the intersection of SPM and DTs. The review comprised a total of 375 documents extracted from Scopus using search queries that combined terms from both fields as illustrated in Figure 1.

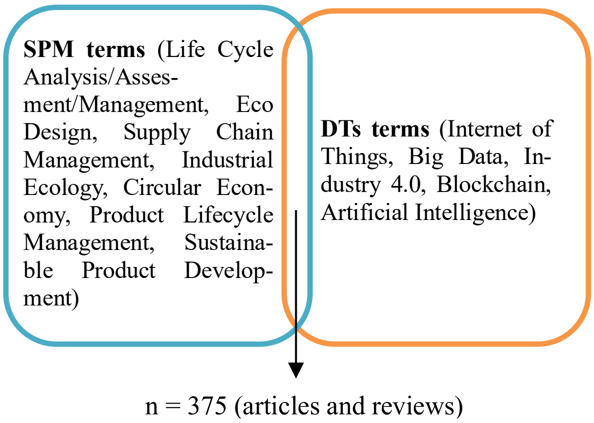

Figure 1: Outline of the search queries

Second, a cross-disciplinary expert focus group workshop was undertaken with ten selected participants (convenience-based sampling) from the industry network of the Christian Doppler Laboratory for Sustainable Product Management enabling a Circular Economy. The focus group comprised of following participants that spanned the product life cycle BOL to EOL: 3 representatives of automotive suppliers, 2 representatives of automotive engineering service providers, 2 representatives of automotive industry clusters, 1 sustainability and compliance-oriented PLM solution provider, 1 IT solution provider, 1 end-of-life treatment and recycling provider. The focus group followed the approach by Henseling et al. [17].

Third, the potential role of PLM solutions for circular product design was investigated by analysing of 85 PLM systems and semi-structured interviews with 6 representatives of those PLM systems. For the analysis of the PLM systems both peer-reviewed literature as well as grey literature was used based on the example of Adams et al. [18] As shown in Figure 2 the search was separated into a search in scientific literature, PLM platform search and social media search. It was searched for both PLM providers as well as PLM products.

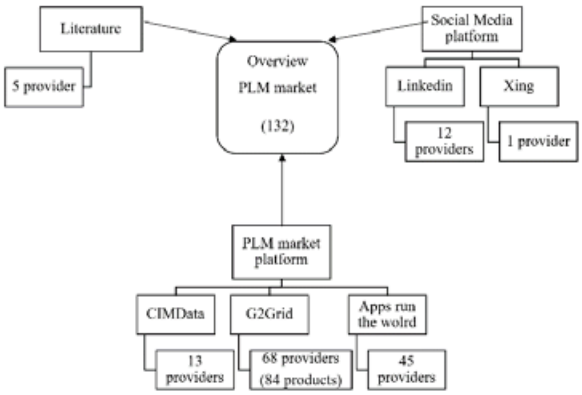

Figure 2: Outline of the search strategy for compiling the PLM solution providers

In total 132 different PLM systems were found. From these 132 systems, six were excluded because the products or providers do not exist anymore or were bought up by another provider. 33 % were furthermore excluded because they were found to be no full PLM but rather specific CAD, customer relationship management (CRM) or SCM solutions or only providers of consulting services.

A total of 26 PLM providers were furthermore contacted and with six of them, semi-structured interviews were conducted (response rate = 27 %). The 26 providers were selected based on their use of DTs and/or their provision of sustainability-related functions (see **Error! Reference source not found.**).

3 Results and Discussion

3.1 Systematic literature review

The findings from the literature review show an increase in publications activity in the intersection of SPM and DTs around 2014/2015 which could be due to the inclusion of the term "Circular Economy" which gained popularity in the last years, especially since the Action Plan for the Circular Economy was presented by the European Commission (Figure 3).

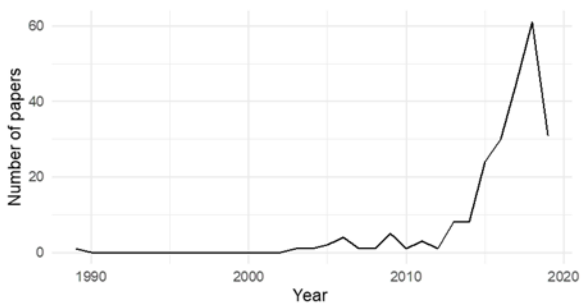

Figure 3: Temporal distribution of the papers analyzed

In total, 375 documents were found and after removing the duplicates 233 documents remained with publication years ranging from 1989 to 2019.

By using an auto coding-search function in MAXQDA, documents in which none of the DT terms were stated explicitly have been excluded from further investigations (exclusion of 33 documents). Additionally, a screening of the documents that used the terms defined for DTs (Figure 1) less than five times in the whole article was conducted and thereby additional 46 documents were excluded, which did not focus on DTs. After this step, 154 documents remained for the qualitative content analysis.

While the results of this qualitative content analysis will be used later on for a comprehensive taxonomy of the SPM of the DTs, this paper focuses specifically on reported applications of DTs for PLM or SPM in industry. In the 154 papers analysed, only 22 cases (mentioned in a total of 10 papers) could be identified where one or more companies were named that apply DTs for PLM or SPM. The descriptions of the given applications varied in their level of detail from merely naming a potential example (e.g. Big Data analytics to improve supply chain efficiency used by the consulting company Accenture) to very detail-rich descriptions of the applied DTs. The following list provides a description of each case and they are classified into the three main product life cycle stages BOL, MOL, and EOL.

Big Data (analytics):

- **Toyota:** Platform for collaboration and knowledge sharing in manufacturing (BOL); Online buyer conversations that appear in social media for feedback on repair orders (MOL) [19]
- **Accenture:** Improving supply chain efficiency (focus on operations) and identification in supply chain risks (BOL-EOL) [20]
- **Pepsi and Kimberly-Clark:** Manage logistics effectively: integrate accurate and finely tuned production schedules, procurement plans, staffing, distribution models (BOL) [20]
- **Amazon:** Mining social media data can help understand consumer preferences toward products with different environmental implications (MOL) [21]
- **U.S. Department of Agriculture:** Estimation of land use, seed use, irrigation, and use of nutrients, manures, and pesticides (BOL-EOL) [22]
- **U.S. Environmental Protection Agency and U.S. Energy Information Administration:** Prepare the "Emissions and Generation Resource Integrated Database3" to provide resource mix, heat input, and select air emissions data for U.S. electric power generation (BOL) [22]

IoT and/or Big Data (analytics):

- **Intel:** Predictive maintenance of equipment (BOL) [23]
- **Alpha**: Monitoring of product condition, status, location and usage to enable product sharing between multiple users and personal advice to reduce energy and water consumption (MOL) [24]
- **Walt Disney World:** Energy management program (MOL) [25]
- **Caterpillar's Marine Division**: Data from shipboard sensors provide new insights into optimal operating practices (MOL) [25]
- **Walmart:** Worker-generated data collected through "LaborVoices" (MOL) [25]
- **Toyota:** Equip cars with smart sensors and continuously collecting data about its locks, location, ignitions, and tyres (BOL,MOL) [19]
- **Santander Spain:** Improving the efficiency of city services and the controlled infrastructure is the street lighting that detect the presence of people and cars (MOL) [26]
- **Rolls-Royce:** Servitized business model, where airline manufacturers no longer buy engines but pay a variable fee for their availability; preventive and predictive maintenance (BOL-EOL) [24]
- **SEAT and Philips Lightning:** Replace its exterior light sources by connected LED lighting (MOL) [27]
- **Cisco's sport shoes:** Tracks shoes condition and identify re-placement needs (MOL, EOL) [27]
- **Arup's circular building**: Maximize utilization of components and materials on a building construction (BOL-EOL) [27]

IoT and blockchain:

- **Maersk and IBM:** More accurate and trustworthy bills of landing attached to maritime containers (MOL) [28]
- **Provenance:** Seafood supply chain for transparency and validity of sustainable practices (BOL,MOL) [28]
- **Ikea:** Supply Chain transparency (BOL) [28]
- **IBM and Energy Blockchain Labs Inc. China:** Carbon asset development and trading (BOL) [28]
- **Social Plastic or RecycleToCoin:** Recycling programs with reward based with tokens (EOL) [28]

The two subsequent empirical research steps expand upon the findings regarding the state of implementation and potentials of utilizing DTs for PLM and SPM in literature by adding different viewpoints from industry experts.

3.2 Focus group

The cross-disciplinarily focus group resulted in a collection of diverse viewpoints and statements from different industry-stands spanning a large proportion of the automotive product life cycle. The results showed that current industry sustainability practices are often driven by legal and customer (e.g., Original equipment manufacturer (OEM) and user) requirements. The meaning of sustainability in a CE context is not sufficiently clear to the experts to derive suitable indicators and relate DTs or (potentially) new data sources for SPM. It was mentioned that there is a perceived lack of harmonization and standardization of database information. A challenge that was particularly mentioned from the participants was the exchange of sustainability data along (multiple) product life cycles, especially regarding the communication between the manufacturing and end-of-life phases. Also, personal and intra-organizational issues should be considered in the discussion about data-driven SPM in a potential circular value chain that should lead to a sustainable CE. Most data sources to develop "data-driven SPM in a circular automotive value chain" were named for the BOL phase. The difficulty with vague product and material information flows after the BOL which was described in theory was also described by the practitioners.

The subsequent research step was conducted to investigate the potential of existing PLM solution providers to manage product and material information flows in a CE.

3.3 Analysis of 85 PLM systems

To address the third research question, the role and potential of commercial PLM systems in data-driven circular product design was investigated. In the first research step, a total of 85 PLM solutions were analyzed regarding their sustainability-related functionalities and their utilization of new technologies and data-science approaches. Second, seven semi-structured interviews were conducted with seven PLM system providers.

As depicted in **Error! Reference source not found.** the large majority of PLM systems handles data during the beginning of life phase (BOL), with the largest share focusing on material data (93 %), followed by product structure (84 %) and processes and technology (53 %). Data from the middle of life (MOL) phase is only handled by 16 % (data during product use), respectively by 15 % (packaging data) of the analyzed PLM solutions (**Error! Reference source not found.**). Data during the product use focuses mainly on the after sales market and includes among others repairs, maintenance services and in some cases replacement activities.

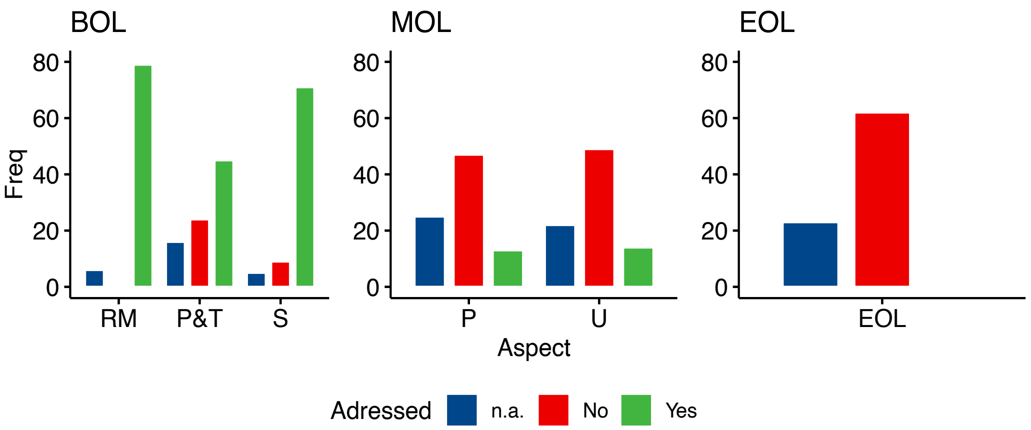

Figure 4: Coverage of life cycle phases by PLM solutions (n=85). RM = raw materials, P&T = processes and technology, S = structure of the product, P = packaging, U = use of the product.

As shown in **Error! Reference source not found.**, 73 % of the studied PLM systems do not deal in any kind with information after the functional lifetime of the products. The other 27 % claimed their PLM systems are able to deal with data of the whole lifecycle including disposal and wastage but there was no evidence if those were not typical marketing slogans but real functions the systems provide. These findings are in line with those of Terzi et al. [6] what indicates no essential progress regarding the coverage of the MOL and EOL phases in PLM systems in the last ten years.

Figure 5a furthermore shows that the majority of the analyzed PLM systems actively promote their capabilities for facilitating internal collaboration across departments and teams and with more than half of the systems it is possible to share data across the enterprise boundaries. 15 % limit the collaboration functionality on internal enterprise processes and for 33 % such functionality was not specifically mentioned. Furthermore, 42 % of the tested PLM systems mentioned the importance of compliance management (Figure 5b) and provide functions to support this. 35 % of the PLM systems do not provide any compliance functions or do not consider compliance management. For 22 % of the cases it was not clear if the PLM systems provide any function to facilitate compliance issues.

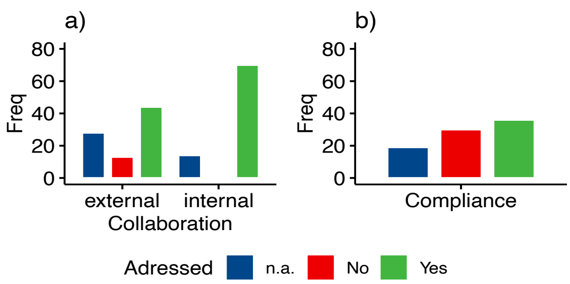

Figure 5: a) Collaboration capabilities of the analyzed PLM solutions b) Consideration of compliance function (n=85).

Finally, the available information about the 85 PLM systems was inductively coded regarding economic, digitization and sustainability-related aspects mentioned. As can be seen in Figure 6, economic aspects dominate in their communication, while digitization related aspects are only mentioned 2 - 15, and sustainability related-aspects only 2 - 6 times.

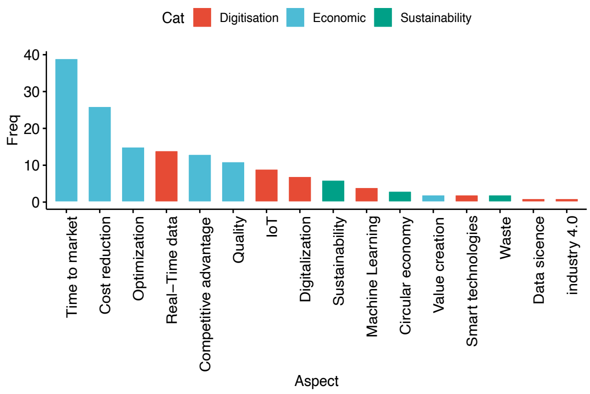

Figure 6: Classification of the functionalities of the analyzed commercial PLM systems.

The six semi-structured interviews with PLM solution providers indicated the increasing emphasis of PLM solutions on the MOL and EOL. Especially the deployment of the digital twin was considered as promising functionality and potential game-changer for the market of PLM systems. Currently, their application is largely limited to the use of production machines. However, the deployment of digital twins along the full product life cycle, was seen as a promising approach to support a circular product design and gather data through the whole lifecycle. As biggest enabler for digital twin applications, the interviewees considered accompanying business models that take into consideration also the EOL phase.

4 Conclusion

In summary, DTs can provide new possibilities for a more dynamic SPM in the future. Currently, the analysed PLM solutions on the market reflect the technological trends that have been identified in the literature review. Various applications of DTs address the issue of optimization and efficiency advancements with the goal of reduced costs. These issues are also important in the communication of PLM system providers regarding the functionalities of PLM systems to shorten the time to market, to enable cost reduction and optimization. Up to now, the full potential of DTs for a comprehensive use in SPM is still largely untapped and the integration of a full life cycle perspective for product-related information is rather discussed in theory than implemented in practice. Therefore, a "translation" into practice is needed to understand real-life impacts and to unlock potentially untapped synergies of DTs for SPM.

The following key lessons can be summarized from this study:

- The advancement of data management along the whole lifecycle of a product is essential for a sustainable CE. Especially proactive approaches to collect and manage product data also in the MOL and EOL are needed. Decision-making in the BOL can be the enabler for a sustainable CE and is a crucial step for the availability of product data in all the subsequent life cycle stages.
- Inter- and intraorganizational collaboration - supported by DTs - from BOL to EOL stages is inevitable for SPM. PML systems facilitate the exchange of product-related data within and outside company boundaries. Especially the gap of EOL coverage in PLM systems needs to be closed to increase information about the (current) state of the product or material at the end of a product´s life and its availability.
- Smart ways of product and material-related information collection and exchange will ease the circularity of resources, which could lead to new competitive advantages, especially in light of an increased scarcity of resources in the future and stricter regulations enforcing the closing of material loops.

Working on comprehensive and holistic data-driven SPM approaches offer unique chances to contribute to a transition towards a sustainable CE. Moving beyond efficiency issues towards a holistic utilization of DTs for SPM will support the necessary transformation towards a sustainable CE.

Acknowledgements

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Going Beyond Regulatory Product-related Compliance – Taking Established Green Data to the Next Level to Support Design for Environment of ICT

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Abstract

The Internet of Things remains the constant enabler for truly innovative business models in monitoring the environment with artificial intelligence, connecting cloud-based IT solutions to smart sensor- and actuator technology. By bridging the gap between the cloud and everyday objects, information and communication technology (ICT) has evolved as the control center of everyday digital life, entering all industries.

However, ICT hardware bears a number of environmental risks that require mitigation and are rooted in the inherent nature of versatile and advanced electronics hardware. Global compliance regulations setup the mandatory requirements for applying environmental considerations to electronics design. Building on the established set of information collected during the regulatory process, the identification of measures and required data to go beyond the regulatory framework is the next logical step in establishing a true Design for Environment (DfE). This leads to a strategy to cope further with the above-mentioned challenges.

This contribution targets at identifying already available information about the product's material composition and supply chain as the result of the necessary due diligence of the compliance assurance process. Using the example of the product class of smart cloud-based devices and wireless sensors for environmental-monitoring in the IoT, green data assessed during the compliance process is discussed. Information compiled in preparation of (technical) documentations covering topics such as Hazardous Substances, Conflict Minerals, Energy Efficiency, Material-Efficiency and Design for Repairability are evaluated with regard to identifying environmental hot spots as the next logical step in prioritizing efforts in improving the product-related environmental impacts.

Keywords: *Compliance, Green Data, Environmental Screening, EcoDesign, ICT*

1 Intro

With the transition from a linear to a circular economy, the focus of legislation continuously extends from improving the inherent environmental risks associated with the product to a more holistic approach of life cycle thinking. Thus, there is a shift from the mere consideration of critical substances inside the system put on the market and energy consumption during the use phase to increasing material efficiency whilst eliminating waste. Integral part of Circular Economy is to foster Design for Environment though all life stages.

Principles supporting the idea of "Design for Environment" (DfE), in the broader sense defined as "EcoDesign", cover a range of approaches to reduce the overall risks to human health and environmental burdens of products, including processes and services, addressing all life phases. DfE has the largest leverage effect when initiated in early product development phases and requires alignment with efforts in meeting technical specifications, i.e. function, appearance and quality and product-related compliance requirements. Synchronizing the latter with EcoDesign approaches seems like the first logical step in going beyond regulatory compliance assurance and improve the environmental performance of electronic products.

In the context of this contribution, "Green Data" is considered all data collected to meet compliance targets. This includes checklists, technical documentations and test reports delivering proof of implementing environmental product regulations. This paper investigates if and how this data can be of additional value to support strategies to improve environmental performance of electronics going beyond the baseline provided by regulatory frameworks.

2 Design for Environment in the ICT industry

The improvement of the environmental dimension of products and services represents a central area in the sustainable development of goods and services. According to the "International Union for the Conservation of Nature" (IUCN) and the "World Wide Fund for Nature" (WWF), sustainability defines "a natural system only in this way to use that its essential characteristics are preserved in the long term" [1]. The description of the Brundtland report of the United Nations from 1987 additionally provides "to satisfy the needs of the present without hindering future generations in their actions" [2].

2.1 Need for environmental sustainability

With regard to the aspect of ecology, sustainable development must take into account the economy as well as the social and demographic development of society (three-pillar model [3]) and thus be geared towards the present and the future. Given the complexity of these cross-links in a globalized world, it is challenging if not impossible to derive generally applicable measures for sustainable action. Likewise, politically, economically or ecologically motivated conflicts of interest inevitably require compromises across all levels of sustainability, so that changes in the prioritization of sub-goals are always determined by different constellations of interest groups. A somewhat stricter formulation of the concept of sustainability calls for "development without growth across ecological boundaries" [4]. This focus on environmental sustainability is based on the assumption that the basis for human existence can ultimately only exist within a functional, continuously regenerating ecosystem. The extremes of ecological boundary limits, including the dimension of climate change are described in more detail in [5]. Acting within these guidelines reduces the risk of irreversible environmental changes, which would adversely affect the habitability of parts of the world and consequently all pillars of sustainability.

2.2 Importance of DfE in ICT

Innovative technologies for the implementation of sensory, actuating and smart computing skills at increased integration density and efficiency allow for a multitude of functionalities leading to Information and Communication Technology (ICT) pervading nearly all areas of life. With the addition of network capabilities, embedded hardware solutions become a virtual representation in the Internet of Things (IoT), connecting objects of the physical with the digital world. Whilst ICT devices function as agents to improve environmental outcomes in other sectors, e.g. energy efficiency, dematerialization, monitoring) the ICT sector is itself taking on significant burdens.

Electronic and electrical equipment contributes to environmental damage, among other aspects, through:

- Complex variety of functional and passive materials that are potentially harmful at least over parts of the life cycle
- Strong dependency on resource-critical materials due to the high degree of functional density in latest innovations
- Use of raw materials and processes with significant environmental backpack, e.g. energy- intensive manufacturing processes for semiconductors and interconnect technologies
- Limited lifetime that requires reuse, repair, 2nd-Life service models to extend the effective use-phase of ICT
- The potential risk of dissipating critical materials that can only be held in the inner- or outer loop of Circular Economy (CE) through considerable efforts

Integrating sustainability into the product and related services thus requires a full, closed-loop product lifecycle environment to mitigate the above-mentioned risks. Besides focusing on the elimination of immediate risks associated with the product itself, large volumes of ICT products can be harvested for extended use or material recovery in accordance with the vision of a circular economy (CE) [6].

2.3 General Strategies for DfE in the context of ICT

To approximate the idea of a circular economy, goals in EcoDesign focus on the avoidance, reduction and circular use of materials and processes associated with significant impact on the environment. Strategies aiming at implementing these overarching goals follow a combination of two major routes:

- Environmentally conscious product design aiming at avoidance and reduction of toxic and/or critical resources and processes with significant environmental backpack. These design decisions are typically optimized based on the primary design requirements set for the originally intended purpose of the product
- A more holistic approach of optimizing the complete life cycle of electronics products, based on the idea of multiple life cycles of the complete system, parts or materials through cascaded use

Both approaches are closely interlinked, as they follow the same overall goal of increased material and energy efficiency at reduced environmental impacts. However, whilst measures on the reduction of product-related environmental impacts are increasingly becoming integral part of in-house product design processes, life cycle oriented design with a multitude of potential 2nd life scenarios for electronics requires a close synergistic cooperation between businesses and industries.

2.3.1 Environmental impact reduction of materials and processes

Reducing environmental burdens of materials and processes directly associated with the final product remains central part of DfE for ICT. In early stages of product design and materials sourcing, substances can already be categorically excluded during requirements engineering, e.g. through negative substance lists. Exclusion criteria are pre-defined by legally regulated material bans and often extended through voluntary commitments in connection with environmental labels or internal company strategies. At the same time, positive lists, e.g. preferred materials suitable for recycling or sustainable alternatives to materials known to be critical can support DfE.

Energy-efficiency of ICT devices is determined by several factors including the interaction of multi-physical hardware components with software layers. For connected services, e.g. cloud-based applications, consumption-related optimization has to be synchronized with back-end processes. However, choice of efficient components for fixed tasks that allow benchmarking is crucial during hardware design and component sourcing.

Reduction of the environmental backpack of electronics focusses on the consideration of burdens associated with raw materials and components sourced during the system design process. Typically, these include semiconductors and electronics packaging processes as well as materials with a high energy and resource demand during manufacturing, e.g. gold. Awareness of these environmental hotspots is crucial to increase the useful life of these elements, thus reducing the overhead generated by ICT technologies.

In the context of this paper, those raw materials are classified as critical for which there is a high dependency coupled with a high supply risk. For electronics, these are primarily metals that are characterized by a high demand at limited resources, concentration of production sites or politically unstable countries of origin. Examples include conflict minerals, typically the metals tantalum, tin, tungsten and gold (3TG materials). The issues arising by the finite availability of already scarce or difficult to access resources is exacerbated for electronic systems by the continuously increasing consumption of metals. Recycling processes are technically limited so that a complete recovery of all initially contained resources, especially in the case of highly integrated systems with complex substance combinations, cannot be fully implemented. If take-back cycles are not established, there remains the risk of dissipation of critical resources that cannot be held in the loop. In the case of raw materials that are difficult to replace, low recycling rates, such as those for rare earths, are problematic from a long-term perspective. Special attention needs to be drawn to these materials to limit their use to in electronics design.

2.3.2 Increased material efficiency through life cycle optimized design

Design measures targeting at the extension of the useful life of electronics incorporate the technical domain of Design for Reliability, i.e. ensuring that ICT devices perform a specified function within a given environment for an expected lifecycle. The level of robustness integrated into the design depends on current and potential future application scenarios adequately representing the originally intended environment and potential use cases in 2nd life of the system or its parts.

Prerequisite to extend the life in service are measures focusing on maintainability, repairability and eventually the upgradability of devices and equipment. This involves the areas of Design for Remanufacture, Design for Assembly and for De-assembly [7]. At the same time, these strategies support multiple use through access to all system levels, allowing for removability of components and materials kept in the loop at end EoL.

DfE has to consider the end-of-life (EoL) once (multiple) use is not an option. Accessibility to elements suited for recycling, e.g. selected plastics and/or metals, modular design approaches allowing for separation of individual fractions optimized for dedicated EoL treatment options is an important step from the perspective of holistic life cycle optimization.

3 Environmental compliance assurance as a source of green data

Due to the specific environmental concerns associated with ICT products, this category of electronics has been subject to a wide range of global regulations. Current legislation in force primarily aims at substances in articles, energy efficiency and treatment of waste of electronic and electrical equipment, batteries and packaging. However, driven by policies, such as the latest implementations of the EU EcoDesign Directive by product groups and policy initiatives such as the European Green Deal, the topic of material-efficiency is increasingly gaining in importance, requiring a holistic approach on optimizing the product life cycle in all stages.

3.1 Green data - Starting point for DfE

Reaching compliance status with product-related environmental legislation starts with the identification of enforced law applicable to the regions of putting the product on the market. Requirements specific to market access and individual product applications are derived by assessment of the manufacturer's, importer's or distributer's personal obligations and the product scope defined by legislation. Based on the findings, a roadmap is developed that allows for the establishment of a procedure to compile reports, conduct testing and possibly receive certification allowing to provide proof of conformity to market surveillance authorities.

The process of assuring compliance with product-related environmental regulations requires a thorough understanding of the technologies in place and collection of corresponding green data, as exemplarily outlined in the following sections.

Green data collected as part of the compliance assurance process has significant advantages when it comes to the following aspects:

- Availability of data, if required as part of minimum requirements defined by legislation and corresponding implementation guidelines
- Documented results as proof of conformity, ideally centralized and easily accessible
- Up-to-date with current legislation in force
- Robustness of data, especially if done in accordance with referenced norm and standards
- Specific to the product to be put on the market instead of generic data
- Non-optional as driven by legal responsibilities spread across the supply chain

Use of this data beyond its original purpose is the next logical step when implementing EcoDesign measures. It is clear, howsoever, that data acquired in this process should be treated as a supplementary source of information, best possibly an initial starting point to support DfE in electronics development.

Not all products are subject to regulation, as general exclusions and application-specific exemptions apply to certain product groups. Beside the product scope, level of granularity of the defined objects affected by regulatory requirements depend on several factors, i.e. the regulatory framework in place, its regional transposition and the specific topic covered. Knowledge of the latter is crucial when redirecting green data acquired during the compliance assurance process to address specific DfE strategies.

3.2 Product scope

Overall applicability of regulations depends on the specific context of the application scenario of the product. To evaluate the completeness of data, potentially relevant exclusions or exemptions have to be considered. Examples include exemptions for lead-content in selected homogenous materials under EU-RoHS if part of a distinguished type of electronic and electrical equipment (EEE) in selected applications. Use of otherwise restricted materials might be regulated by exemption in cases that do not allow for its replacement from a technical perspective or when comparing its environmental impacts against alternatives reveal less advantageous results from a more holistic perspective. At the same time, particular product categories like large-scale fixed installations might benefit from a general exclusion under RoHS, i.e. in this case, risk assessments and related evidence documents will not be available.

Moreover, it should be determined which element in the hierarchy of material composition is affected. Typically, compliance data relates to one of the following elements:

- Substance
- Homogenous Material
- Article
- Component
- System

Whilst EU RoHS regulates maximum threshold values for presence of hazardous substances on homogenous material level, EU REACh focusses on monitoring and authorization of substances of very high concern (SVHCs) in articles as part of the product. Substance-specific regulations and their threshold values can also apply to complete products, e.g. the ban of mercury in selected batteries regulated by individual state-laws in the US.

Thus, potentially available data from substance regulations relates to limited product groups and even different product-levels. Further examples include energy-efficiency requirements applying to only selected product groups, e.g. energy-related products under the EU EcoDesign Directive or products serving as parts, e.g. external power supplies regulated by existing mandatory US federal energy efficiency standards in accordance with the Energy Policy and Conservation Act.

3.3 Compliance with substance regulations and interlinks to DfE

In general, compiling checklists resembling current and upcoming legislative requirements provide for an initial starting point in checking the presence of potentially hazardous materials included in the product. Compliance with European product-related regulations include knowledge of concentrations of ten hazardous substances under RoHS on homogenous material-level, the Candidate List of SVHCs and location of the latter inside articles as part the product, enforced by upcoming legal requirements around the SCIP (Substances of Concern In Articles) database. Further prominent examples include the knowledge of concentration level above or below safe harbor levels for Proposition 65 substances under California law and corresponding warnings to be issued.

Negative lists might already go beyond fulfilling the minimum baseline set by regulatory compliance, e.g. through company-own initiatives in outsourcing hazardous or critical materials or participation in voluntary certifications or labels, as part of purchase agreements with suppliers.

Positive lists such as material declarations provide the main source of support in the compliance assurance process as they provide insight into the material composition of the product under investigation. Besides determining the regulatory status, these documents can serve in delivering essential information on

- Product structure
- Type of components applied
- Inventory of materials contained in these components
- Concentration levels of included substances

Whilst reporting formats ideally follow a standard, e.g. IPC-1752A Class D (full material disclosure at the homogenous material level), in practice, suppliers often provide material declarations on a case-by-case basis, depending on how the purchasing contract has been negotiated. However, all information collected from bills of material (BOM) that might just contain a flat list of components up to full material declarations can support the first screening of potentially toxic or resource critical materials, either listed or likely associated with the component group included in the product. Also, BOMs will support the identification of active parts, narrow down components and technologies associated with a high environmental backpack and help locate materials and parts when improving the circular design of the system.

Energy efficiency requirements are narrowed down to high-impact product categories and components. The US Department of Energy (DOE) implements minimum efficiency standards for certain appliances and equipment, and currently covers more than 60 different products. Battery chargers and external power supplies are the most prominent example of ICT peripheral equipment regulated.

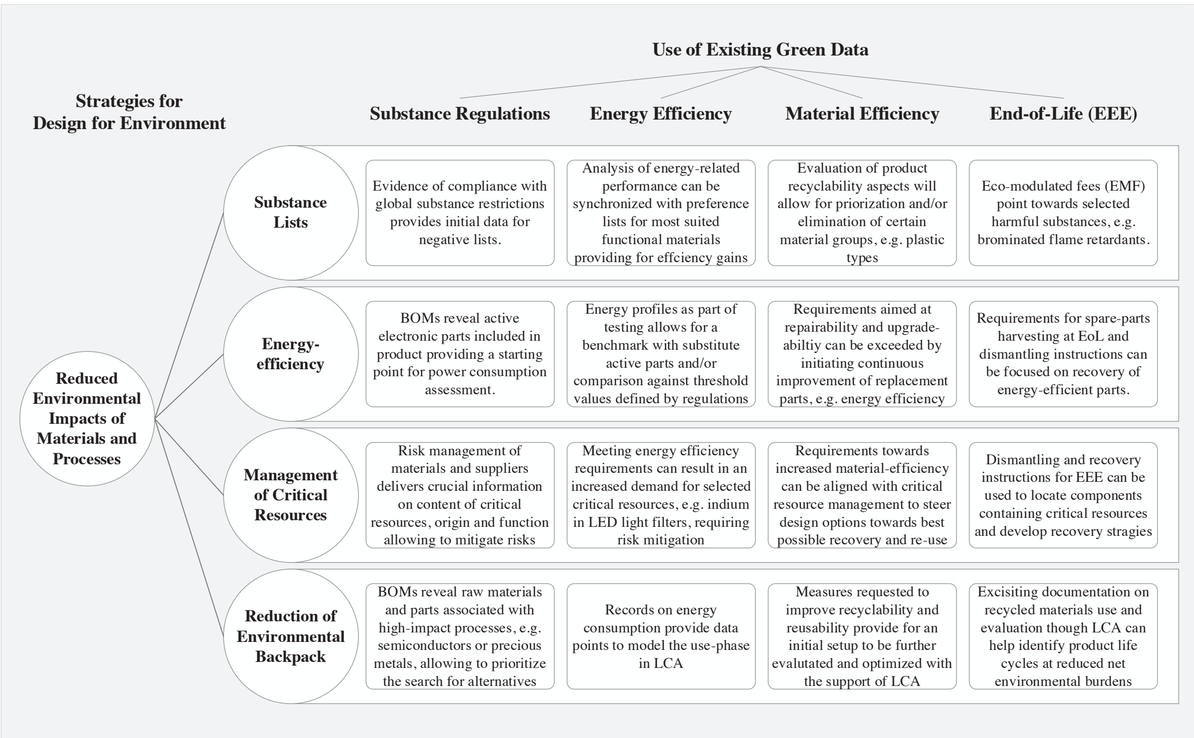

Figure 1 – Use of Green Data to support DfE strategies supporting the reduction of environmental impacts through materials and processes

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The European Energy-related Products Directive (ErP) is implemented through product-specific regulations limited to high-impact product groups, e.g. electronic displays, directly applicable in all EU countries. While the Ecodesign Directive's primary aim is to reduce energy use, it has the overall aim of enforcing environmental considerations beyond mere energy use, increasing material-efficiency, reducing water use, polluting emissions, waste issues, recyclability and repairability. The Directive establishes a framework for setting of ecodesign requirements for energy-related products with the ultimate aim that manufacturers of energy-using products will, at the design stage, be obliged to reduce the energy consumption and other negative environmental impacts of products. Upcoming requirements for electronic displays already include the use of joint and fastening techniques not hindering removal of certain components, the indication of plastic parts and types and access to repair and maintenance information [8].

With regulations on material and energy efficiency moving forward, more green data can be expected for a larger group of products but is currently limited in scope. However, documentation of existing compliance requirements can provide examples to be transferred to other systems when developing strategies to close the loop of product life cycles.

End-of-Life compliance requirements, e.g. as set by the WEEE directive in the EU have been facilitating the reuse, dismantling and recovery of waste electrical and electronic equipment. Through extended producer responsibility (EPR) environmental costs associated with the product life cycle are (partially) covered by producers through fees paid to a stewardship organization, which finances the collection and recycling of waste products. With the recast of the WEEE Directive the EU is promoting the idea that fees paid by manufacturers into organizations that implement the principle of extended producer responsibility (EPR), should be eco-modulated. The implementation of certain DfE criteria would be rewarded with reduced fees [9].

Although mandatory implementation of eco-modulated fees are still under policy development, fee-modulation for electrical and electronic equipment, Ecologic [10], one of France’s national WEEE take back schemes, already today offers monetary incentives for

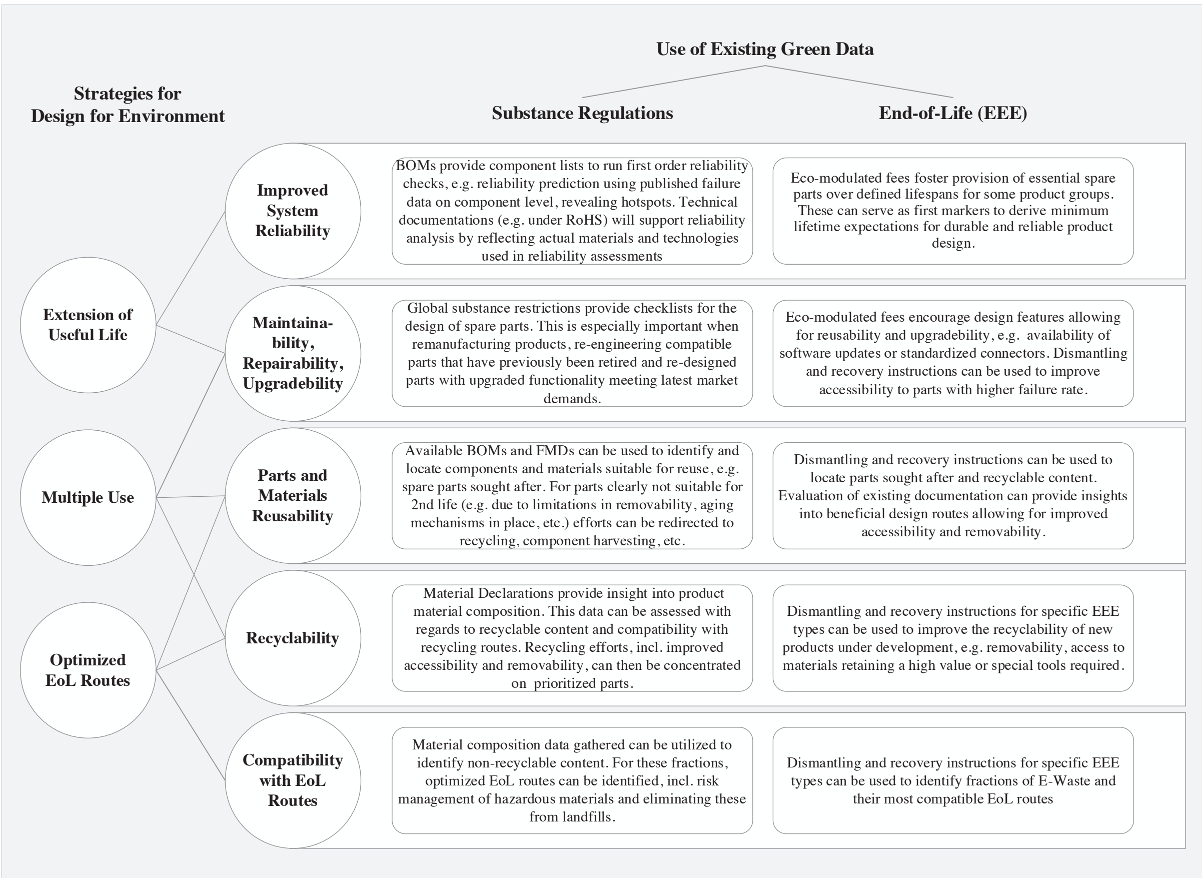

Figure 2 - Use of Green Data to support DfE strategies supporting increased material efficiency through life cycle optimized design

environmentally-conscious design of selected equipment, incl.:

- Reduction of hazardous materials, e.g. plastic parts containing brominated flame retardants above threshold level
- Fostering long useful life, e.g. through availability of software updates or standardized connectors
- Product upgradability, e.g. through use of standard tools
- Repairability, e.g. through provision of technical documentation for electrically authorized repairers, essential parts for equipment
- Recyclability: Use of post-consumer recycled materials and absence of paint and coatings incompatible with recycling and reuse on plastic parts

Although voluntary, participation in eco-modulation will provide documentation of contributions to selected EcoDesign topics and products, thus allowing to transfer knowledge and data acquired (e.g. on plastic types) to other product groups within the available or future product portfolio.

Legal requirements for manufacturers to provide dismantling and recovery instructions already existed with the previous version of the latest WEEE Directive 2012/19/EU, however, Article 15, requires producers to provide information free of charge about preparation for re-use and treatment for each type of EEE placed on the market.

In practice information contains:

- Corporate and product information
- Declaration and location of materials requiring selective treatment
- Declaration of valuable materials and materials of interest to recyclers

In an initiative of industry associations, platforms such as I4R were developed, to facilitate a centralized database to provide recycling instructions [11]. These documents provide insights into measures supporting or limiting repair, re-use, recycling or environmentally conscious disposal. Compiling these documents and review of instructions related to previous product generations will allow for identification of potentials to improve DfE measures aiming at the complete product life cyle.

Interlinks between compliance assurance data and DfE approaches are outlined in Figure 1 and Figure 2. These can trigger first assessments that already might require more extensive data acquisition for EcoDesign activities.

4 Conclusion

Already established data sets to fulfill product-related environmental compliance requirements provide a starting point for taking green data to the next level of conducting Design for Environment.

Most useful sources of green data include material declarations collected in the process of dealing with substance requirements. Simplified screening based on material composition data will allow the identification of hotspots in system design in need for DfE measures. Full disclosure of substances allows for the identification of critical and potentially hazardous materials and their allocation to product (sub-) assemblies. Moreover, components depending on processes with a significant environmental backpack can be identified, triggering more detailed analysis.

With the aim of closing the loop in circular economy, material-efficiency is increasingly addressed by upcoming regulations. As of now, data is limited to a few selected product groups and topics. For energy-efficiency, maximum power consumption is defined for some of the most critical power consumers in markets such as the EU, covering only a limited selection of devices.

Dismantling and recovery instructions delivered to recyclers along with WEEE disposal can provide useful information on best-practice in hardware layout when it comes to accessibility of system elements in need for repair, refurbishment or even upgrade to extend the useful product life. Eco-modulated fees, currently still a voluntary option offered by selected compliance schemes in France, will provide leverage and data foster further DfE measures to support life cycle optimized design.

It is clear, however, that green data will remain a supplementary source of information when it comes to the establishment of DfE in the discussed fields. Data demand will depend on the methods chosen for product optimization and require complete data sets to cover all system parts with relevant environmental impact. Maximizing the outcome of green compliance data requires the communication of existing data, the identification of data gaps and the synchronization of data management in-between environmental compliance and design departments.

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Fairtronics: a Social Hotspot Analysis Tool for Electronics Products

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Abstract

Electronics products are not only associated with an environmental, but also a social footprint. Potential social sustainability problems can be identified along the whole life cycle of an electronics product: for example, the mining of so called “conflict minerals” that finance armed conflicts in Central Africa or cases of child labor in artisanal gold mining. Due to the complexity of electronics supply chains, the evaluation of these social risks poses a challenge. To address this, we have developed a specialized, easy to use tool for the social assessment of electronics products. The idea is to allow businesses to come to an initial idea of potential social risks in their supply chain based on the bill of materials (electronic components) of a product under consideration. Our contribution consists of four parts: First, we discuss the specific social issues in electronics supply chains as laid out above. Second, we present our method to calculate the social risks based on guidelines for Social Life Cycle Assessment (S-LCA). Specifically, we collect data on material composition of electronics components, production rates of these materials in different countries, and social indicators for these countries. The result is a social hotspot analysis based on a generic as well as component-specific assessment of social issues. Third, we further describe the current state of an open source web-based tool that implements the presented method. Finally, we discuss open challenges regarding data availability, interpretation and communication of the results and possible future extensions of the method.

1 Introduction

The production, use and disposal of electronics products is associated with a variety of social risks and potentially negative effects to human welfare. Recent reports about child labor in gold mining [1] and so called “conflict minerals” that finance armed conflicts Central Africa [2] are examples for such social risks that occur during the extraction of raw materials and are “built into” electronics products. In order to address these issues, manufacturers and other interested stakeholders, need to understand these risks. However, the complexity of electronics supply chains and the multitude of social issues pose a major challenge. To address this, we have developed Fairtronics, a web-based app that is intended to give electronics manufacturers and other stakeholders interested in the sustainability impacts of electronics products an easy entry point into social sustainability analysis. The initial version presented here was developed over the course of 6 months with funding provided by the Prototype Fund / German Federal Ministry of Education and Research.[1] Core values pursued in the development of the app are: (1) transparency, by using only free/libre open source software and providing all results under free/libre open source license. Furthermore, only publicly accessible data sources were used and all sources documented in the repository. (2) usability, the software should be usable without extensive training and provide initial results also when only limited data is available to the user.

In the following we describe the basic concepts of social sustainability analysis in section 2, and then describe their application in Fairtronics in section 3. For selected aspects, we describe the current state and lay out potential future developments. Section 4 gives a simple example for the risk calculations performed in the app and a final conclusion and outlook are given in section 5.

2 Social Life Cycle Assessment

We orient the approach of assessing social impacts in the Fairtronics app on Social Life Cycle Assessment (S-LCA) guidelines [3] and methodological sheets [4]. S-LCA itself is based on (Environmental) Life Cycle Assessment (LCA), which is a method to analyze potential environmental impacts throughout a product’s

[1] https://prototypefund.de/

life cycle (from raw material extraction to final disposal). S-LCA complements LCA by addressing social and socio-economic aspects. The S-LCA guidelines and corresponding methodological sheets structure potential social impacts in five different stakeholder groups (Worker, Local community, Society, Consumer and Value Chain Actor). For each stakeholder group, several subcategories are given. In the case of the stakeholder group Worker, these are Child Labor, Fair Salary, Hours of Work, Forced Labor, Equal Opportunities / Discrimination, Health and Safety and Social Benefit / Social Security. Each of the proposed subcategories may be measured by several indicators. For conducting an S-LCA study, the guidelines distinguish the four phases (1) goal and scope definition (setting the focus of the analysis), (2) inventory analysis (collecting data), (3) impact assessment (identifying sustainability impacts) and (4) interpretation (deduct learnings).

Several S-LCA studies on electronics components and products such as integrated circuits, mobile phones, laptops and desktop pcs are available [5], [6], [7], [8], [9]. There are also studies that focus on raw material extraction [10] and recycling [11], [12]. For our implementation, we mainly drew inspiration from [9], who describe an approach to perform a hotspot assessment when only limited generic data is available.

3 Application of S-LCA in Fairtronics

In the following, we describe how the analysis is implemented in Fairtronics, the identified constraints and possible future developments along the phases of an S-LCA study.

3.1 Goal and Scope

Goal: The goal of the assessments performed in Fairtronics is to highlight hotspots in electronics products: components, materials, countries, where it is likely that negative social impacts occur. The results should motivate and direct more detailed inspections and improvement measures.

Functional unit and system boundary: The Fairtronics app allows the user to compose a to-be-assessed electronics product at runtime, so the functional unit differs for each assessment performed with Fairtronics. However, it will always be one electronics product consisting of one or multiple components. For each of the components, we collect data about its raw material composition. Ideally, the assessment should cover the full life cycle of an electronics product and all potentially affected stakeholders. However, in the initial iteration of the implementation, the scope of the data collection and calculation is restricted to the extraction of metals and potential impacts associated with the stakeholder group Worker.

Activity Variable: In the initial implementation, Fairtronics uses the relative weight of a material or component to determine the significance of social impacts. For future developments, further data collection is planned in order to use workers' hours as preferred activity variable (as suggested in the guidelines).

Data quality: We focus on the collection of country-specific data for the social indicators. For data about material extraction quantities and material composition of components, we rely on publicly available data. This allows us to be as transparent as possible for the presentation of the results.

3.2 Inventory

3.2.1 Raw material data:

General considerations: The material's world production share of different countries can be obtained from agencies such as the U.S. Geological Survey [13].

Current state: Currently, we consider the materials Bauxite, Chromium, Copper, Gold, Iron, Nickel, Palladium, Silver and Tin. Implicitly, we assume that each of the materials in a component is a mix from different origins, according to the world production share.

Possible extensions: Further (also non-metal) materials will be added in the future. Currently, the distinction between ore and smelter output is not always clear. Future iterations of Fairtronics should extend the internal system model to reflect different supply chains for materials and extend the scope of the analysis from raw material extraction.

3.2.2 Component data:

General considerations: By components we mean the parts of an electronics product. Of interest for the analysis is, what the components are "made of", which can be understood differently. In the simplest case, this means the material contents of a product after production. This level of data is especially useful for electronic waste analysis [14]. For a complete sustainability analysis, however, data about waste during production and auxiliary materials used during production is necessary. The difficulty of obtaining such data for electronics products is discussed in [15]. Primary data sources for data about the material composition of components can be provided by manufacturers or generated by analytical means (e.g. [16]). Useful secondary sources may be life cycle inventory databases or handbooks and publications of various kinds (e.g. [17]). There also exist commercial B2B platforms that provide relevant inventory data (examples are CDX or iPoint Material Compliance App). One can suppose that manufacturers know about the material composition of their products, however most do not share this information freely. There are notable exceptions, however. Publishing a full material declaration (FMD) also has advantages for manufacturers [18] and we identified several manufacturers that indeed freely provide an FMD in various data formats, and some others provide the data upon request.

Current state: Ideally, for the purposes of Fairtronics, the data should be complete, machine readable, up to date, freely accessible and freely publishable. We collect data about the material composition of electronics components (like resistors, circuit boards, cables, ...). Currently, we only consider electrical components, so screws and cases are excluded. So far, we have collected data for 31 different components from full material declarations by manufactures that are published on their websites. While we intend to extend the collection, many manufacturers do not publish full declarations for their products, and so, when configuring a product from the component list, it might be necessary to select a component that is reasonably similar to the one that is actually part of the modeled product.

Possible extensions: Our consideration of components is currently restricted to the printed circuit board (PCB) and everything that is mounted on it (solder, cable, etc.). Larger products (e.g. a desktop computer) however, consist of multiple parts (such as hard disk, motherboard, …), that themselves consist of electronic components. This modularity can not be modeled in the current state of Fairtronics. Another possible feature that may mitigate the lack of data would be to allow a scaling of example components in the database.

3.2.3 Product data:

General considerations: From our analysis of electronics design software such as LibrePCB, Autodesk Eagle and KiCad EDA, we conclude that (semi-)structured data about product composition is mostly available in PCB layout data (mostly Gerber format [19]) and component lists (bill of material or BOM). LibrePCB provides an export feature that distinguishes between fabrication data for the PCB and a BOM. Autodesk Eagle provides a PCB layout data format and a schematics format including a BOM. KiCad EDA provides a customizable BOM export. Commercial LCA software such as GaBi LCA (via DfX extension) and MiLCA apparently provide a BOM import function. Another possibly relevant data type are circuit schematics that present a graphical representation of an electrical circuit. These don’t contain layout data (for PCB), however, a BOM may be compiled from them. BOMs differ in their specificity: Open Hardware projects, for example, mainly describe components by their required electrical and mechanical properties. For commercial hardware, specific supplier lists are available but rarely disclosed. Notable exceptions are Fairphone [20] and Nager IT [21]. As last resort, dismantling a device may reveal the included components.

Current state: We have collected data about the composition of the Nager IT computer mouse, Arduino Uno and MNT reform v2 laptop. The user interface allows to specify the list of components and their quantity from a predefined list of components we have collected so far.

Possible extensions: In the future, it may be possible to streamline the process for the user, e.g. by providing import functionality for BOMs and Gerber files. We also intend to collect further product data, especially from Open Hardware projects.

3.2.4 Social indicators:

General considerations: Global institutions like the International Labor Organization or Unicef provide reports and estimates for human rights conditions in different countries. While one singular supplier might perform better (or worse) than the country average, we assume that these estimates provide an indication how likely it is that human rights were violated during the production of materials in this country.

Current state: for each of the subcategory for workers described in the S-LCA methodological sheets (Child Labor, Freedom of Association, Fair Salary, Hours of Work, Social Protection, Discrimination and Health), we have selected one relevant indicator from the Ilostat database provided by the International Labor Organization.

Possible extensions: The currently selected indicators may not be sufficient to measure the full scope of an impact category (see [22]). Future iterations may add more indicators per subcategory and cover further stakeholder groups. Providing sector-specific data and data on a higher regional resolution would also improve the quality of the analysis.

3.3 Impact Assessment

Activity value: Based on our basic concepts and assumptions explained in section 3.1, we calculate an activity value (share of total product weight) that can be associated to each involved component, material and country. The activity value is dependent on the corresponding relative weight. Activity values

- for materials express the share of this material in total product weight (across all involved components).[2]
- for components express the share of the component's weight to the total product weight.
- for countries express the share of the materials produced in this country to total product weight.

An activity value above 10% is interpreted as "High Activity", and below 1% as "Low Activity". Anything in between is interpreted as "Medium Activity".

Risk value: For each social indicator, the values are sorted and the highest 25% of values are interpreted as "High Risk", the lowest 25% of values as "Low Risk", and everything in between as "Medium Risk" (depending on the indicator interpretation, this may also be inverted, with lowest values as "High Risk", and highest values as "Low Risk"). Via our assumed distribution of material production across countries and the material composition of countries, these risk values are associated with countries, materials and components (for a detailed description see the example calculation in section 4). When an indicator does not provide a value for an involved country, this is denoted as "Unknown Risk".

Hotspot identification: Hotspots are those countries, components and materials that show the highest activity and highest risks. For each component, we highlight the two components that show high risk and have the highest activity as hotspots. If no components show High Risk, we highlight the two Medium Risk components with highest activity etc. The same procedure applies for material and country hotspots. Finally, a table gives a complete overview of shares and risk ratings.

3.4 Interpretation

In the app, users are guided through a process, where they configure an electronics product from a library of components (see figure 1). Afterwards they can obtain a report that presents the results of the impact assessment.

[2] Since we restrict the scope of the analysis currently to metals, it is more specifically the "total weight of metals in the product".

Figure 1: Product configuration in Fairtronics.

To support the interpretation of the results, we break down the results separately for each of the dimensions (materials, components and countries). For each dimension, we first present an explorable tree map with the activity (weight) share (see figure 2), and then highlight the corresponding hotspots.

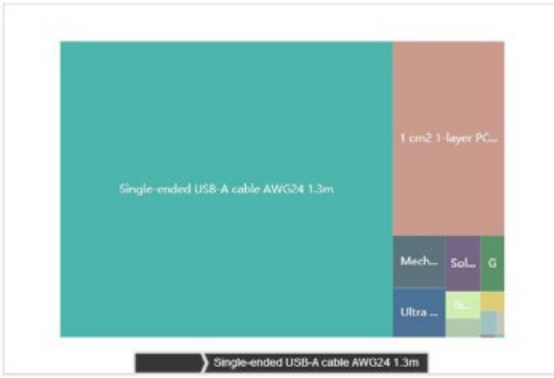

Figure 2: Example for a tree map showing the shares in weight for different components of a product.

To visualize the risk levels, we provide a traffic light visualization for High, Medium, Low and Unknown Risk (see figure 3).

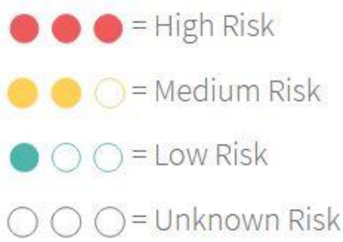

Figure 3: Traffic light visualization of risk levels.

4 Example Calculation

In order to exemplify the calculations that are performed in the app, we give a brief, simplified example with 2 components (C1 and C2), 2 materials (M1 and M2), 2 indicators (I1 and I2) and 2 involved countries (L1 and L2). The first type of data we collect is the share of different materials in components. Table 1 shows an example, where component C1 consists of 7g material M1 and 13g M2. Component C2 consists of 6g M1 and 4g M2. We then want to find out, where these materials are produced. In the example given in table 2, we can see that 60% of the world production of M1 stems from country L1 and 40% from country L2. For M2, the distribution is 20% from L1 and 80% from L2. In order to assess the social risks, the indicators I1 and I2 are given. The indicators may have different scales, in the example, we assume that possible values for I1 range from 1 to 5 and for I2 from 0 to 100.

	C1	C2
M1	7g	6g
M2	13g	4g

Table 1: Material share for different component.

	L1	L2
M1	60%	40%
M2	20%	80%

Table 2: Material production shares for different countries.

	I1	I2
L1	2	80
L2	5	100

Table 3: Indicator values for different countries.

Based on this data, the total product weight is 30g. The activity values are calculated as follows:

- C1: 66,66% (2/3 of total product weight)
- C2: 33,33% (1/3 of total product weight)
- M1: 43,33% ((7g + 6g) / 30g)
- M2: 56,66% ((13g + 4 g) / 30g)
- L1: 37,33 (60% * 43,33% + 20% * 56,66%)
- L2: 62,66% (40% * 43,33% + 80% * 56,66%)

In the next step, the indicator values for materials and components are scaled, according to their contribution.

- $I1_{M1}$: 3,2 (2 * 60% + 5 * 40%)
- $I2_{M1}$: 88 (80 * 60% + 100 * 40%)
- $I1_{M2}$: 4,4 (2 * 20% + 5 * 80%)
- $I2_{M2}$: 96 (80 * 20% + 100 * 80% = 96)
- $I1_{C1}$: 3,98 (35% * 3,2 + 65 % + 4,4)
- $I2_{C1}$: 93,2 (35% * 88 + 65% * 96)
- $I1_{C2}$: 3,68 (0,6 * 3,2 + 0,4 * 4,4)
- $I2_{C2}$: 91,2 (0,6 * 88 + 0,4 * 96)

In order to keep this example simple, we further assume the thresholds for Medium and High Risk as given, with an I1 indicator value of 3 as threshold for Medium Risk and 4 for High Risk. For I2 we assume 50 as threshold for Medium Risk and 90 as threshold for High Risk. As described in section 3.3, these values would normally be calculated from the highest and lowest 25% of values.

Based on the given threshold we can categorize for indicator I1:

- Low Risk for L1
- Medium Risk for M1, C1 and C2
- High Risk for L2 and M2

And for indicator I2:

- Medium Risk for L1 and M1
- High Risk for L2, M2, C1 and C2

In terms of hotspots, C1 would be ranked higher than C2, as it has a higher weight contribution to the product. M2 would be highlighted as material hotspot, as it shows High Risks and has the higher activity value. L2 shows High Risks and higher activity values as well.

For a more detailed example with real data, we provide the analysis of a computer mouse as an exemplary application of Fairtronics under https://fairtronics.org/browse/. The analysis covers 13 components, 9 materials and 40 countries.

5 Conclusion

In this paper, we have described the concept and implementation of a social analysis tool for electronics products. It is intended as a simple to use "entry point" to social sustainability analysis. In the future, we plan to extend the data base, internal model and calculation to cover further materials, life cycle stages and sustainability aspects.

6 Acknowledgments

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Hotspot Mapping for product disassembly; a circular product assessment method

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Abstract

Designing products for the Circular Economy requires closing and slowing of loops by means of repair, remanufacturing, refurbishment, parts reuse and/or recycling. Ease of product disassembly facilitates these processes to be more cost-effective, resulting in a better circular strategy fit. In this paper we present the Hotspot Mapping method. The objective of this method is to help designers in (re)designing their products for ease of disassembly, by assessing which parts in the product architecture are most critical for ease of disassembly. Critical parts are parts with a high failure rate or maintenance need and/or with a high economic and environmental value, that should be easily accessible with low effort to enable cost-effective recovery processes. A product's ease of disassembly is determined by factors that help or hinder the disconnection of critical parts from the rest of the product. The Hotspot Mapping method is a spreadsheet-based tool that indicates ease-of-disassembly by flagging five 'hotspot' indicators: (i) time needed to disconnect parts, (ii) difficulty of access, (iii) priority parts, (iv) environmental impact and (v) economy valuable parts. The Hotspot Mapping method adds to recent repairability assessment methods proposed in standards such as EN45554:2020, by also taking into account other aspects than failure-rate and functionality, such as economic and environmental value of the parts and materials. This paper describes the Hotspot Mapping method and applies the method to a household blender.

1 Introduction

In the 1990's a number of methods was developed to assess the ease of disassembly of products. In those days, these methods were already considered as important for environmental reasons – in particular for product recycling [1]–[3]. The disassembly process was visualized in reverse fishbone diagrams or disassembly trees [4], [5]. Recently this work has come under renewed scrutiny, and there has been considerable activity to modernize and build upon these 'design for disassembly' methods [6], [7], reinforced by the European Green Deal and the commitment of the European Commission to promote a circular economy [8]. Ease of disassembly is not only necessary for successful recycling, but also for repair, refurbishment, remanufacturing and parts harvesting for reuse.

The recent EN45554:2020 [9] standard focuses on a "general method for the assessment of the ability to repair, reuse and upgrade energy related products". In this standard the identification and ranking of so-called "priority parts" is the first step in assessing a product on its repair, reuse and upgrade. The standard determines that a priority part is a part with "(i) the likelihood of the need to replace or upgrade the part; (ii) the suitability of the part for reuse; (iii) the functionality of the part". Besides this new standard another standard in the series of Material Efficiency standards [10] is the EN45555:2019 [11] which promotes recovering materials for recycling purposes and focuses on the recyclability and recoverability rate and the efficiency of recycling and recovery processes. However, both the EN45554 and EN45555 do not consider the environmental benefits of avoiding the production of equivalent amounts of primary materials and energy carriers, nor the impacts associated with the end-of-life treatment processes [12]. This is the reason we developed the Hotspot Mapping method, which allows a designer to focus on the recovery of 'priority parts', as well as those parts with a high economic and environmental value ('valuable parts').

To keep products in use for longer and to facilitate their reuse, a product's design should facilitate different circular recovery strategies. For each of these strategies (i.e. repair, refurbishment, recycling), it is vital that the product is easy to disassemble. This enables cost effective operations and makes products fit for all circular strategies. In the Hotspot Mapping method, we focus on 'critical parts', which consist of (i) priority parts, based on their functionality, and failure/maintenance rate, and (ii) the valuable parts, based on their embodied economic value and the embodied environmental impact. Hotspot Mapping is a method to pinpoint these critical parts, locate them in a product's architecture and to assess them on the ease of disassembly. Within the method all parts in a product are assessed and prioritized on these aspects in order to make them easy to

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reach while disassembling. The Hotspot Mapping method is a spreadsheet-based tool that indicates ease of disassembly by flagging five 'hotspot' indicators: (i) time needed to disconnect parts; (ii) difficulty of access (for instance the amount of force needed to disconnect a part); (iii) the part's failure rate and/or maintenance need; (iv) the part's economic value; and (v) the part's embodied environmental impact.

The first two indicators, time needed to disconnect parts and difficulty of access, are important factors for product repair and maintenance, but also for parts-harvesting for reuse. These indicators are also of value for the end of life recycling process, but considering that small household appliances (such as the blender in this paper) are generally not dismantled, but shredded as a whole [13] we think this indicator cannot be used for this purpose. Automated dismantling processes however are increasingly common for dismantling complex products that contain precious metals, such as for smartphones [14]. For these processes determining the ease of disassembly of critical parts might helpful.

Together with a visualization of the teardown sequence, the so-called disassembly map [6], it is now possible to locate the critical parts in the product architecture and assess them on the ease of part-disassembly. The Hotspot Mapping method is presented in the next section, followed by a product case study, where we applied the Hotspot Mapping method to a Solis household blender. We will discuss the learnings from the product case study and finalize with a conclusion.

2 Hotspot Mapping Method

Ease of disassembly depends on product-related aspects, such as the type of tools used and their availability, and on context-related aspects, such as the availability of a repair manual. The Hotspot Mapping method focuses only on the product-related aspects. It assesses the product architecture by locating critical parts and the ease of reaching these.

2.1 Recording teardown activities

In order to locate the critical parts, a product is dismantled to its core. Each step in the dismantling process is logged sequentially in a spreadsheet, which was based on the Disassembly Evaluation Chart from Kroll [15]. A screenshot of the spreadsheet can be found in Figure . Each row represents one step in the dismantling process. The operator logs the necessary data to determine the five hotspot indicators: general properties, activity properties, difficulty of access, functional sensitivity and material properties. These data entries are described below.

<u>Property 1.</u> *General properties* include the part or subassembly's name, whether it's a single part or subassembly that is removed, and from which part or subassembly it is taken. When a part entry is assigned as being a subassembly it can and should be dismantled further in the disassembly map.

<u>Property 2.</u> The *Activity properties* consist of the activity (e.g. unscrewing), tools involved and their size, and the time needed to for the activity described. The time is the actual time involved while disassembling, because proxy times for pre-defined activities [16]–[18] are still too unreliable at the time of writing [12]. The tools used during the disassembling procedure are classified according to the EN45554 standard, where hand or basic tools are defined as class A tools and proprietary tools as class D, see table 1.

Category Description	Class
Feasible with the use of no tool, or a tool or set of tools that is supplied with the product or spare part, or basic (common) tools	A
Feasible with product group specific tools	B
Feasible with other commercially available tools	C
Feasible with proprietary tools	D
Not feasible with any existing tool	E

Table 1: Classification of tools as defined in the EN45554:2020 standard [9], [19].

<u>Property 3.</u> The *Difficulty of Access* can be described by three properties: (i) the level of force needed in the process, (ii) the accessibility of the fastener and (iii) the positioning of the tool needed for the specific process.

- The amount of force has been defined on three levels based on the Maynard Operation Sequence Technique (MOST) work measurement system [16] as described in [6]. The operator can choose between three levels of force intensity: light (less than 5N), moderate (5 to 20N) and heavy resistance (exceeding 20N);
- The accessibility of the fastener is measured in three levels: clear access (where the fastener is visible for the operator), recessed access (where the fastener is accessible but not visible), and obstructed access (where the fastener is covered by another part or item like a sticker);
- The positioning of the tool is again divided in three levels which define the degree of precision required to position a tool or hand: no-to-low precision (when no tool is needed for successful finishing the particular step), moderate precision (when a tool is

needed but positioning is not precise), and high precision (when a tool is needed which is positioned with high precision).

Property 4. In the *Functional sensitivity* column, the operator enters data concerning the level of maintenance needed and the risk of failure during use. When available the operator can make use of the manufacturer's failure-rate and repair data. For certain product categories (for instance vacuum cleaners) this data is available in literature [20], in studies by the European Commission [21], and in consumer association statistics [22]. When no data is available the operator should rely on experience and common sense.

Property 5. In the *Material properties* column, the operator enters data about the part's material composition and its weight. When the operator has access to the Bill of Materials (BoM) of the assessed product it can make use of this data, otherwise the material has to be determined by using existing material-determination tables in literature. In the spreadsheet-tool the operator can choose from a range of material groups (like thermoset, metals, etc.), electronic components (like batteries, PCBs, etc.), or choose the option of mixed materials (with a main material contribution). In Hotspot Mapping, electronic parts like PCBs and batteries are not fully dismantled and should be logged as a part. The weight is measured with the help of a weighing scale and is entered in grams. To avoid duplicate contributions to the hotspot indicators the material properties data is entered only once per part.

2.2 Hotspot identification

Once the product is disassembled and the table is completed the spreadsheet flags hotspot areas, based on five hotspot indicators.

The first indicator, *Time*, shows the steps which take the most time, where the 80th percentile is flagged as yellow and the 90th as red.

The second indicator shows the difficulty of the *Activity* involved in disassembly, is calculated by summing the penalty points for the required tool(s) needed P_{class}, the force involved P_F, the accessibility P_{Acc} and the difficulty for positioning the tool(s) P_{Pos}.

$$Activity = P_{class} + P_F + P_{Acc} + P_{Pos}$$

Penalties for the used tools P_{class}, are classified according to the to the EN45554 standard, where class A tools are not penalized (0 points) while class B to E tools are penalized with a penalty of 1 to 4 points. The other three penalties range from 0 to 2 penalty points, where 0 points is given to a no-to-low level of impact (level 0), 1 to moderate impact (level 1) and 2 to high impact (level 2). For instance, for the force penalty, zero points are given for forces less than 5N (no-to-low, level 0), 1 point for forces in between 5N to 20N (moderate resistance, level 1) and 2 points when activity involves forces above 20N (heavy resistance, level 2). The activity indicator is flagged yellow when it equals or exceeds 4 penalty points, and red when it equals or exceeds 6 penalty points.

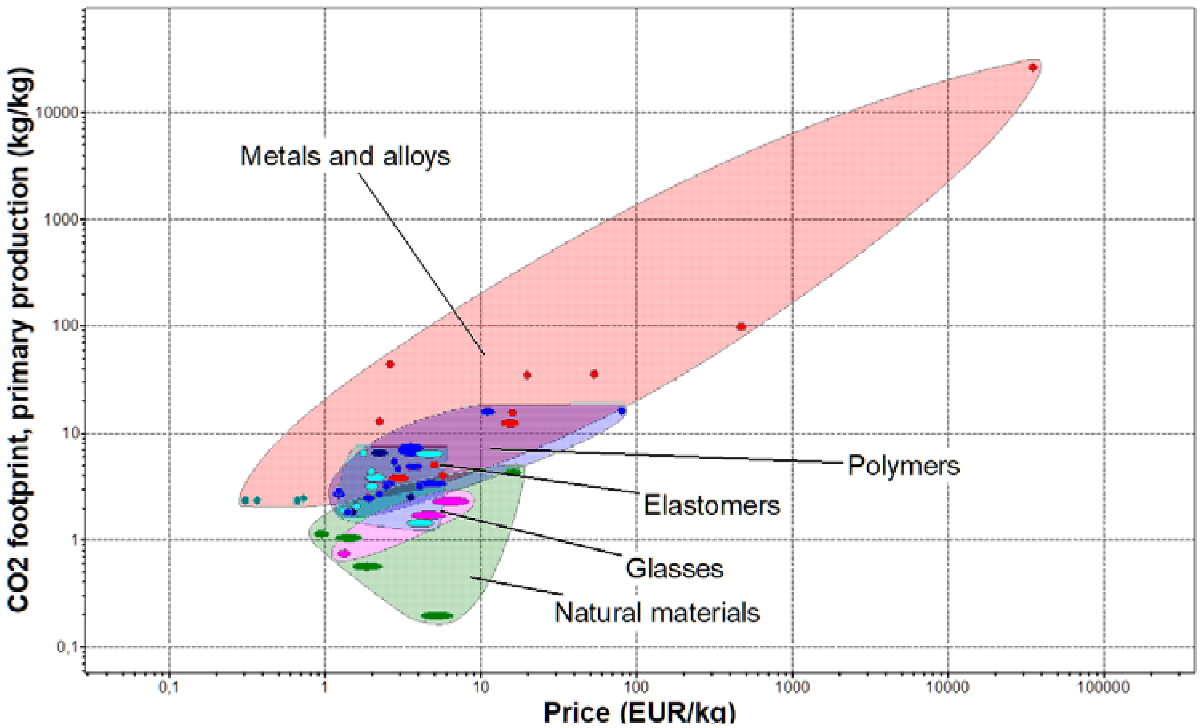

Figure 1: Different material groups' economic value versus embodied environmental impact [23].

The third indicator shows the *Priority of the Part*. Priority parts, as defined by EN45554 are parts which have a high functionality and involve high maintenance. These parts require priority when improving ease of access and depth in the product architecture. Parts which are flagged yellow or red are the priority parts. This indicator is the result of summing penalty points from the level of Maintenance P_{Main} and the level of Functionality P_{Funct} for the part involved in this particular step.

$$Priority\ Part = P_{Main} + P_{Funct}$$

Just like the penalty points in the second indicator, three levels are defined, where no-to-low impact (level 0) is not penalized, and moderate (level 1) and high impact (level 2) are penalized with respectively 1 and 2 points. The activity indicator is flagged yellow when it equals or exceeds 3 penalty points, and red when it equals 4 penalty points.

The fourth and fifth indicator are based on the embodied *Environmental impact* and the embodied *Economic value* of the part in question. The most valuable parts are important for effective recycling strategies but also for parts reuse purposes for instance in refurbishment or remanufacturing. The embodied environmental impact and the economic value of each part is calculated using the averaged CO_2 footprint and averaged material price based on the Cambridge Engineering Selector (CES) Edupack level 1 database [23]. Figure 1 shows the range of impact for several materials and material groups. Both the *Environmental* and *Economic Indicators* are flagged when the part has the highest embodied impact or value, where the 80th percentile is flagged as yellow and the 90th as red.

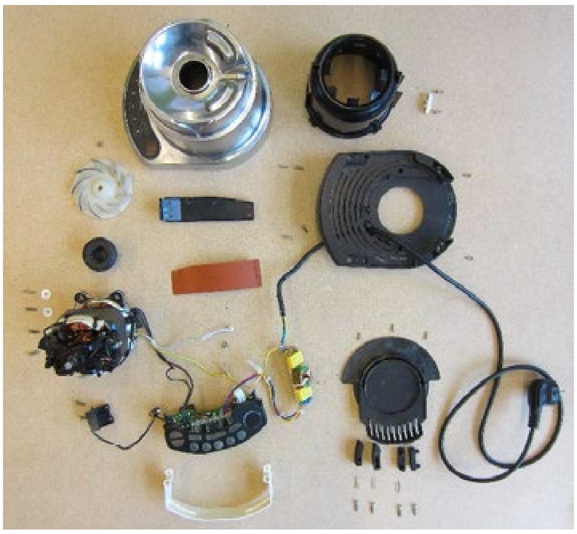

Figure 2: a "knolled" layout of the bottom motor-assembly of the Solis household blender.

Critical parts and associated disassembly activities can now easily be identified by the coloured flags in the indicators, the. Together with a visualization of the teardown sequence, the so-called Disassembly Map [6], [7], it is now easy to locate them in the product architecture. The disassembly map gives a visual impression of the disassembly depth of each critical part, and the use of specifically designed icons and colour codes makes it easy to assess how time-consuming and difficult it is to reach these parts. With this knowledge a designer can rearrange the parts in the product architecture where critical parts are easier to disassemble.

3 Blender case study

To illustrate the tool and its functionality for assessing a product's architecture on circular recovery strategies the Solis 837 household blender was disassembled and evaluated [24]. Figure 2 shows the "knolled" image of the bottom base module and figure 3 shows the complete product.

The blender was disassembled and evaluated using the Hotspot Mapping method. The product consists of two major subassemblies, the top-half can-assembly (including the cutting knife set, the transmission and the glass jug), and the bottom-base motor assembly (including all the electronics and the motor). The product is a sturdy blender containing a large number of parts and materials, including metals, plastics, rubber and glass, but also a large number of electronics such as PCB's, a display and a high-power electromotor. The disassembly process consisted of non-destructive activities and was stopped at the point where irreversible fasteners like solder was involved, and de-soldering or cutting was needed to disconnect the parts.

Figure 4 shows the Hotspot Map of the blender. 55 disassembly operations, or tasks, were needed to disassemble 39 parts, and in 12 of the disassembly steps, 6 different **tools** were needed. All parts were relatively **easy** to disconnect: no red flags are shown in the **activity** indicator column, only two yellow flags:

Figure 3: the Solis 837 household blender. Left the Bottom Base module and right the Top Half.

HotSpot Mapping Datasheet

General project information

Brand name	Solis		<-------- You can enter data in the light blue cells
Product category	Blender	top & bottom module	
Authors	IP & BFL		
Date	jun-20		
Location	Delft		

Overall HotSpot Results

Total:		**Average:**		
- time to disassemble	211 sec	- force	2	[1=low .. 5=high .. 10=extreme]
- number of tasks	55	- accessibility	1	[1=clear .. 5=moderate .. 10=difficult]
- number of steps	39	- positioning	3	[1=easy .. 5=moderate .. 10=difficult]
- number of tools	12			

General properties				Activity properties					Difficulty of Acc			Functional sensitivity		Material properties		HotSpot Indicators					
Step number	Name	Subassembly	Part of ...	Activity	Required tool	Tool size	Task frequency	Time to disconnect (sec)	Force	Accessibility	Positioning	Maintenance	Functionality	Material group	Weigth (g)	Time	Activity	Priority part	Environmental	Economic	Notes
1	Top half	yes	main assembly	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	No-to-low precision									Top of the blender
2	Lid	yes	Top half	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	No-to-low precision									
3	Top lid cap	no	Lid	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 1 -	Thermoplastic	23						
4	Top lid	no	Lid	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 1 -	Mixed materials mainly	148				⚑	⚑	
5	Blade holder	yes	main assembly	Unscrew	Hands		1	5	level 1 -	level 0 -	level 1 -	Moderate precision				⚑					
6	nut	no	Blade holder mo	Unscrew	Wrench	10	1	10	level 2 -	level 0 -	level 2 -	level 0 -	level 0 -	Stainless Steel	3	⚑	⚑				
7	washer	no	Blade holder mo	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Stainless Steel	1						
8	Blade 01	no	Blade holder mo	Remove	Hands		1	2	level 0 -	level 0 -	level 0 -	level 1 -	level 2 -	Stainless Steel	22			⚑			
9	Blade 02	no	Blade holder mo	Remove	Hands		1	2	level 0 -	level 0 -	level 0 -	level 1 -	level 2 -	Stainless Steel	5			⚑			
10	Blade 03	no	Blade holder mo	Remove	Hands		1	2	level 0 -	level 0 -	level 0 -	level 1 -	level 2 -	Stainless Steel	7			⚑			
11	Washer	no	Blade holder mo	Remove	Lever / Prybar		1	20	level 2 -	level 0 -	level 1 -	level 0 -	level 0 -	Stainless Steel	1	⚑	⚑				
12	Rubber washer	no	Blade holder mo	remove	hands		1	2	level 0 -	level 0 -	level 1 -	level 2 -	level 2 -	Rubber	1			⚑			
13	Screws	no	Blade holder mo	Unscrew	Screwdriver	T3	4	40	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Stainless Steel	5	⚑					
14	Bearing module	yes	Blade holder mo	Remove	Hands		1		level 0 -	level 0 -	level 0 -	No-to-low precision									
15	Rubber bearing	no	Bearing module	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 1 -	level 2 -	Rubber	1			⚑			
16	Washer bearing	no	Bearing module	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Stainless Steel	1						
17	Axis unit bearing	no	Bearing module	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 2 -	level 2 -	Stainless Steel	64			⚑	⚑	⚑	because we dont dismantle this assembly any further we don't define
18	Rubber Sheath	no	Blade holder mo	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Rubber	12						
19	Can Bottom	no	Blade holder mo	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 2 -	Mixed materials mainly	143				⚑	⚑	
20	Can base module	yes	Top half	remove	Hands		1	1	level 0 -	level 0 -	level 1 -	Moderate precision									
21	Screws	no	Can base module	Unscrew	Screwdriver	T10	4	20	level 0 -	level 0 -	level 1 -	level 0 -	level 0 -	Stainless Steel	5	⚑					
22	Outer can base	no	Can base module	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Stainless Steel	107				⚑	⚑	
23	Inner can base	no	Can base module	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Thermoplastic	106						
24	Can holder ring	no	Top half	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Thermoplastic	28						
25	Can rubber	no	Top half	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 2 -	Rubber	12						
26	Glass jug	no	Top half	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 2 -	Glass	1549				⚑	⚑	
27	Motor casing	no	main assembly	Remove	Hands		1	10	level 0 -	level 0 -	level 0 -	level 0 -	level 2 -	Thermoplastic	78	⚑					
28	Motor unit	yes	main assembly	Unscrew	Screwdriver	Ph1	4	30	level 0 -	level 0 -	level 1 -	Moderate precision				⚑					Bottom of the blender
29	Shaft connector (screw bit)	no	main assembly	Unscrew	Uncommon tool		1	5	level 1 -	level 0 -	level 1 -	level 1 -	level 2 -	Mixed materials mainly	26	⚑		⚑			
30	Motor unit	yes	main assembly	Unscrew	Screwdriver	Ph1	1	5	level 1 -	level 0 -	level 1 -	Moderate precision				⚑					
31	Switch holder	no	main assembly	Remove	Screwdriver	Ph1	1	5	level 1 -	level 0 -	level 1 -	level 0 -	level 2 -	Thermoplastic	22	⚑					
32	Motor unit	yes	main assembly	Unscrew	Screwdriver	Ph1	2	5	level 1 -	level 0 -	level 1 -	Moderate precision				⚑					
33	Casing	no	main assembly	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 2 -	Stainless Steel	750				⚑	⚑	
34	Interface casing	no	Motor unit	Disconnect s	Lever / Prybar		4	4	level 1 -	level 0 -	level 1 -	level 0 -	level 2 -	Thermoplastic	6						
35	DC motor	no	Motor unit	Remove	Hands		1	20	level 0 -	level 0 -	level 0 -	level 1 -	level 2 -	E-motor	1635	⚑		⚑	⚑	⚑	
36	Interface casing	no	Motor unit	Disconnect s	Lever / Prybar		4	4	level 1 -	level 0 -	level 1 -	level 0 -	level 2 -	Thermoplastic	6						
37	Buttons 01	no	Motor unit	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 2 -	Thermoplastic	6						
38	Button 03	no	Motor unit	Remove	Hands		1	1	level 0 -	level 0 -	level 0 -	level 0 -	level 2 -	Thermoplastic	2						
39	Buttons 02	no	Motor unit	Remove	Lever / Prybar		1	1	level 0 -	level 0 -	level 1 -	level 0 -	level 2 -	Thermoplastic	5						
40																					

Figure 4: the Hotspot Map of the Solis Blender.

- Step 6 required high force, as the blade holder module was tightly screwed with a nut and bolt. Unscrewing them also required a high precision placing of the tools.
- Step 11 needed high-force prying, because a washer was tightly clipped around the bolt, and it took considerable time before it slid from bold.

Figure 5: the axis bearing module with the worn down rubber sheath keeping it in place and protecting the bearing.

In step 12 and 17 two **priority parts** were addressed, the rubber sheath keeping the axis bearing module in place and the axis bearing module itself, see figure 5. Both parts are crucial for the functionality of the product, where the rubber sheath deteriorates over time because of its close contact with acid liquids dripping from the glass jug through the bearing module to the bottom motor subassembly. When the rubber sheath is deteriorated, the liquids from the jug drip slowly in the bearing, wherein the bearing is going to run rough and finally jams. Replacement of the rubber sheath should be easy to extend the life of this product.

The **time** required for disassembling was critical for more parts. Some parts required multiple tasks before they could be removed. For instance, to reach the bearing module, four screws had to be unscrewed (step 13) before the bearing module could be removed (step 14).

Based on the 5 indicators, the DC electromotor came out as the main critical part (step 35). It is red-flagged on the time-to-remove indicator, and both the environmental and economic indicator. Because this part is required for the primary function but only needs low maintenance the part is flagged yellow on the priority

Figure 6: the three second-critical parts derived from the hotspot map: glass jug (left), the can bottom (top right) and the metal blender casing (bottom right).

part indicator. Obviously, this part is the most important part and should be easily accessible in the product architecture.

Other critical parts, with each two red flags under the **environmental** and **economic** indicators are (i) the can bottom (step 19), (ii) the glass jug (step 26) and (iii) the metal bottom-casing (step 33), see figure 6. All three of them contain valuable materials with a large embodied environmental impact (metals and glass) and all have a high mass. These parts are very well reachable within the current product architecture, and thus easy to disassemble for refurbishment or recycling purposes.

The indicator system also shows other parts with a moderate impact (with one red flag or multiple yellow flags), which are not discussed further here.

4 Discussion & Conclusion

In this paper, we have proposed a method to identify hotspots for ease-of-disassembly in a product architecture. The systematic approach of evaluating the disassembly of a product can be used by designers to assess the suitability of a product design on circular aspects. The Hotspot Mapping method combines the disassembly of a product with the logging of all steps needed to reach the most critical parts in the product architecture. This results in five indicators: time needed to disconnect parts, difficulty of access, priority parts, environmental impact and economy valuable parts, which show the criticality of the part or the activity involved. The Hotspot Mapping method is unique because it also includes the economic and environmental value of parts, which distinguishes this method from existing repairability assessment methods. In this way, it gives designers a focus for redesign towards the Circular Economy and allows designers to learn from earlier iterations and from assessments of others.

Based on the assessment of the Blender case we identified a priority part we did not anticipate before the analysis, the rubber sheath containing the axis bearing unit. This part wears down during use, and should be easy to replace when a longer product life is wanted. Furthermore, based on the environmental and economic indicators, the bigger metal and glass components and the bigger electronic parts (the DC motor) contribute the most to the product's value. These parts do not tend to fail that often and could easily be harvested for refurbishment or remanufacturing processes.

While logging all activities in the Hotspot map, it became apparent that time varies depending on the operator, and a standardized proxy-time per activity is preferred over measured time. Currently, there are several researches investigating proxy times [12], [17], [25] but this has not matured sufficiently to be implemented in this tool yet.

The more qualitative assessment criteria referring to the Accessibility and the Functional Sensitivity columns, are not strictly defined yet, and their assessment depends on the category the product belongs to. For instance, there is a difference in force needed to dismantle a dishwasher compared to the dismantling of a smartphone. Also, knowledge on failure rate and maintenance is not always readily available to the user of the Hotspot Mapping. To further improve the tool, it could incorporate scoring criteria as used in the FMEA method, which is commonly used to predict the chances of failure of the parts in products.

A final point for discussion is that the embodied environmental impact indicator and the economic value indicator are both based on averaged data for material-only aspects, leaving out the influence of the production process. Generally speaking, the impact of materials exceeds that of the production impact and thus this approach could be a good and simple route to follow. The simplicity of the database limits its use for mass-produced consumer products embodying only commonly used materials. When the product contains special or technical materials a more detailed environmental impact and economic value analysis should be executed. Consequently, this tool is very applicable for mass-produced consumer products using common materials and to a lesser extend to products using specialty materials.

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Further development of the Disassembly Map, a method to guide product design for disassembly.

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Abstract

The Disassembly Map is a modelling method which allows to visually represent the architecture of a product, describing disassembly precedence and dependencies of components and operations necessary for their complete non-destructive removal. It introduced new standard visual elements to communicate the influence of specific design features on disassembly tools, sequences and time. A first iteration of this method was created during a study focused on a single product group, vacuum cleaners [1]. This paper presents a further development, meant to improve its versatility for application in diverse product groups. This was developed and tested by analysing four products (pressurized steam generator, coffee maker, child car seat and washing machine). This study shows the versatility of the Disassembly Map and introduces a new coding of action blocks, that allows the representation of a more extensive range of disassembly actions.

1 Introduction

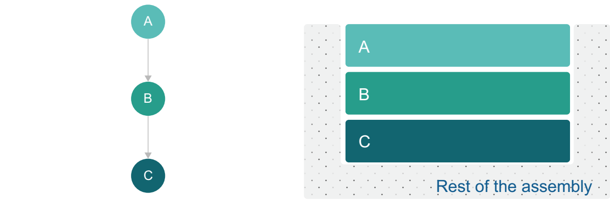
In 2020, the European Commission expressed a strong commitment towards promoting a more circular economy [2]. New regulations resulting from the European Green Deal [3] are expected to compel manufacturers to account for serviceability and repairability in product development. Many studies have been recently conducted concerning the assessment of product repairability and upgradability [4, 5, 6, 7, 8, 9]. In particular, the European standard EN 45554 [10] and the scoring system developed by the European Commission Joint Research Centre [6] have pointed out that a main product related requirement for repair and upgrade is design for disassembly. According to these documents, there are four parameters to be considered in order to assess design for disassembly: disassembly depth/sequence, fasteners reusability/reversibility, type of disassembly tools required and disassembly time. General formulas and scoring values for the assessment of these parameters are also provided, as a final score aggregation framework. Although these assessment systems describe the level of ease of disassembly of a product through a final numeric score, they do not provide clear redesign insights to actually improve the overall architecture of a product for disassembly.

The Disassembly Map

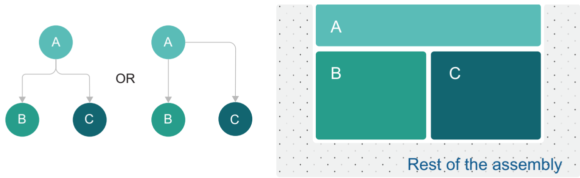
The Disassembly Map is a modelling method, meant for supporting product designers and engineers to identify main design features facilitating or hindering ease of disassembly of a product. This allows to identify non-optimized design features and provides useful input at the beginning of a next product development cycle. Its usefulness was demonstrated by redesigning a vacuum cleaner, enhancing its ease of disassembly in a cost-effective way [1].

Within the literature analysed for the creation of this method [1], it was found how architecture mapping and modelling techniques have been used in studies concerning design optimization for assembly, disassembly and End of Life [11, 12, 13, 14, 15, 16, 17, 18, 19]. Based on the different representation techniques found in literature, the latest research concerning the assessment of repair and upgrade [4, 6, 10] and the empirical assessment of vacuum cleaners, a new mapping methodology was created. This is based on a series of standardized logic representations, that describe different disassembly precedence relations and dependencies of components to correctly assess their disassembly depth/sequence. These logic representations, which are illustrated in Figure 1, are sequence dependency (a), sequence independency (b), multiple dependency (disassembly dependency from two or more disassembly operations independent from each other) (c), components clustering (d) and alternative disassembly operations (e).

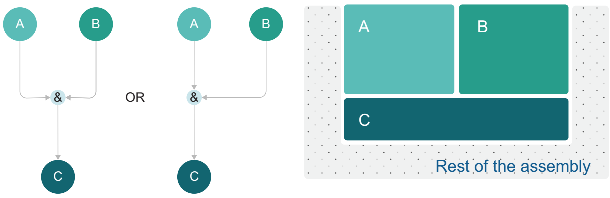
However, disassembly depth is not sufficient to determine the ease of disassembly of a product. In fact, the required disassembly effort encountered at each step also has an influence [6, 10]. This can be quantified by the time required to complete each disassembly operation. The EN 45554 indicates the Maynard Operation Sequence Technique (MOST) [20] and related eDiM



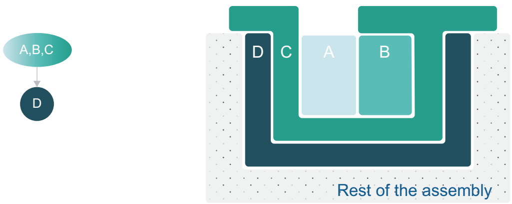
A: Representation of sequence dependency



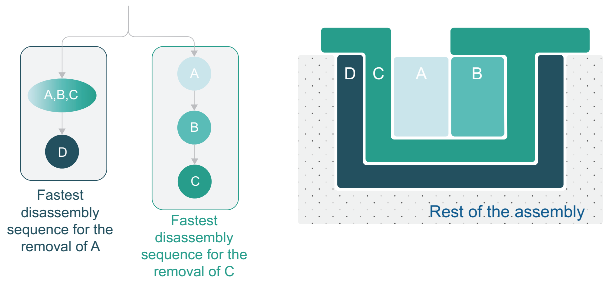
B: Representation of sequence independency



C: Representation of multiple dependency



D: Representation of components clustering



E: Representation of alternative disassembly operations

Figure 1: Logic representations used in the Disassembly Map to indicate different types of disassembly precedence relations and dependencies

[4] as two methods that can be used to assess disassembly time. MOST is a predetermined motion time system that describes the time required to carry out basic actions, considering an averagely skilled worker working at normal pace and under supervised working conditions. These basic actions are represented by parameters (indicated using letters) which express the type of activity, and numerical indexes that describe variation in action time based on task conditions (e.g. force intensity required, part of the body involved in the movement, number of task repetitions). A sequence of basic actions can describe more complex activities, also defined as sequence models, like the use of a tool for the removal of a fastener. The Disassembly Map integrates the representation of single disassembly operations necessary to completely remove a component by using "action blocks", visual elements positioned in between components. These blocks are coded using different shapes, colours and colour tones. This coding is defined based on the MOST, and its aim is to clearly highlight the most unoptimized design features, hindering disassembly time, hence increasing disassembly difficulty. The disassembly map is completed by the use of indicators that point to "target components", component with the highest importance for circular design strategies, thus those that should be easy to remove. These target components include components that have; the highest failure rate and functional importance (for repair and upgrade), the highest mass and/or cost values in the BOM and remaining useful life (for part harvesting), and the highest embedded environmental impact (for recycling).

The Disassembly Map was created and tested by analysing only a single product group: vacuum cleaners. The aim of this study is to determine the versatility of the Disassembly Map for other types of consumer products and, if necessary, improve the method.

2 Method

Four products belonging to different categories were selected (Table 1). All products were fully disassembled; the identification and indication of target components was neglected since not relevant for the scope of this research. Components were disassembled following the fastest and most effective sequence (lowest number of steps and disassembly time), and the complete disassembly process was recorded for later reference. A disassembly step was considered finished with the action that determined the complete removal of a part. Any modelling limitation (impossibility of representing disassembly operations by using the action blocks coding as originally proposed [1]) was noted. These were further analysed by establishing the most suitable BasicMOST parameters (tool use fastening/loosening values) to correctly describe them. Based on this process, a more comprehensive coding of action blocks was created.

Product	Price range (euros)	Rationale
Coffee maker	< 100	EEE consumer product composed of both electric and hydraulic components
Pressurized steam generator	> 100 < 200	EEE consumer product composed by two main sub-assemblies (iron and base) connected by a specific component (cord)
Washing machine	> 900 < 1000	Large EEE consumer product that includes unconventional disassembly operations (e.g. hammering)
Child car seat	> 300 < 400	Consumer product (not EEE) that includes unconventional disassembly operations (e.g. cutting and sliding)

Table 1: Products analysed in this study

3 Results and Discussion

3.1 Method improvements identified

The Disassembly Map method proved to be a useful tool for analysing the product architecture of the different products. Some extensions to the original procedure were needed, which will be discussed in more detail below. The resulting maps are shown in high resolution in the Appendix.

Three main improvements, meant to enhance the method versatility have been identified:

1. *Improved representability of disassembly actions*

In this research, a much wider range of different fasteners and tools was encountered compared to the earlier study focused on vacuum cleaners, and the original action blocks coding system was found to be too limited. This has been improved by analysing each new operation using the "Tool use" BasicMOST data card and fasteners disconnection sequences presented in eDiM [4, 9]. The final coding is represented in Table 2 and 3. Disassembly actions have been categorized based on the type of motion:

a. *Single motion actions* (Table 2); these require one single loosening/fastening movement (e.g. releasing a snap fit using a spudger) and the amount of disassembly time they require is mainly determined by the level of force applied (intensity of motion). Single motion actions are indicated in the Disassembly Map using rectangular action blocks.

b. *Multiple motion actions* (Table 3); these require multiple loosening/fastening movements (e.g. unscrewing a screw or nut with a screwdriver or wrench) and the amount of disassembly time necessary for their completion is determined mainly by the number of motion repetitions they imply. Additionally, they typically require an additional action of removal of the fastener, to completely extract the unfastened connector (e.g. final removal of screw, nut, bolt). They require an overall longer disassembly time compared to single motion ones. Multiple motion actions are indicated in the Disassembly Map using hexagonal action blocks.

Furthermore, it was observed that the use of a tool usually increases operation time, since additional time must be considered to grab, position and change the tool. This was also found in the previous study [1] and pointed out by previous research [4, 20, 21]. Therefore, a clear distinction was made in the representation of actions carried out with and without the need of a tool using different action block base colours:

- Actions not requiring a tool are indicated using green for single motion actions and aqua for multiple motion actions
- Actions requiring a tool are instead indicated using orange for single motion actions and pink for multiple motion actions

Three levels of intensity of motion (which determine different disassembly time) were considered for both single motion actions (mainly based on force intensity) and multiple motion ones (mainly based on number of motion repetitions). Variations in motion intensity have been represented by using different tones of the action blocks base colours indicated before.

2. *More precise representation of the final removal of a component.*

During this study it was observed that the time required by the final removal of components varies considerably, e.g. the simple removal of a lightweight coffee maker plastic water bucket (around 1 seconds, MOST parameter indexing considered 1) compared to the removal of a heavy washing machine concrete counterweight (almost 4 seconds, MOST parameter indexing considered 6). However, in the first iteration of the method [1], the final action of removal of any component was always considered a standard disassembly task, as suggested by the eDiM [4]. For any component, 1,4 seconds (MOST sequence A1B0G1 + A1B0P1; 40 TMU) was taken and the representation of component removal was neglected in the map to avoid redundancy. On the contrary, in this study the action of removal was represented in the map using single motion action blocks. Based on the assessment of the four products, and the standard disassembly task for removal proposed by the eDiM [4], the action of removal was defined as an activity meant to partially or completely disassemble a part kept in position by its own weight (laying in position). The lifting force necessary for its removal is only determined by the part weight. If the part was instead kept in position by the friction created in contact with another component, this was considered as a "friction fit" connection, and a "pulling" single motion action was then considered. The level of motion intensity (MOST indexes 1, 3 and 6) for "removal" actions was determined based on the weight of the component itself or if a part had to be removed following a specific controlled path (e.g. extracting a wire through an articulated and narrow path). This was defined in

Single motion disassembly action — Action block shape and color: Hand, Tool

MOST index	Remove	Press/Pull	Tap/Strike	Cut	MOST index
	Hand, Spudger, Lever, Prybar, Plier, etc.	Hand, Spudger, Lever, Prybar, Plier, etc.	Hand, Hammer, etc.	Scissors, Pliers, Knife (up to 80cm cut), etc.	
	No fastener present. Parts are kept in place just by their own weight	Friction fits, Snap fits, Single turn knobs or lid, Buttons, Hinges, Electronic connectors, Adhesives, Zippers, Velcro's, etc.	Connectors requiring a short up-down tapping/striking motion (e.g. nails, washing machine bearings)	Electronic cables, wires, tighteners, surfaces to be cut using scissors/knife, etc.	
1	The part to be removed is light requiring mainly fingers action (indicatively F<5N) and without having to follow a specific controlled removal path	Light press/pull force required (indicatively F<5N), applied mainly using fingers action (also in case a tool is used)	Light tap (not strike), force required (indicatively F<5N), applied mainly using wrist action (also in case a tool is used)	Pliers: light grip force, no cut (e.g. holding in place wire for soldering) Scissors: simple cut requiring light force (e.g. paper or fabric) (No knife, no cutting pliers)	1
3	The weight of the part to be removed is moderate, requiring wrist/hand action (indicatively 5<F<20N) and/or having to follow a specific controlled removal path	Moderate press/pull force required (indicatively 5N<F<20N), applied mainly using wrist action (also in case a tool is used)	Moderate strike force required (indicatively 5N<F<20N), applied mainly using arm action using a hammer (not simple hand tap)	Pliers, Scissors, Knife: Moderate cutting force required (indicatively 5N<F<20N), applied using one hand and requiring one cut action	3
6	The part to be removed is heavy, requiring two hands action (indicatively F>20N) and/or having to follow a specific controlled removal path	High press/pull force required (indicatively F>20N), applied mainly using arm action (also in case a tool is used)	High strike force required (indicatively F>20N), applied mainly using arm action using a hammer (not simple hand tap)	Only Pliers: High cutting force required (indicatively F>20N), applied using one or two hands and requiring up to two cut actions	6

Table 2: Single motion disassembly actions and MOST loosening/fastening indexes considered

Multiple motion disassembly action — Action block shape and color: Hand, Tool

MOST index	Finger action	Wrist action			Arm action				Power Tool	MOST index
	#Spins	#Turns	#Strokes	#Cranks	#Turns		#Strokes	#Cranks	Std*Screw head diam	
	Fingers, Screw driver	Wrist, Hand screwdriver, Ratchet, T-wrench	Wrench	Wrench, Ratchet	Ratchet	T-Wrench, 2-Hands	Wrench	Wrench, Ratchet	Power screwdriver or wrench	
1	1	-	-	-	-	-	-	-	-	1
3	2	1	1	1	1	-	1	-	<6mm	3
6	3	3	2	3	2	1	-	1	<25mm	6
10	8	5	3	5	4	-	2	2		10
16	16	9	5	8	6	3	3	3		16
24	25	13	8	11	9	6	4	5		24
32	35	17	10	15	12	8	6	6		32
42	47	23	13	20	15	11	8	8		42
54	61	29	17	25	20	15	10	11		54

*Standard screw (length holding threads is 1 to 2 times the head diameter)

Table 3: Multiple motion disassembly actions and MOST loosening/fastening indexes considered

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accordance with the "controlled movement" sequence model and the "Placement" parameter defined in the MOST.

3. *More consistent visual representation of the disassembly depth*.

The Disassembly Maps on vacuum cleaners already showed inconsistencies in the visual indication of the disassembly depth of the analysed products [1]. In this study a grid was used to position action blocks with a uniform separation between them in the vertical axis, allowing a more reliable representation of disassembly depth and improving comparability of different maps.

3.2 Analysis of the Disassembly Maps obtained

As it is possible to see from the Disassembly Maps shown in Appendix, the five logic representations identified in the previous study (Figure 1) allowed a complete mapping of four new product categories. The models show clear differences between architectures presenting more sequence dependent disassembly operations (e.g. the child car seat, whose map develops vertically) and architectures presenting sequence independent disassembly operations (e.g. the pressurised steam generator, whose map develops more horizontally). Additionally, the representation grid helps to compare the disassembly depth of different components and disassembly operations.

The new action block coding system allowed to represent also unconventional operations (e.g. hammering, unzipping, ripping Velcro) and to highlight differences in multiple motion actions (e.g. unfastening a screw with a hand screwdriver, with a power tool, or removing a bolt using a wrench). In the map of the pressurised steam generator the number of motion repetitions was indicated in the action blocks to show how even screws sharing the same type of head might require a different number of turns, and how using a power tool drastically decreases disassembly time. The shapes, basic colours and colour tones used to code the actions blocks help to immediately spot disassembly actions requiring shorter or longer time. For instance, it is immediately visible how in the disassembly map of the washing machine there are many medium and high intensity multiple motion actions that have to be carried out using a tool (represented by pink and dark purple hexagonal blocks). On the contrary, the coffee maker requires mainly single motion disassembly actions (rectangular blocks), most of which can be carried out by hand (green blocks).

The penalty icons already presented in the previous study [1], based on the eDiM [4], have been used also in this research. These are also important indicators of unoptimized design features hindering disassembly.

Common features present in maps of products that could be considered to be easier to disassemble are:

- Target components should ideally be as close as possible to the top of the map;
- The map should be as horizontal as possible, which means that components can be disassembled independently from each other;
- As many action blocks as possible should be rectangular and green, indicating that most of the disassembly operations are single motion actions carried out without the need of a tool (requiring the least amount of disassembly time according to the MOST);
- Alternating action blocks of different colour and shape should be avoided as much as possible, since changing tool increases disassembly time;
- No penalty icon should be present.

4 Conclusions and recommendations for further improvements

The Disassembly Map method [1] was tested by mapping four different products. The method proved to be useful in mapping the disassembly of a variety of consumer products. However, some improvements to enhance the versatility of the method are presented in this paper.

Firstly, a more comprehensive range of disassembly actions have been taken in account: new tools and types of disassembly motions have been coded based on the BasicMOST. Clear guidelines have been defined for their correct representation though the action blocks visual elements.

Furthermore, a more precise representation for the final removal of a component was established by coding those activities meant to partially or completely remove a part kept in position by its own weight, and further differentiating their impact on disassembly time based on tasks conditions (e.g. part's weight).

Finally, a grid was used to make the vertical dimension of the Disassembly Maps more uniform to establish a more intuitive representation of disassembly depth through the vertical dimension of the map and facilitate comparison between maps.

The methodology still presents some limitations. Regarding the above-mentioned improvements, some actions (such as de-soldering) have not yet been studied. Also, the vertical grid cannot yet be considered a reliable indicator of disassembly depth, as the vertical dimension of the map depends not only by the number of disassembly steps, but also by the number of action blocks. Investigations into a wider range of products are considered worthwhile to further test the versatility and extend the Disassembly Map.

5 Literature

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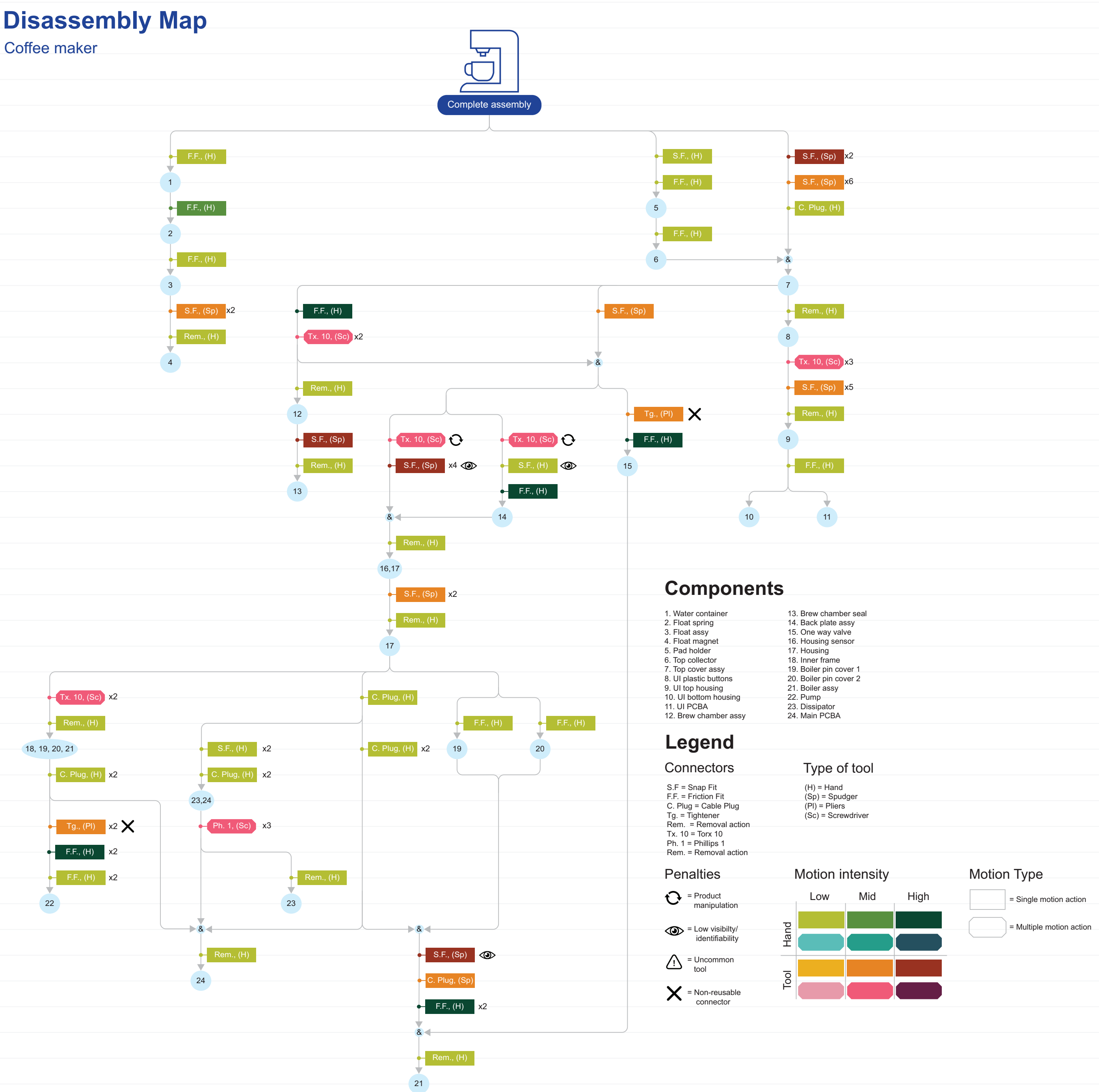
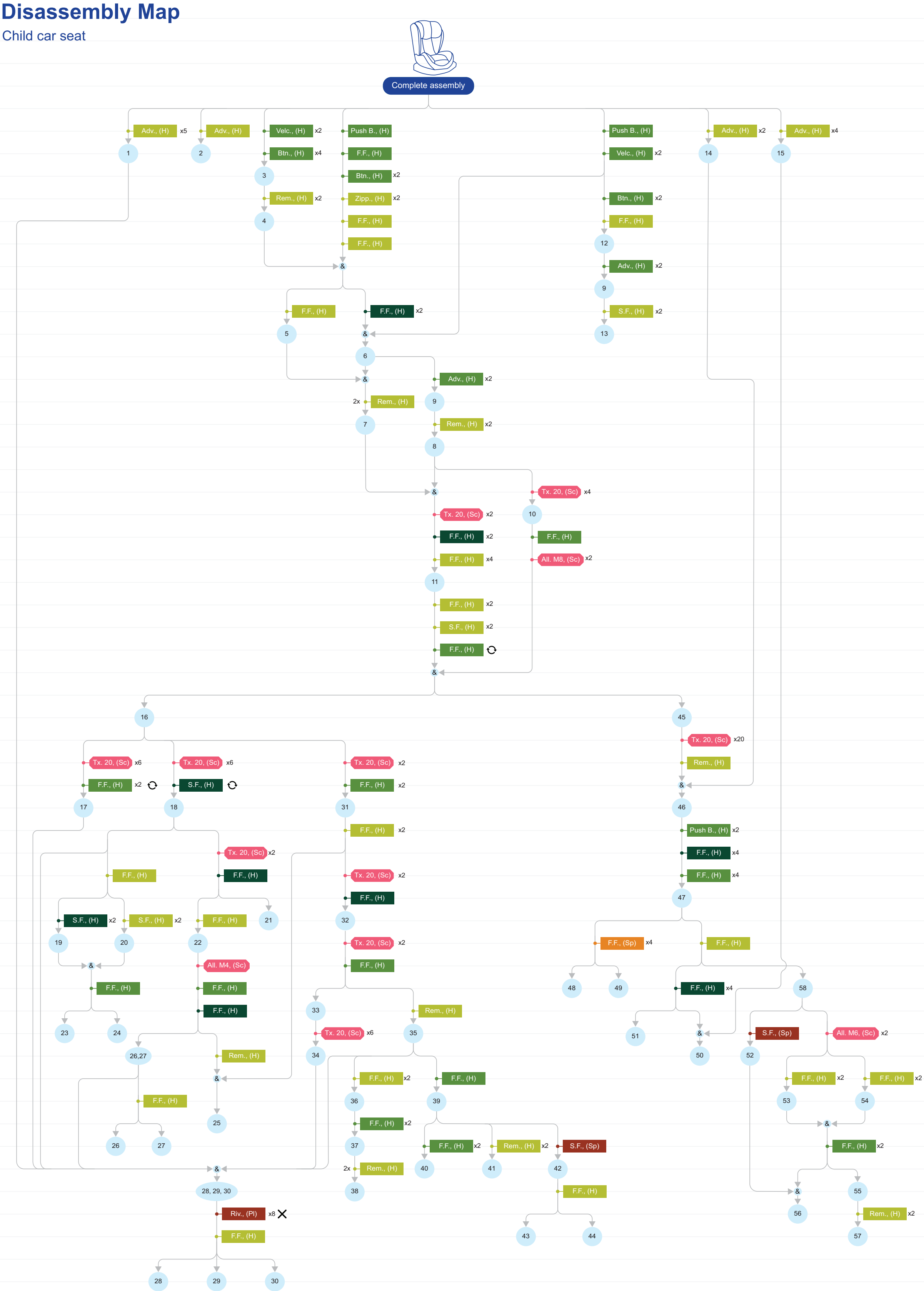
Appendix: Disassembly Maps of four different products



Disassembly Map

Child car seat



Components

1. Sticker A
2. Seat Cushion
3. Shoulder pads
4. Side support
5. Base foam
6. Fabric ASSY
7. EPS lower
8. EPS top
9. Sticker B
10. Seat cover
11. Fixation plate
12. Headrest cover
13. Headrest
14. Sticker B
15. Sticker C
16. Seat shell ASSY
17. Seat front cover
18. Frame
19. Guiding axle
20. Spring A
21. Crotch bracket
22. Crotch strap
23. Reclining handle
24. Reclining housing
25. Harness
26. Central button
27. Central button cover
28. Recline rims
29. Back handle
30. Seat shell
31. Seat rear cover
32. Adjusting handle
33. Headrest shell
34. back handle
35. Headrest adjust assy
36. Friction strap
37. Axle sleeves
38. Pad axle
39. Headrest axis
40. Covers axis
41. Axis guiders
42. Headrest spring
43. Locking plate
44. Glider
45. Seat base assy
46. Top cover base
47. Reclining block assys
48. Lock springs
49. Reclining pad
50. Bottom cover base
51. Bottom cover dampers
52. Seat hook cover
53. Recline end plate
54. Recline cam part
55. Reclining lock assys
56. Weld assys
57. Slide bearing
58. Frame assy

Legend

Connectors

S.F. = Snap Fit
F.F. = Friction Fit
Push B. = Push Button
Adv. = Adhesive
Th. = Thread
Riv. = Rivet
Velc. = Velcro
Zipp. = Zipper
Btn. = Button
Tx. 20 = Torx 20
All. 4 = Allen 4
All. 6 = Allen 6
All. 8 = Allen 8
Rem. = Removal action

Type of tool

(H) = Hand
(Sp) = Spudger
(Pl) = Pliers
(Sc) = Screwdriver

Penalties

= Product manipulation
= Low visibilty/ identifiability
= Uncommon tool
= Non-reusable connector

Motion intensity

Low Mid High
Hand
Tool

Motion Type

= Single motion action
= Multiple motion action

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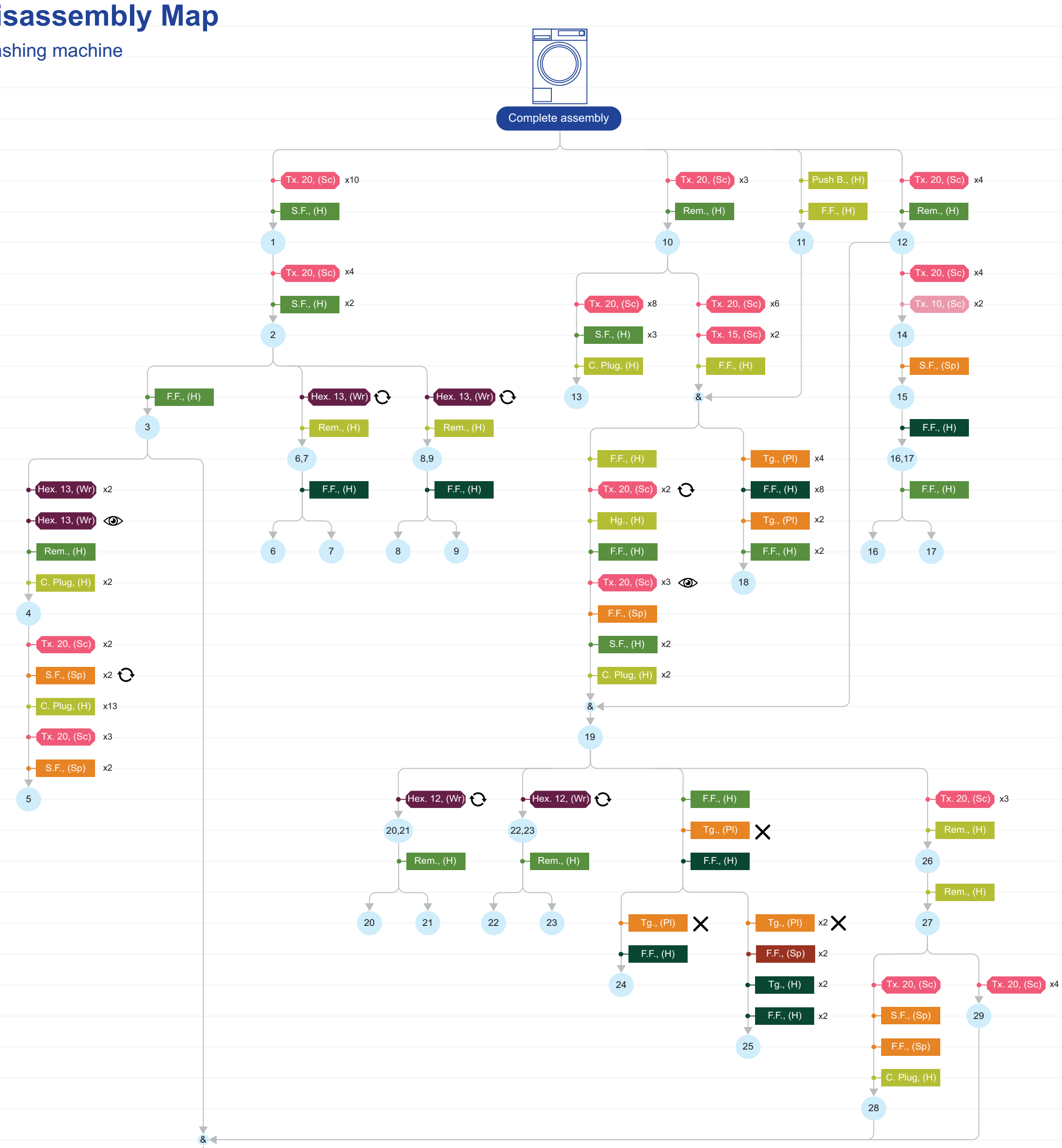
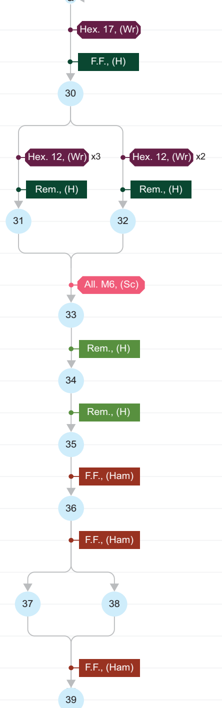
Disassembly Map

Washing machine





Components

1. Back panel
2. Middle support
3. Motor drive belt
4. Motor
5. PCBA Power control
6. Leg damper 1
7. Shock absorber 1
8. Leg damper 2
9. Shock absorber 2
10. Top panel
11. Soap drawer
12. Door Assy
13. UI PCBA
14. Door frame assy
15. Door frame exterior
16. Inner door frame
17. Door seal (rubber ring)
18. Soap dispenser Assy
19. Front panel Assy
20. Leg damper 3
21. Shock absorber 3
22. Leg damper 4
23. Shock absorber 5
24. Pump
25. Drain hose
26. Hinge plate
27. Tub cover
28. Lock
29. Hinge
30. Pulley assy (with washer)
31. Bottom counterweight
32. Top counterweight
33. Clamp ring
34. Tub front
35. Tub panel
36. Drum Assy
37. Sealing bearing
38. Bearing
39. Ball bearing

Legend

Connectors

S.F. = Snap Fit
F.F. = Friction Fit
C. Plug = Cable Plug
Push B. = Push Button
Hg. = Hinge
Tg. = Tightener
Tx. 10 = Torx 10
Tx. 15 = Torx. 15
Tx. 10 = Torx. 20
Hex. 12 = Hexagonal 12
Hex. 13 = Hexagonal 13
Hex. 17 = Hexagonal 17
All. M6 = Allen M6
Rem. = Removal action

Type of tool

(H) = Hand
(Sp) = Spudger
(Pl) = Pliers
(Sc) = Screwdriver
(Wr) = Wrench
(Ham) = Hammer

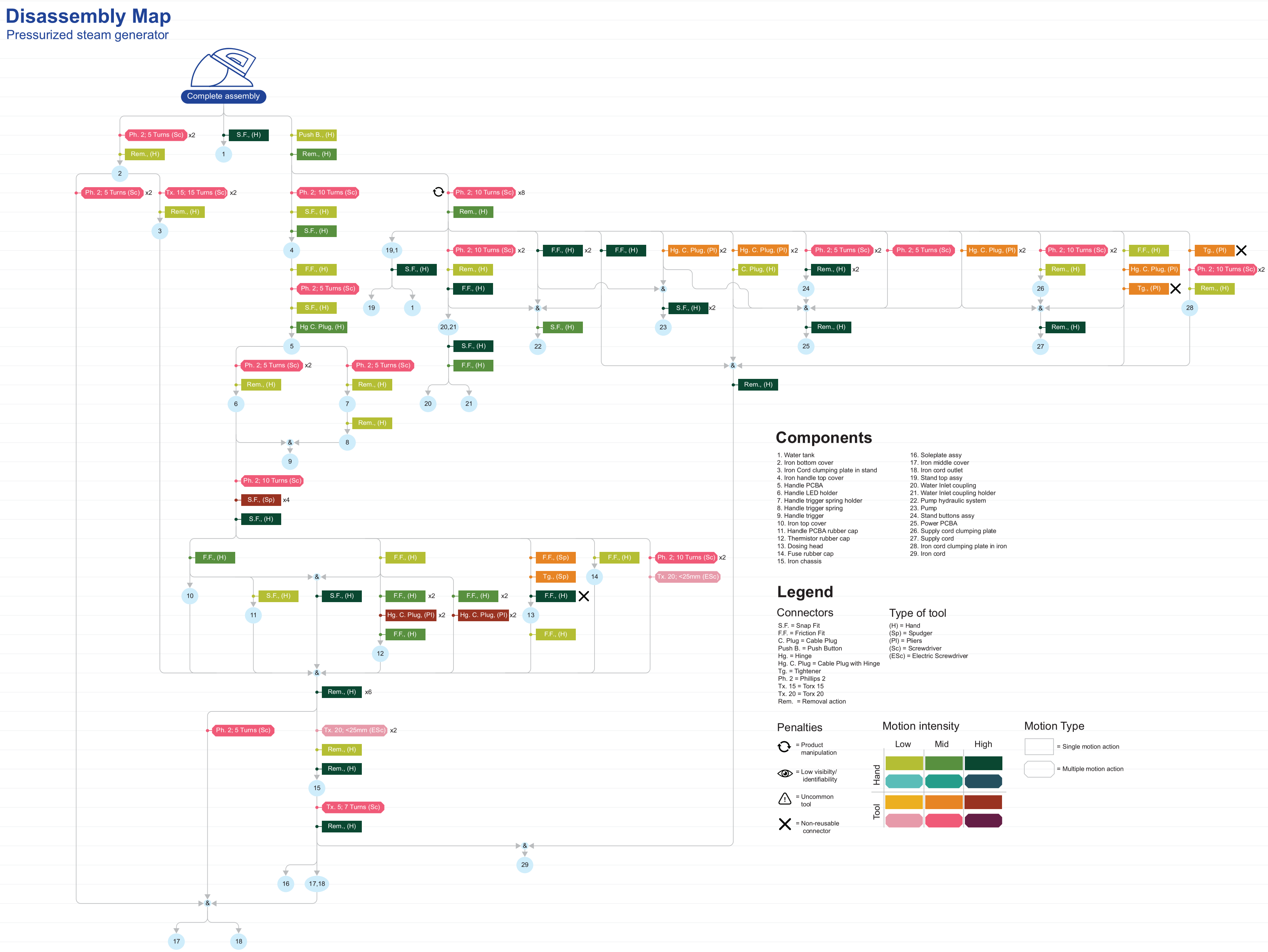
Penalties

= Product manipulation
= Low visibility/ identifiability
= Uncommon tool
= Non-reusable connector

Motion intensity

Motion Type

= Single motion action
= Multiple motion action


Disassembly Map
Pressurized steam generator
Complete assembly
Components
1. Water tank
2. Iron bottom cover
3. Iron Cord clumping plate in stand
4. Iron handle top cover
5. Handle PCBA
6. Handle LED holder
7. Handle trigger spring holder
8. Handle trigger spring
9. Handle trigger
10. Iron top cover
11. Handle PCBA rubber cap
12. Thermistor rubber cap
13. Dosing head
14. Fuse rubber cap
15. Iron chassis
16. Soleplate assy
17. Iron middle cover
18. Iron cord outlet
19. Stand top assy
20. Water Inlet coupling
21. Water Inlet coupling holder
22. Pump hydraulic system
23. Pump
24. Stand buttons assy
25. Power PCBA
26. Supply cord clumping plate
27. Supply cord
28. Iron cord clumping plate in iron
29. Iron cord
Legend
Connectors
S.F. = Snap Fit
F.F. = Friction Fit
C. Plug = Cable Plug
Push B. = Push Button
Hg. = Hinge
Hg. C. Plug = Cable Plug with Hinge
Tg. = Tightener
Ph. 2 = Phillips 2
Tx. 15 = Torx 15
Tx. 20 = Torx 20
Rem. = Removal action
Type of tool
(H) = Hand
(Sp) = Spudger
(Pl) = Pliers
(Sc) = Screwdriver
(ESc) = Electric Screwdriver
Penalties
= Product manipulation
= Low visibilty/ identifiability
= Uncommon tool
= Non-reusable connector
Motion intensity
Low
Mid
High
Hand
Tool
Motion Type
= Single motion action
= Multiple motion action

Scoping a Digital Twin for a circular reusable plastic packaging

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Abstract

This paper identifies potentials of the Digital Twin to contribute to the sustainable, circular use of plastics and plastic products in the sense of a Circular Economy. To this purpose, the principles, objectives and challenges that can be associated with the transformation to a Circular Economy are briefly described and the term Digital Twin is defined. A systematic procedure for the scoping of a product-specific Digital Twin is presented. Results of the scoping process, which is currently being carried out to develop a Digital Twin for a circular reusable plastic packaging, are summarised. Identified challenges, efforts and benefits related to the development of a Digital Twin are pointed out.

Keywords: digital twin, circular economy, circular plastics economy, smart packaging, product lifecycle information management

1 Introduction

Environmental and resource problems and digitalisation are both central issues of the 21st century. They are interlinked with one another and digitalisation is widely believed to be a lever to tackle environmental challenges. This paper explores the Digital Twin as one means to address environmental challenges via digitalisation.

Circular Economy

Global resource consumption has increased steadily over the past decades, causing complex and interlinked environmental challenges such as climate change, loss of biodiversity and an increasing number of critical raw materials [1], [2]. The increasing resource consumption can be explained by the prevalent linear economic system and consumer behaviour, in which products and their components are often used only once and over a short period of time before they are disposed [3]. The linear economy is therefore also known as the take-make-dispose system or end-of-life-concept [4], [5]. In order to reduce the environmental and resource problems caused by this linear system, the transformation to a Circular Economy is sought at the economic, societal and political level. At European policy level, this ambition is particularly demonstrated by the Circular Economy Action Plan, which was first launched in 2015 by the European Commission. [6]

Based on the widely used definition of the Ellen MacArthur Foundation [7] and a scientifically developed definition of Kirchhoff et al. [4], the Circular Economy can be described as follows:

The Circular Economy is an economic concept. It replaces the prevalent linear end-of-life-concept, through the reducing, re-using, repairing, refurbishing and recycling of products, product components and materials at the end of a use period. The concept covers all phases of product life cycles. The transformation from a linear to a circular economic system requires the consideration of various system levels and suitable business models.

Reducing, reusing, repairing, refurbishing and recycling is described as a circulation of the products and their components. Circulation aims to lead to a lower strain on the environment in its function as source and sink for industrial and consumption processes, their products and by-products. [8]

However, an economically and ecologically successful circulation of products is coupled with a number of challenges. In particular does it require a change in the relationship and cooperation of the different actors in a product life cycle and the availability and transparency of information on characteristics and condition of a specific product.

Digital Twin

This paper discusses how a Digital Twin can help to meet these transformational challenges. It aims to answer the question of how a Digital Twin can contribute to a more sustainable, circular use of products and components and thus to the transformation towards a Circular Economy.

Established institutions and companies promote the Digital Twin as one of the most promising and significant information technologies of the upcoming years [9], [10]. Interest in the Digital Twin has increased significantly over the past five to ten years, as for example the development of the number of publications per year on the topic clearly shows (figure 1).

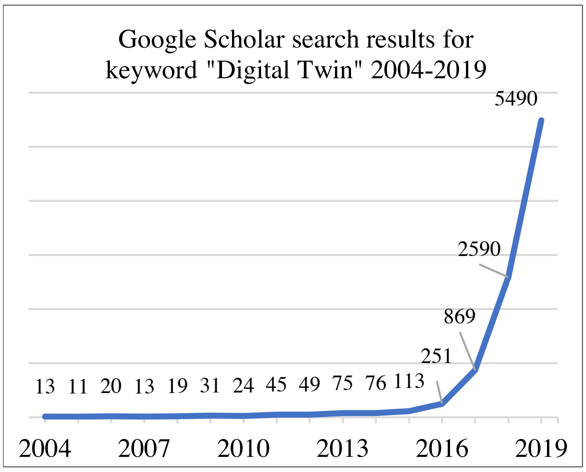

Figure 1: Development of the number of publications regarding the Digital Twin per year [11]

However, there is no uniform definition of the term Digital Twin. There is also a lack of standards regarding the development and implementation of this information technology [12], [13]. Based on the description of possible contributions of the Digital Twin to the transformation to a Circular Economy, a systematic scoping procedure for a product-specific Digital Twin will be outlined within this paper. Insights in the application of this procedure to develop a Digital Twin for a circular reusable plastic packaging will be given. The methodological approach chosen for this purpose is described below.

2 Methods

The research presented in this paper follows a systematic approach. To answer the question of how a Digital Twin can contribute to the circular use of products and components, the concept of the Circular Economy, different principles of the circular use of products and the challenges associated with the implementation of these principles were analyzed. For this purpose, a comprehensive literature research and complementary expert interviews were conducted. A brief summary of the identified transformational challenges is given in section 3.

In order to gain a clear understanding of the potential use and benefits of a Digital Twin, a definition for the term was developed and validated. For this purpose, a working definition was derived from descriptions and definitions of the scientists Michael Grieves and John Vickers, who are said to be the originators of the idea for a Digital Twin [13], [14], [15]. To validate this working definition, it was compared to other descriptions and definitions of the Digital Twin published by research institutions and companies. For this, eight key characteristics were identified in the working definition. In order to validate the working definition, it was checked whether these eight characteristics were also included in the comparative descriptions and definitions. The results of the comparison are documented in table 1. The row totals show the matches of the respective comparative source with the working definition. The column totals display the sum of all comparative sources that match the respective key characteristic. The results of the comparison show that there are strong correlations between the working definition and the comparative descriptions and definitions.

Source	KC 1	KC 2	KC 3	KC 4	KC 5	KC 6	KC 7	KC 8	∑
[12]	1	0	1	1	1	1	0	1	6
[13]	1	1	0	1	1	1	0	1	6
[16]	1	1	1	0	0	1	0	1	5
[17]	1	1	1	1	1	1	1	1	8
[18]	1	1	1	1	0	1	1	1	7
[19]	1	1	1	1	1	1	1	1	8
[20]	1	1	1	1	1	1	1	1	8
[21]	1	1	0	1	1	1	1	1	7
[22]	1	1	1	1	1	1	1	1	8
[23]	1	1	1	1	1	1	0	1	7
[24]	1	1	1	0	1	0	1	1	6
∑	11	10	9	9	9	10	7	11	

Table 1: Results of the comparison of the working definition with other definitions and descriptions of the Digital Twin (KC = key characteristic, 1 = KC occurs in the source, 0 = KC does not occur in the source)

Based on the results, the following working definition for the Digital Twin was considered validated. The Digital Twin is (1) a virtual collection of information. Based on this virtual information (2) a specific, planned or already existing product (3) is described from an atomic micro level to a general macro level. The Digital Twin contains all information about the respective product and its condition that is relevant for the management and control of the product life cycle. (4) It is a distributed, decentralized concept for managing product information (5) along the entire life cycle of the specific product. (6) It is based on a physical information link with the real product. (7) If possible, the information is transmitted in real time. (8) To enable an information link, the Digital Twin and its physical counterpart must be embedded in a suitable software and hardware environment.

Based on this definition the state of the art in the understanding and distribution of the Digital Twin in different industry and product contexts was considered. To this end, literature and internet research, including scientific publications, websites of companies and research institutions, journals, etc., on planning, development and implementation of the Digital Twin within different product and business context was conducted.

The results of the research on the Circular Economy and the Digital Twin were then merged to identify possible synergies related to the connection of these two concepts. The results are described in section 4.

Subsequently a framework for the development and scoping procedure of a Digital Twin was defined. The first five steps of the procedure are aligned to the steps of a requirements analysis, which is a common method used in the development of product and system solutions across a variety of industries and engineering disciplines [25], [26]. All steps of the procedure are shown in figure 2.

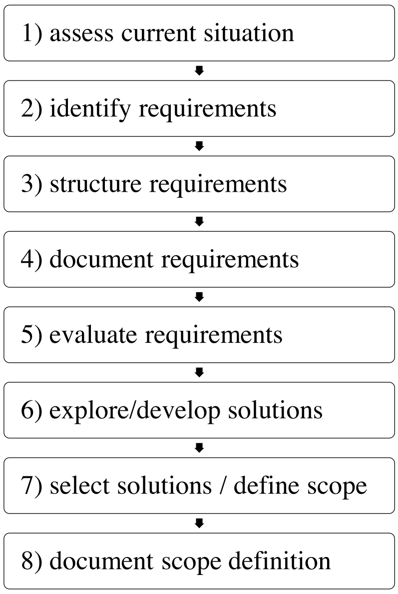

Figure 2: Process of scoping a Digital Twin

The first step is "assess current situation". Problems and objectives associated with the development of the Digital Twin are comprehensively analyzed: Which problems are to be solved with the Digital Twin? What benefits are expected from the Digital Twin? The environment of the problem, for example related IT structures, systems, processes and actors as well as their relationships to each other are considered as well. Information sources may include stakeholder interviews and organizational documents. To document relevant actors, their points of contact, processes and information flows, a visual documentation using the Business Process Model and Notation (BPMN) was found to be suitable.

Based on the results of step 1, software, hardware and data/information (etc.) requirements for the Digital Twin need to be identified (step 2). Which requirements for the Digital Twin can be derived from the assessment of the current situation?

In step 3, the identified requirements are structured, e.g. by software and hardware requirements, technical and functional requirements etc.

The structured requirements are documented in form of a requirements document (step 4). The documentation of requirements in form of a requirements document is done in natural, clearly understandable language. Technical language should be avoided if possible. The documentation should be understandable for all stakeholders, regardless of their particular academic background.

In step 5 the documented requirements are evaluated. This includes e.g. answering the following questions: Is the requirements document complete? Are there contradictions between individual requirements? Are the requirements feasible?

The requirements evaluation is followed by step 6 "explore/develop solutions". In cooperation with experts from different areas, e.g. computer scientists, programmers, process engineers etc., possible solutions for the documented requirements are explored. To this end, the various experts must be brought together. An information exchange and discussion space must be created. In this step the discussion of possible solutions takes place on a rather general level. The aim is more to explore different possibilities for solutions for the individual requirements than to work out these possibilities in detail.

In step 7, the solutions to be implemented are selected. The selection of the solutions (from step 6) to be actually implemented can be based on a cost-benefit analysis. It aims to compare different possible solutions and to evaluate if chosen solutions outweigh related costs. The costs and benefits can be the costs required for the further development and implementation of the individual solutions and the savings and profits achieved with the implementation. However, with regard to the objective pursued with the development of the Digital Twin, costs and benefits can also be defined in other ways. In case of the development of a Digital Twin to enable sustainable, circular product use, a measurement in the form of resource expenditures and resource savings related to the implementation might be more reasonable, than a solely monetary weighing. The selection of the solutions to be implemented equals the definition of the scope of the Digital Twin.

Finally, the definition of the scope of the Digital Twin is documented (step 8). The documentation of the scope is the basis for final development and implementation of the Digital Twin.

The procedure described suggests the chronological execution of the eight steps. However, the execution on

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the basis of a product example has shown that in practice it is always necessary to take partial steps backwards and supplement the results of earlier phases.

The product example mentioned is a circular reusable plastic packaging, which is currently under development in the Fraunhofer Cluster of Excellence Circular Plastics Economy CCPE. Insights into and lessons learnt from the development and scoping processes for a Digital Twin for this product are described in section 5.

3 Challenges in the transformation to a Circular Economy

The Circular Economy aims to use products, components and materials in a circular way and thereby to preserve resources. Circular use can be based on different cycle principles. A general distinction is made between the cycle principles sharing, re-use, repair, refurbishing and recycling. These can also be implemented in combination. To maintain the value of products and the resources used for their manufacturing at a high level for as long as possible, the principles of sharing, re-use, repair and refurbishment tend to be preferred instead of recycling. Recycling involves destroying the form and functionality of the product and the recycled materials obtained are often of inferior quality compared to new materials. [27], [28]

The economically and ecologically successful implementation of the cycle principles is associated with various challenges. Beside the partly different definitions and understanding of the term Circular Economy and the lack of legal and economic incentives, are missing technological developments as well as information gaps the central transformational challenges. [4], [29], [30]

Present established system infrastructures for the collection, sorting and treatment of end-of-life products are designed towards energy recovery and recycling. There is a lack of development and broad implementation of economically and ecologically attractive technologies and systems, e.g. for collection and sorting of used products (reverse logistics) for superior cycle principles and for the automation of refurbishment processes. [31]

Increased transparency and availability of information could improve the circular use of products. Transparency and information about the location and condition of a product can help to better calculate and control the return of products and materials for the purpose of sharing, re-use, repair (e.g. predictive maintenance), refurbishing and recycling. [30] More transparency regarding the material properties of returned products could further enable better recycling. Information about the condition of a specific product can facilitate a profound and decentral decision for the best possible cycle principle, taking into account both economic and ecological criteria. Testing and inspection processes that are regularly required in the context of sharing, re-use and refurbishment business models can be made easier. Currently, the transparency and availability of product-specific information during the product life cycle is often incomplete. Due to individual motives or simply a lack of life cycle-spanning information systems, information gaps usually arise when transferring products from one actor/phase to the next. In the course of the life cycle, therefore, a lot of information is lost or wide spread over a multitude of both public and closed information sources. [9], [30], [32], [33]

Greater transparency and information availability could make the implementation of cycle principles more economically attractive for companies and consumers and thus foster the development of innovative business models. National and international monitoring systems could facilitate governments to control the compliance of companies and consumers to legal requirements concerning the Circular Economy, e.g. recycling quotes. [29], [30], [34] The following section explains how a Digital Twin can help meet these challenges.

4 Potential contributions of the Digital Twin to the Circular Economy transformation

Due to a lack of technological prerequisites and high development costs, the use of the Digital Twin was only possible and economically viable to a limited extent in the past. Meanwhile, the possibilities of using a Digital Twin at economically reasonable costs have improved significantly due to technological advances in areas such as data collection, storage, and processing. [9], [35]

The Digital Twin is considered to be an efficient concept for linking the real and virtual world and can be used in a variety of applications for different purposes [9]. By using suitable sensor technology and linkages with relevant information systems/data bases, the Digital Twin can collect, store, process and map data, which is relevant to different actors and processes in the product life cycle (e.g. location, age, material properties etc.), in real time. It can thus help to optimize processes and use resources more efficiently throughout the entire product life cycle. [33], [36]

Even before the real product depicted by the Digital Twin is manufactured, the product behavior under different conditions can be simulated using the Digital Twin. Physical prototypes may thus become mostly redundant. [9], [17] Data collected during a product life cycle can be used for the development of new products and contribute to the improvement of product design. For example, life cycle data from existing products can be used to draw conclusions about design requirements for product longevity in future product developments. [9], [30]

Data collected during the use and operation of products can be used to optimize product performance and detect incorrect user behavior. This information can be used, for example, to monitor user behavior in sharing systems. It can also help the user to gain a better understanding of the function and correct handling of a product. [37], [38]

Any lack of information complicates the selection and implementation of cycle principles. By providing information about the condition of a product, the Digital Twin can, for example, be decisive in the decision to buy a used product. With information about the location and availability of a product, users of sharing systems can find available products in their neighbourhood. Condition data can be used to plan and carry out repair and maintenance work on products in advance (predictive maintenance). [37], [38]

The Digital Twin can be used to better record and control return flows of products, which are no longer in use. Based on location and condition data, products can be better tracked and returns can be calculated. The Digital Twin can close information gaps. Based on the condition information, a profound selection of the most suitable cycle principle for a specific product may be possible. Condition information about a specific returned product can be used to accelerate or automate the testing and inspection processes necessary to implement the cycle principles refurbishing and repair. [30], [36], [37], [38]

All in all, the Digital Twin can contribute to the optimization of product life cycle management. By enabling greater transparency and traceability, it can strengthen confidence in Circular Economy business models and products, as well as the collaboration between different actors. [33], [36]

5 Case study: development and scoping of a Digital Twin for a circular reusable plastic packaging

Within the Fraunhofer Cluster of Excellence Circular Plastics Economy CCPE, six institutes have joined competencies around the topic of sustainability in plastics, aiming at transforming the current linear plastics economy into a circular plastics economy. The cluster aims to achieve this goal by advancing material research for biobased and biodegradable plastics and additives, by developing new recycling technologies and digitalisation approaches, and by demonstrating new products and business models.

Considering the increasing packaging consumption and the corresponding increasing packaging waste, there is a great potential in the packaging industry, to achieve economic and ecological benefits through establishing reusable packaging systems. Especially in the field of parcel delivery, there is a large volume of disposable transport packaging due to the high number of consignments of paper and cardboard. In 2018 in Germany alone more than 3.5 billion shipments were sent and delivered [39]. Central challenges in this area are large numbers of returned items and failed delivery attempts on the last mile. Statista estimates the number of returned parcels in Germany in 2018 to be 280 million [41]. [40]

Carrying out the scoping procedure (see section 2) for a Digital Twin of a circular reusable plastic packaging within the Fraunhofer CCPE began with the identification of relevant actors involved in the lifecycle of the physical packaging. Plastic producer, packaging manufacturer, pooling system operator, CEP provider, repair service, end user and recycler were identified as central actors in multiple-use packaging systems. The processes, information needs as well as physical and virtual interfaces of the single actors were analysed and documented within a business process model. Legal frameworks for transport packaging were considered.

Depending on the application, industry and business model context, actors and particularly relevant processes and information can be very different. Additionally, norms and standards for transport, handling and characteristics of the packaging vary widely depending on the specific use case.

Focus for further analysis of the current situation within the scoping process of the Digital Twin for a circular reusable plastic packaging was therefore laid on potential user stories in the industries fashion, electronics and food. These industries differ significantly in their characteristics and, accordingly, the respective requirements for the circular reusable plastic packaging and its Digital Twin. This is, for example, due to the fact, that clothing is much less sensitive to shocks and temperature fluctuation than electronic products or food. For high-value and shock-sensitive products, a detailed transport and handling profile, e.g. based on data on location, motion and condition as well as access monitoring can be useful, especially for all those stakeholders which have temporary or lasting responsibility for the shipped good. In the food sector, especially for fresh foods, the traceability and verifiability of a maintained cold chain is also important.

However, the requirements for the Digital Twin resulting from the objective to enable the circulation of the plastic packaging according to the principles of the Circular Economy (e.g. re-use, repair, recycling) are relatively similar within the three industry contexts.

The requirements identified through the analysis of the industries, stakeholders, processes and information flows were structured, documented and evaluated according to the steps of the scoping procedure outlined in section 2. Based on the requirements document, possible solutions for this system of requirements are currently being explored and developed. For example, a selection of possible sensor types for the collection of relevant data for the Digital Twin has been made. Roles and visualization options for the effective and convenient use of the Digital Twin are being developed based on information needs, access rights, user skills etc. In parallel to the further exploration and development of solutions, the preparation of a cost-benefit-analysis for some partial solutions is planned to start soon.

An important insight gained from the steps of the scoping procedure for the Digital Twin of the circular reusable plastic packaging carried out until today is that steps back occur. Actors and experts involved in the development and implementation of the solution should be integrated into the scoping process as soon as possible. This could e.g. reduce comprehension problems regarding descriptions of requirements and thus reduce regression steps within the scoping process. Central challenges regarding the scoping are to bring the multitude of different stakeholders together and to convince them of the potential use and benefits of the Digital Twin, which is for many unknown. It will not be possible to complete the scoping for the Digital Twin before the development of the circular reusable plastic packaging is completed.

6 Conclusion

Within this paper, central challenges of the transformation to a Circular Economy were described. Potentials of the Digital Twin to master these challenges and to contribute to the successful circulation of products were discussed. A procedure for scoping a Digital Twin was outlined and insights in the implementation of this process using the example of a circular reusable plastic packaging were given.

One of the central objectives of this paper was, to describe contribution potentials of the Digital Twin to environmentally friendly, resource saving, circular use of products, components and materials. The development of the Digital Twin within the Fraunhofer Cluster of Excellence Circular Plastics Economy CCPE aims to explore the same potential for the circular use of plastic products and plastics. To quantify and evaluate this potential holistically, the resources required to develop, implement and use the Digital Twin (e.g. build up IT infrastructure, store data) have to be quantified in comparison to the resources that can be saved through the circulation of products, components and materials. Quantifying these costs and savings in different industry and product contexts is a prerequisite to make further statements on the potential of the Digital Twin for the Circular Economy and will be a central part of future research.

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Estimation Method of SDGs Related to ICT Services Using Vector Representation of Words

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Abstract

In this paper, we propose a method for estimating the level of association between Information and Communication Technology (ICT) services and the Sustainable Development Goals (SDGs). In this method, text documents outlining various IT services are used as a basis for identifying the most applicable SDGs. We analyse the semantic structure of Japanese sentences outlining the169 SDG targets, and redefine them into expressions that can be compared with the characteristics of various ICT services. Text words were vectorised and the cosine similarity between redefined SDG targets and ICT service documents were calculated. Various ICT services, including cloud business and teleconference systems, were evaluated using this method. This method allows ICT services to be examined in detail at the 169 SDG target level. While human evaluation of association between SDG targets and ICT services tends to be subjective, this method provides a logical basis for decisions in pairing ICT services with specific SDG targets. It also significantly reduces the burden of evaluating the association between ICT services and SDG targets manually, reducing the evaluation time by around 90%.

1 Introduction

In 2015, the United Nations Summit adopted the "2030 Agenda for Sustainable Development" with the Sustainable Development Goals (SDGs: Sustainable Development Goals) at its core. The SDGs consist of 17 goals and 169 targets. A number of companies have started to consider solutions to each goal. ICT (Information and Communication Technology) services in particular are expected to make a significant contribution in the transition to a sustainable global economy. The explanatory sentences of each SDG target contains a large number of highly abstract behavioural goals, which take time to analyse in detail. This high level of complexity means that when determining specific SDG goals relevant to an ICT service, the full detail of the SDG targets may not be properly considered. With this kind of oversight, there is a risk that the effects of ICT services may be overlooked or overestimated.

The purpose of this research is to (1) apply a redefinition of the target document of SDGs by semantic structure analysis, (2) employ an expression method using the vector representation In natural language processing to evaluate the relevance of each SDG to a given ICT services, and (3) to realize an automated support tool to assist with human-judgement in evaluating the relationship between SDGs and IT services. This result provides a method of evaluating the association of ICT services at the SDG target level, which, due to ambiguities in human-judgment, has not been sufficiently implemented up until now. By providing concrete reasoning for associating ICT services with SDG targets and narrowing down the number of targets relevant to a particular service, the result provides a tool for the promotion of ESG management in Businesses.

2 Related research

Keyword extraction methods are commonly employed in the association of respective SDG targets with business activities [1]. In the case of ICT services, it is necessary to clarify the cause-and-effect relationship between ICT services and societal contribution. It is therefore difficult to determine what factors contribute to the realization of SDG targets by using keywords alone. On the other hand, in recent years, research into question answering techniques, in which artificial intelligence answers questions, in particular machine reading, has attracted attention [2]. Machine reading is a question answering technique that enables a system to read and understand a document in natural language and to answer a question related to the passage by finding and extracting information to be an answer from the passage. It has been reported that question answering by machine reading can achieve high answer accuracy through deep learning [3]. However, there are still challenges in applying machine reading to complicated sentences such as the target sentences of SDGs. It is difficult to understand words with multiple meanings and to obtain sufficient accuracy in answers to ambiguous questions with current machine reading techniques [4]. In this research, we introduce a technique to estimate the relationship between each SDG target and text sentence of an ICT service using Word2Vec [5], which is one of the vector representation techniques of words in natural language processing. By understanding the essence of the SDGs target document, and associating words relevant to an ICT service through vector expression, we aim to realize an automated association tool to support human-judgment. This tool can serve as a starting point for the evaluation of SDGs relevant to a given ICT service.

3 Estimation method

3.1 Creation of redefined targets by semantic structure analysis of SDGs target text

We analyzed the semantic structure of the 169 SDG target sentences in Japanese [6] and redefined them into expressions suitable for evaluating the characteristics of ICT services. Since SDG target documents are often difficult to read due to lack of sentence subject and object, we first analyzed the relationship between important words and sentence subject and object manually. Figure 1 shows the procedure for creating redefined targets from semantic structure analysis. Figure 2 shows an example of the result of semantic structure analysis for Target 13.1 of SDG Goal 13. In each target, the most important phrase was extracted from each sentence and a causal relation and adjective relation between important phrases were arranged. Next, the important phrase extracted from each target was arranged into each corresponding goal. The arrangement of causal relations between important phrases and problems allowed for the clarification of the purpose of each goal. This process underpins the preparation of redefined targets. We created 109 redefined targets from the 169 SDGs target documents. Table 1 shows an example of a redefined target from SDG1.

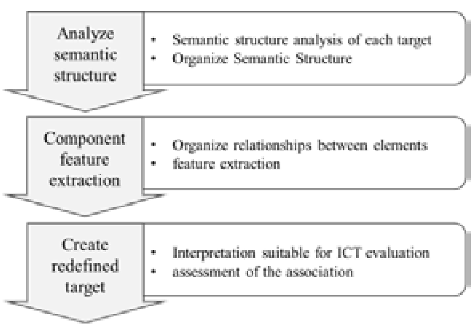

Figure 1: Flow for creating redefined targets

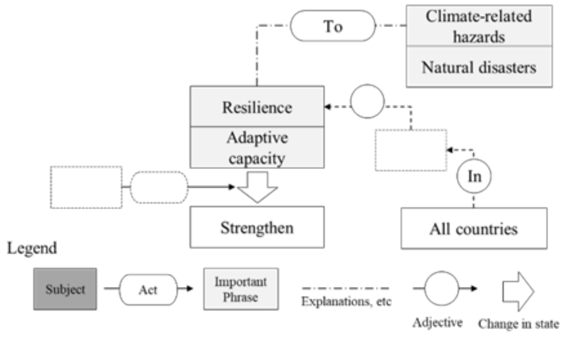

Figure 2: Semantic structure analysis results for Target 13.1

SDG	Redefined targets
1 NO POVERTY	Anti-poverty measures
	Social security system
	Ensuring ownership and control of property
	Ensuring access to basic services
	Building resilience of the poor against disasters

Table 1: Redefined targets for SDG1

3.2 Association estimation method using vector representation in natural language processing

To perform relation estimation, each redefined target is represented as a word vector, and explanatory sentences of each ICT service are analysed morphemically. Following this, cosine similarity between the ICT service and the redefined word vector is calculated. Word2vec was used for the vector representation. Word2vec is a technique to acquire vector representation (a low-dimensional vector representation of a word) of words using a neural network. A neural network learns from a large amount of text and obtains a concept vector for a word. In this research, we use the Word2vec model [7] that has been learned from Japanese wikipedia. The procedure is as follows.

1. A vector representation of a redefined target is obtained by a learned Word2vec model (200 Dimensions). The keywords of each redefined target are integrated and normalized. Since the redefined target consists of plural words, this normalized vector is treated as a semantic vector of the redefined target in this research.

2. A word list is created through morphological analysis of descriptive sentences of the given ICT service. Nouns and adjectives (excluding numerals and proper nouns) are extracted.

3. The cosine similarity between each ICT service and each redefinition target is calculated. The cosine similarity between each word and the vector of each redefinition target is calculated and sorted based on similarity. Vector integration and similarity are calculated from the words of higher ranking. If the vectors to be compared are x and y, the cosine similarity can be calculated using Equation (1). The smaller the angle between the two vectors, the more similar the vectors. Maximum relevance is defined as 1, occurring when cos (0) = 1.

$$cos(\boldsymbol{x}, \boldsymbol{y}) = \frac{\boldsymbol{x} \cdot \boldsymbol{y}}{|\boldsymbol{x}| \times |\boldsymbol{y}|} \tag{1}$$

4 Evaluation experiment

4.1 Experimental method

The proposed method is applied to 13 kinds of ICT services provided by the NTT group, explanations of which are openly available on the Internet. The 13 services include security clouds, teleconference systems and AI contact centres. Figure 3 shows the work flow of the relevance calculation. To perform morphological analysis using MeCab, a text document explaining the relevant ICT service is input. Next, vectorization using Word2Vec is performed. The relevance be-tween the word vector created from the ICT service text and the semantic vector of each redefined target is calculated. The cosine similarity was calculated after extracting the top 20 words of highest relevance and normalizing them. A final selection result for 13 kinds of ICT services has been obtained through this method, incorporating discussion with the development department responsible for the respective services. In this experiment, we compare and verify the results of the proposed method using vector representation with the final selection of the relation redefinition target undertaken through combining the relation estimation method with manual human-judgment.

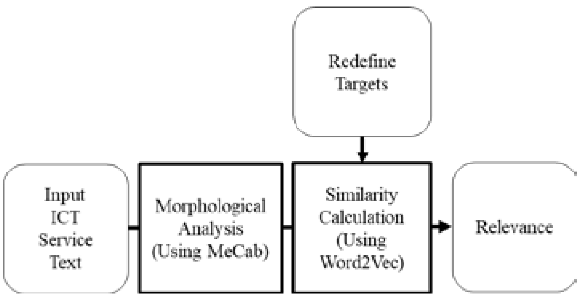

Figure 3: Relevance calculation flow

4.2 Result of the association estimation

Table 2 shows an example of results for the evaluation of a security cloud service, one of the 13 ICT services. 20 words are extracted from the service text, the top 5 results of the calculation the cosine similarity with each redefined target displayed. Figure 4 shows the final selection of the redefined targets, selected after discussion with the responsible development department. Work productivity and innovation were selected in the SDG8, sustainable infrastructure was selected in the SDG9, and disaster risk management was selected in the SDG 11. Regarding the construction of sustainable infrastructure, the cosine similarity, shown in Table 2, was 0.86, ranking fourth, indicating that the degree of relevance was calculated through terms such as security, safety, and systems. This shows that the semantic vectors of building a sustainable infrastructure, which is a redefinition tar-get, are similar in meaning to word vectors such as security, safety, and systems. By showing the redefined target as the result of judgment of association, it was clarified what kind of viewpoint it contributed.

SDG	Redefined Targets
8 DECENT WORK AND ECONOMIC GROWTH	Promotion of technological improvement and innovation to improve labor productivity
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Building a sustainable and resilient infrastructure
11 SUSTAINABLE CITIES AND COMMUNITIES	Disaster risk management

Figure 4: Redefined targets as selected by the development department

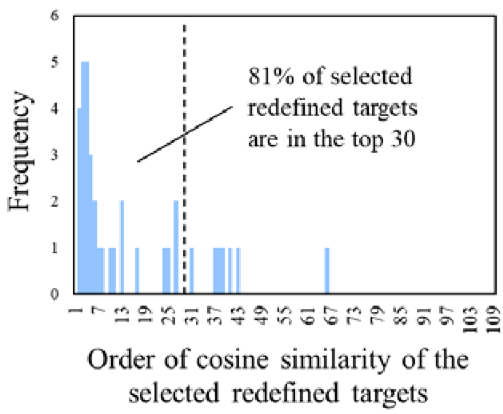

Figure 5: Histogram of SDGs Estimation Results for 13 ICT Services

SDG	Redefined Target	Cosine similarity	Extracted word (20 Words)
	Access to housing and basic services	0.898	Services, Safety, Comfort, Appropriate, System, Convenient, Solution, Security, Infrastructure, Optimal, Fast, Environment, Terminal, Business, Business, Needs, Function, Product, Business, Simple, Communication
	Providing universal and inexpensive Internet access to least developed countries	0.874	Services, Solutions, Business, Security, LAN, Access, Infrastructure, Systems, Implementation, Terminal, Gateway, SaaS, Search, Product, Penetration, Encryption, Environment, Company, Convenience, Features,
	Access to safe, inexpensive and easy transport systems	0.862	Safety, Comfort, Convenience, Appropriate, Rapid, Environment, Infrastructure, System, Needed, Optimal, Insufficient, Advanced, Security, Service, Business, Things, Functions, Uniformity, Countermeasures,
	Building a sustainable and resilient infrastructure	0.86	security, safety, systems, solutions, business, services, communications, functions, comfort, environment, access, proper, convenient, advanced, rapid, business, control, defense, information, gateway,
	Building infrastructure and industries with high resource utilization rates and consideration for the environment	0.855	environment, infrastructure, system, safety, function, control, security, solution, advanced, analyzed, countermeasure, problem, level, comfort, product, access, appropriate, necessary, method, optimal

Table 2: Top five results of the association estimation

4.3 Comparative verification

Figure 5 shows histograms of redefined targets that underwent final selection by the development department of the 13 ICT services. For each of the 13 ICT services, 2 ~ 4 redefined targets were selected, for a total of 37 redefined targets. As a result of the selection, in particular, Promotion of Technological Improvement and Innovation to Improve Labour Productivity, which are the redefined targets of SDG8, and Building a sustainable and resilient infrastructure, which is a redefined target of SDG9, were selected more frequently. This indicates that the efficiency improvement of ICT services and the security measures in cloud services are most frequently evaluated. In fact, SDG8 picks up words such as optimization, speed, cost and reduction, while SDG9 picks up words such as security and safety.

Figure 6 shows a comparison between the results of the proposed method and results selected by the Development Department for the 13 ICT services. The horizontal axis indicates the order (Up to 109) of the redefined targets in each service, and the vertical axis indicates the frequency. In this research, 13 ICT services were associated with 37 redefinition targets, and the results show the rank of cosine similarity among the results of the association estimation for each ICT service. It can be said that the accuracy of the relation estimation is higher as the frequency is on the left side. As for the redefined targets that were selected, 81% of them ranked within the top 30 of the cosine similarity in the proposed method.

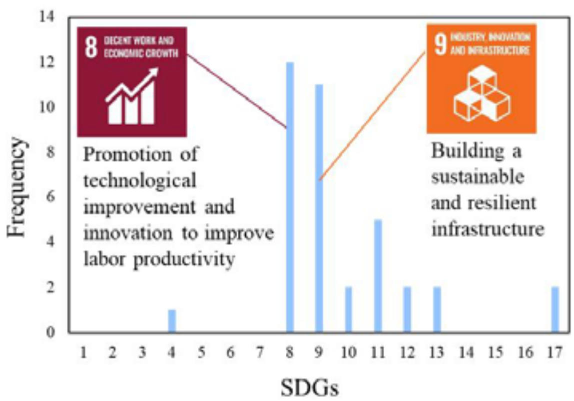

Figure 6: Histogram of cosine similarity evaluation rankings of related estimation results of the 13 ICT services

5 Conclusion and discussion

This paper describes the results of the redefinition of target sentences by semantic structure analysis and the application of an association estimation method using vector representation of words as the evaluation method of SDGs association with ICT services. The proposed method has made it possible to show the grounds for judgment, which was a problem in conventional methods. In addition, through an exchange of opinions with the development department of relevant services, it became clear that it was possible to estimate relationships without reading target sentences of SDGs as in the past, and that the method was effective in reducing the time taken in judgment operations. The accuracy of the proposed method has been confirmed to some extent, but it is not possible to use it as a sole selection method. It is recommended that our method be used as support tool for manual human-judgment. In addition, this method uses explanatory documents for ICT services as an input, so it is not possible to evaluate viewpoints that are not contained in the document. A future avenue for investigation is how to achieve both accuracy improvement through machine learning and an improvement in serendipity.

Acknowledgments

I would like to thank Natsumi Futakuchi and Tamami Hirota of NTT Communications Corporation for their cooperation in selecting the SDGs Association evaluation.

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D.2
SOCIETAL PERSPECTIVES:
GLOBAL CHANGE, ACTIVATING USERS, EDUCATION

The Limits of Categorical Responses to Climate Change

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Abstract

This paper presents a theoretical comparison between the response to the ozone depletion crisis and the response to the climate crisis. Considering that literally millions of discrete climate change mitigation projects have been initiated by governments, businesses and individuals, why does it seem that no real action has been taken? In contrast, when the ozone hole was identified, a handful of discrete actions resolved the crisis within a few decades.

The reason for this is that unlike ozone depletion, climate change defies categorization, and this makes our categorical responses ineffective. Climate change is amorphous, uncertain and variable, while ozone depletion is clear, categorical and linear. The global response to climate change cannot be modelled on ozone depletion. Rather, it must be universalized across all sectors: politics, technology, entertainment and infrastructure. It is also critical to focus on how we use and misuse people's attention in order to combat misinformation, which is probably the greatest danger we face right now. Fortunately, in thermodynamics and information theory, we have probabilistic methodologies that allow us to describe systems uncategorically..

1 Introduction

Climate change is not a function of devices or technology. Climate change is a function of space, time, and attention. Specifically, people in the wrong place at the wrong time, focused on the wrong thing. To clarify what I mean, I'd like to look away from information technology and ask why cities are built in grids? Grid patterns are rare in nature, but people have been laying down cities in grids for at least 4,000 years.[1] This is genuinely odd. Grids, waste material on road segments that are little used while wasting time on intersections that are prone to gridlock. The most efficient way to lay out a city is in a logarithmic double spiral. This would maximise the entropy of the relationship between connectivity and flow, allowing the most interactions between objects packed as tightly as possible, which is why we see spirals in whirlpools, galaxies, plants, mollusc shells, DNA, and muscles. In technical terms:

> double spirals obey a maximum-entropy path-integral variational calculus ("the principle of least exertion", entirely comparable to the principle of least action), thereby making them the most likely geometry (also with maximal structural stability) to be adopted by any such system in space-time. [2]

Figure 1. Spiral Galaxy [3]

So why do we use a grid instead of the pattern we find in so many other dynamic systems? I suspect that there is no "reason" behind it. The grid emerges, like a spreadsheet, as the optimal form of data representation. Every location on the grid can be represented uniquely in two numbers, and the form of representation can be deduced from the geometry alone. Logarithmic spirals follow the principle of least exertion, the grid follows the principle of least data.

This inverse relationship between data representation and dynamic efficiency represents a fundamental constraint on a categorical response to climate change. What I mean to point out here in the introduction is that we intuitively choose categorical efficiency over thermodynamic efficiency. This paper describes the limitations this bias imposes on our efforts to prevent and mitigate the effects of climate change and suggests that a unified approach to climate change is possible if we deploy our data in service of thermodynamics rather than the other way around, as is our wont.

2 What is a Category

First, let me explain what I mean by "category." A category is a group of objects that are equivalent in some specific ways. Barry Mazur describes this in terms of canonical isomorphism:

> A uniquely specified isomorphism from some object X to an object Y characterized by a list of explicitly formulated properties—this list being sometimes, the truth be told, only implicitly understood—is usually dubbed a "canonical isomorphism." The "canonicality" here depends, of course, on the list. It is this brand of equivalence, then, that in category theory replaces equality: we wish to determine objects, as people say, "up to canonical isomorphism." [4]

In other words, 5 oranges are equivalent to 5 elephants, but only with respect to a specific list of properties – DNA, countability, 5-ness – encompassing their common attributes, or canon. Engineers will be familiar with the isomorphism of the canonical ensemble from statistical mechanics. Lawyers will have to reach a bit deeper, but will remember that criminal laws only prohibit acts that fit the list of elements that make up a given crime. But it is critical to appreciate that If we get too close to the details of the subject matter – if we try to juice the elephant – the equivalence breaks down.

Above all, categories are relational objects, not representative objects. That is, a category describes a set of relationships between objects; it does not contain or define the objects themselves. What makes the application of categories so challenging is that these relationships do not define themselves, and there is no objectively correct library of classifications that we can consult for validation. As information scholar Luciano Floridi explains, "relational entities are unknowable not because they are somehow mysteriously unreachable, but because their epistemic malleability is inexhaustible."[5] In order to have a coherent category, someone has to deliberately draw the line separating it from the infinitude of possibilities.

Take an electric car, a phone and a smart coffee machine. They all plug into the mains power; they all have wi-fi radio transmitters; and they all have microprocessors. They are equivalent within the category of connected devices. The problem, from a regulatory standpoint, is that this category is evolving to include everything else as well. "Electricity and heat" already dominate CO2 emissions at a sector level. [6]

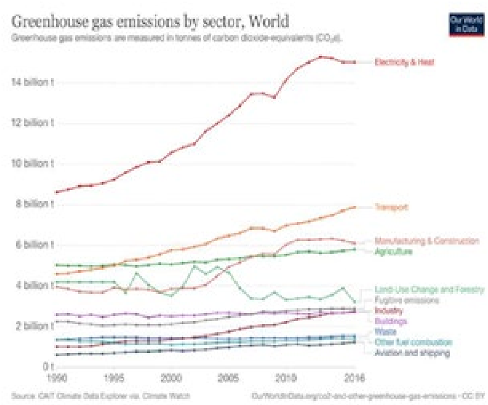

Figure. 2: Greenhouse Gas Emissions by Sector

3 Ozone Hole Success

In order to understand why this is a problem, let us take a look at the difference between our successful response to the ozone hole and our (thus far) failed response to climate change. Climate change and ozone depletion are both caused by chemicals released into the atmosphere, so it seems like they might be similar problems with similar solutions, but if we look at why the Montreal Protocol worked, we can see important differences.

> The implementation of the Montreal Protocol has been highly successful for a number of reasons. The chemicals and sectors (refrigeration, primarily) involved are clearly articulated. This let governments prioritise the main sectors early. The Montreal Protocol also provided a stable framework that allowed industry to plan long-term research and innovation. It was a happy coincidence that there were benefits for industry of moving away from ODS. CFCs were old technology and well out of patent. Transitioning to newer, reasonably priced formulations with lower- or no-ozone depleting potential benefited the environment and industry.[7]

The elements that made it possible to solve the ozone depletion are missing from the climate crisis. Unlike ozone depletion, where the affected categories of industries and products could be isolated and replaced, climate change implicates every possible category of product and activity. Everything we do has a carbon footprint. We are all in this category together.

To some extent, our success in addressing the crisis of ozone depletion has created a false confidence. Surely, if an atmospheric disaster like a hole in the ozone layer could be solved by science so painlessly, then we can expect the climate crisis to be resolved in similar fashion. Science will find a replacement for CO2 and slot it into position without any real inconvenience. This is the allure of carbon capture and electric vehicles. Unfortunately, they occupy a categorical fantasy world unfettered by entropy.

4 Categorical Blow-up

About 6 years ago I took it upon myself to write a summary of global television energy efficiency regulations, thinking naively that they would comprise a simple set of similar requirements. What I found was a bewildering mis-match of categories. European televisions were efficient under the EU rules, but not under the Chinese rules, while Chinese televisions were efficient in China but not in the EU. Whether this anomaly came down to products designed for the local test methods or test methods written for local industry was unclear. Whatever the cause, the result was that no comparison chart could capture the ambiguity or compare one regulation with the other. The project disintegrated when I came to Japan, where the regulations apply separate efficiency factors to 64 different categories of television. [8]

From an industry perspective, this micro-categorization is fair. It means that every configuration of components is accounted for. From the perspective of a consumer or policy maker, the sheer number of categories makes it impossible to assess good choices or determine whether the regulations actually promote energy savings. [9] Indeed, it raises the question of what "efficient" means for a television. A standard 12 inch B&W television consumed 45 watts in 1979, while the average television sold in 2000 consumed about 66 watts.[10] Moreover, efficiency only reduces consumption if usage remains the same. According to statistics from Nielsen, the average American home had 2.86 television sets in 2009.[11] In 1990, the average was 2.0, while in 1975, it was 1.57. What I mean to emphasize here is not that television efficiency has or has not been improved by energy efficiency regulations, but rather that we could quibble over the proper categories and subcategories of televisions for the rest of our lives without reducing CO2 emissions in the least.

Moreover, it is not clear that televisions are significant producers of CO2. Given the amount of content now streaming on phones, tablets, laptops and computers, the television may be surpassed by the data processing required for on-demand content: an hour of video streaming uses as much energy as seven days of running a domestic refrigerator; by 2030, the power requirements of digital services may outstrip Japan's current power generation capacity.[12] The Bitcoin system, we are told, uses as much energy as Switzerland.[13] We are not told whether this is very much, very little, or even something we should think of as important.

We are also told that the transport sector produces 14% of global CO2 emissions.[14] Within the transport sector, surely we must treat rail transport, which accounts for less than 2% of transport emissions, differently from road transport, which accounts for more than 70%.[14] And yet France's Yellow Vest protests illustrate the danger of regulating even road transport as one category. The people who are dependent on automobiles are distinct from those who only drive when they choose to do so.[15] Not only that, but vehicle-dependency is not a choice people make; it is the result of a century of bad decisions made by the powerful people in both public and private sectors. In sum, however we try to carve them out, the categories of CO2 emitting industries, products and activities explode into an incomprehensible mess of complex relationships.

5 Climate Mitigation

So, what can we do? First, we need to migrate with the weather. Wealthy people already do this. We just need to follow them. Second, we need to rebuild our cities to support migration and human-powered transportation. If these things sound unrealistic, remember that they are already happening, but not in a good way.[16] For migration and reconstruction to happen in a way that is not violently reactionary, we need a different way of building and a different way of representing the world around us.

Broadly speaking, climate mitigation has two fronts: physical infrastructure and data representation. They may seem like different worlds, but they have become intertwined in both the emerging internet of things and the dreary art of regulatory compliance. If we are involved in 5G implementation, then we are involved in infrastructure. If we are involved in telecommunications, then we can help people to migrate at the right time in the right direction. If we make products, then we are reporting data on everything from chemical use to recycling and every major company has representatives lobbying governments around the world for favorable regulatory treatment.

Most climate action focuses on infrastructure, mobility and efficiency, but the quality of our data is no less important. At present, there is profound resistance to even considering migration as a real aspect of climate change:

> Even as the scientific consensus around climate change and climate migration builds, in some circles the topic has become taboo. This spring, after Proceedings of the National Academy of Sciences published the explosive study estimating that, barring migration, one-third of the planet's population may eventually live outside the traditional ecological niche for civilization, Martien Scheffer, one of the study's authors, [said] that he was asked to tone down some of his conclusions through the peer-review process and that he felt pushed to "understate" the implications in order to get the research published. The result: Migration is only superficially explored in the paper. "There's flat out resistance," Scheffer [said], acknowledging what he now sees as inevitable, that migration is going to be part of the global climate crisis. "We have to face it." [17]

Mass migration is not merely inconvenient, but beyond the pale, as if living like a potted plant has become part of what it means to be middle class. If this does not change, catastrophic climate change and violent forced migration are inevitable.

However, planned migration depends on coordinated action, which is impossible without coherent communication. Without a clear picture of what is going on, physically, we have no basis for a coherent response, and if there is one thing we do not have right now, it is a clear picture of what is going on. As Wired Magazine founder Kevin Kelly explains, "for every fact there is a counterfact and all these counterfacts and facts look identical online."[18] Indeed, the biggest information technology companies – Amazon, Apple, Facebook, Google, Twitter – make no claims that their data represents anything real, true or physical. Our data represents only itself. So it is unsurprising, but "vexing," as Kara Swisher puts it, "to see that a lot of the focus from tech companies has been around direct air-capture of carbon – a kind of Ghostbusters approach of sucking up the baddies."[19]

This focus on fantasy solutions is not merely financially wasteful; it also produces a stream of misleading data suggesting that carbon capture will save us from the inconvenience of even having to understand climate change. This proliferation of conflicting and self-referential data highlights the limitations of categorical approaches to climate change, but I do not mean to suggest that we should avoid categories altogether. We can no more communicate without categories than breathe without air. Rather than abandon categories, we need categories that follow the basic principles of physics. We must insist that our data represent physical reality and work to improve the underlying physical conditions, not the data representation.

6 Simple Principles

If you have visited Barcelona with children, you have experienced the extraordinary impact of its pedestrian policy – there are simple, outdoor play areas everywhere. But it is important to understand that this is the result of a profound insight into urban development:

> On a cold, clear April 3, 1979, the city then known as "Grey Barcelona" held its first free local election since 1934. Soon after, the city's new planning director, Oriol Bohigas, helped devise a novel strategy for rescuing the city's urban life from the Franco-era haze of corruption and neglect that brought the unwelcome nickname. Instead of the master plans and showpiece projects usually beloved of mayors and planners, the city undertook a rapid and remarkable investment in the so-called "homogeneity" of the city's pedestrian spaces. In a widespread act of care and repair, new carpets of granite and tile spread across sidewalks and plazas, in both rich neighborhoods and poor. [20]

The anti-categorical principle of "homogeneity" has counterintuitively produced a city where every neighborhood feels like it is worth visiting. Similarly, climate change will be mitigated by the deliberate application of clear principles, not by clever designs or brilliant schemes. In this regard, 21st century information technology is both an opportunity and an attractive nuisance. As the Center for Humane Technology notes, we have people's attention.[21]

Humane Tech would like us to give that attention back, so that technology consumers regain their agency, but this misses the point of why people are turning to their IT devices in the first place. Information technology allows us to ignore the space and time we live in and wallow in representations of well-defined categories. We do not need a more user-friendly Instagram. We need a world worth instagramming.

The problem of representation may be exacerbated by information technology, but it is not new. Werner Herzog described this situation in the 1980's as "the emergency of our lack of adequate images":

> Es sind so wenige Leute heute auf der Welt, die sich wirklich etwas trauen würden, für die Not, die wir haben, nämlich zu wenig adäquate Bilder zu haben. Wir brauchen ganz unbedingt Bilder, die mit unserem Zivilisationsstand und mit unserem Inneren, allertiefsten, übereinstimmen. [22]

Herzog emphasizes that it is not enough to eliminate misinformation; we must have the courage to create images that encompass the world and our inner experience of it, both individually and as a civilization. Adequate images and language are essential in our battle against climate change because, as the IPCC dryly notes, "the implementation of land-based mitigation options would require overcoming socio-economic, institutional, technological, financing and environmental barriers that differ across regions."[23] That is to say, real climate mitigation depends on a complete reimagination of our civilization.

Shifting our focus away from categories of industries, sectors and products to the geometry of our infrastructure would allow us to describe these barriers in terms of accessibility and compactness, without being drawn into the endless ways in which they can be categorized or recategorized. We can further abstract this principle of geometrization to everything we do: are we building a spiral or a spreadsheet? The bias in favor of data representation makes it hard to avoid spreadsheets, but logarithmic spirals have certain advantages. They highlight the core of the project and make it easier to eliminate peripheral elements and other waste; even in abstract information, accessibility and compactness have clear benefits. A geometric approach can also simplify our modelling, as Jeynes and Parker point out:

> a very simple calculation using the apparatus of geometrical thermodynamics is capable of a result entirely consistent with experiment, where this result is not available without heavy computation using standard methods in physical chemistry.[2]

Finally, logarithmic spirals give us something we can visually confirm as more or less right; they are ubiquitous; and they are beautiful.

Figure 3. Morning Coffee

Regardless of what we do, if we focus on the infinite array of objects that populate our spaces, we will be trapped in an endless battle against space and time, fighting through one object to reach the next, only to be pulled, pushed or spread to another set. What I hope to have shown in this paper is that there is a better way. It is inconvenient from the perspective of data representation, but modern information technology is sufficiently sophisticated that thermodynamics can be made accessible even to non-scientists. It just needs our attention.

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How long do we care? The role of consumer practices for sustainable electronics

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Abstract

Electronic devices are often used shorter than their technical lifetime would allow. In a face-to-face survey we explored how product use times are influenced or "made" by users and their practices. Main questions were: What meanings do users attribute to longevity and how are they related to length of usage? What factors do better predict the usetime of products: individual factors, like meanings and personal norms, or situational factors, like the availability of repair services? These questions were investigated in a survey study, which covered several electronic devices but mainly focused on washing machines in comparison to smartphones. Multiple regressions were applied to explore different predictors of the length of usage and the decision to repair. Multiple regressions show that the desire for the new was the strongest predictive factor for the usetime of smartphones. Care practices did significantly increase the use time of washing machines. The decision to prolong lifetimes through repair was among influenced by the users' competence: Users who assess their knowledge about their devices functions rather high, are more likely to repair it. The results can serve as a background for strategies to enhance consumer competences to care for longevity.

1 Introduction

According to the UN's Global E-waste Monitor 2020 a record 53.6 million metric tonnes (Mt) of electronic waste was generated worldwide in 2019, an increase of up 21 per cent in just five years [1]. The negative socio-ecological effects are exacerbated by the fact that many consumer items, in particular electrical devices, are often used much shorter than the technical lifespan would allow and are often replaced even though they still work or can easily be repaired. Thus, the lifetime of consumer electronics and their environmental impact, depends not only on technological design and material longevity, but also on consumer practices. The frequency of use, care practices and the willingness to repair, for example, can prolong a product's lifetime.

Based on literature research as well as preliminary studies [2], [3], [4] several factors were identified that could lead to an increase in the useful life of electronic devices. This includes practices of new purchases, maintenance and careful handling during the usage phase, as well as repairs. The execution of such practices, on the one hand, depends on the social meaning, i.e. attitudes towards the devices, and towards practices that prolong usage as well as expectations concerning their useful life. On the other hand, the skills and competences of the users, the support from the social environment, as well as the infrastructure and the availability of the necessary equipment determine the likelihood of usage-prolonging practices. The focus of the investigation was on (1) the meaning of longevity and the actual usetime of products, (2) the prevalence and popularity of usage-prolonging practices, and (3) the influence of the social setting, infrastructures and social support for lifetimes and repair as a usage-prolonging practice.

2 Methods and Sample

The contribution of usage practices to the life of the devices was explored in a representative interview study in 2019 with 1000 participants.

A survey method was selected that, on the one hand, recorded parameters for the useful life of five representative electronic devices, from televisions, laptops and smartphones as entertainment devices to kettles and washing machines as classic household appliances. Practices and their predictors for washing machines and smartphones were recorded in more detail. Washing machines represent so-called "workhorses", which have a more practical and functional value for users. Smartphones, on the other hand, represent "up-to-date" products, where it is more important to own the latest model and present a certain kind of status with the device [5].

The sample was collected by a panel organization using the ADM Mastersample method, a three-stage random process to draw a representative face-to-face sample for all households in Germany. Interviewees were at least 14 years old, with no upper age boundary. The sample has a mean age of M(SD) = 49.9 (17.0), Median household income is 2000 - 3000 €, 53.8 % of participants are female, and education levels are 33.1% primary, 41.4% secondary and 25.4% tertiary level. 61% of the sample were full or part-time employees, 24% were retired and the rest still in training or unemployed.

3 Results

3.1 Ownerships and usetimes of electronic devices

Product ownership was assessed by a list of 16 electrical household and seven IT-devices. On average, the respondents owned M (SD) = 12.9 (4.0) household appliances, of which M (SD) = 12.1 (3.0) or 93% were in use (within the surveyed categories). When it comes to digital and entertainment devices, more devices than in the household category are not used regularly. Here, on average, M (SD) = 3.5 (2.6) devices are owned, but M (SD) = 2.8 (1.8) or 80% are used.

79% of the respondents own at least one smartphone, 60% at least one laptop, netbook or notebook, 98% at least one television, 97% a washing machine, and 81% at least one kettle. Of these five items, we asked the usetime of the last device. The most recently owned smartphones had an average lifespan of M (SD) = 2.7 (1.5), laptops 4.2 (2.3) years, kettles 5.4 (4.7) years, televisions 9.6 (6.2) years, washing machines 10.1 (5.8) years. Between 19% and 32 % of the users assessed the usetimes as insufficient, particularly in the case of notebooks and smartphones.

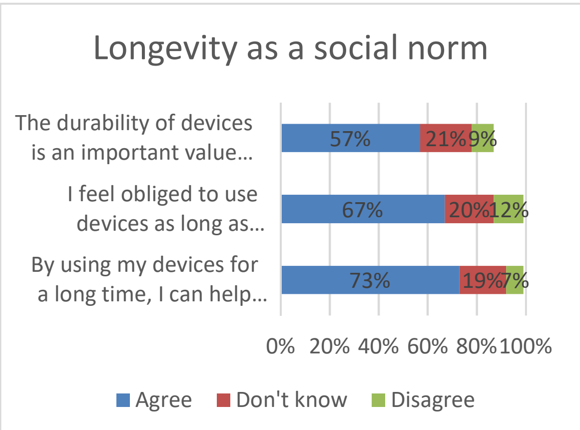

Figure 1: Attitudes concerning longevity of electronic devices (n = 1.000 participants)

If participants were asked about their general attitudes concerning lifetimes of products, it seems that there is a certain social norm to use products longer: 67% said that they feel obliged to use electronic products as long as possible and 57% indicated that longevity is an important societal norm. 73% thought they can reduce environmental pollution by using products as long as possible. Nevertheless, for the case of smartphones only 33% indicated that they bought their new phone because the old one was broken (65% in the case of washing machines).

Thus, we could assume that there is a certain desire to buy something new in the case of up-to-date products even though a currently used device is still working. This interpretation was to some extend covered by the data: If asked about the reasons for buying a new phone 54 % indicated that they wanted a phone with a better performance and more capacity. 48% said that they feel joy having a new phone.

3.2 Lifetime prolonging practices

Users have several options to prolong the lifetime of products, e.g. by good maintenance and care, by buying second hand or by repairing a broken device. These practices require a certain practical know-how and competence, for example about how to assess the quality of a used product or where to find a reliable repair service provider.

Thus, participants were asked first, how they would assess their own competence to properly maintain their smartphones or washing machines. Maintenance competence was higher in the case of washing machines, where 42% assessed it as high or rather high, compared to 32% for smartphones. This low competence assessment seems to show in the actual practices. A high percentage of smartphone users for example indicated that they are not using their storage space or the capacity of their battery carefully or efficiently enough (e.g. by letting the batteries discharge completely frequently or by not deleting unused apps or files). Moreover, 40 % frequently drop their phone.

To realize longer usetimes practices like repair need to become part of rroutines. Routines are well-established ways of interpreting and acting without needing to reflect too much on the options. In most cases, this saves time and energy. Certain events trigger familiar reactions. If they repeat themselves often, they are also called "habits". The interviews tried to reveal among other if participants had a habit of second hand buying

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or what they usually do when an electronic device breaks.

Second hand purchases are very infrequent for a range of products. The highest value was reached for washing machines where 11% had bought at least one washing machine second hand in the past. Smartphones where at least once bought second hand by 9%, Laptops by 5% and kettles by 3% of participants.

Usetimes could also be prolonged by repair. On average, we found very low repair rates in our sample: 86% of respondents never repaired a smartphone and 71% never repaired a washing machine. If we ask about what people usually do after a device breaks we found that for most devices the usual habit is to replace it instead of repairing it (see figure 2).

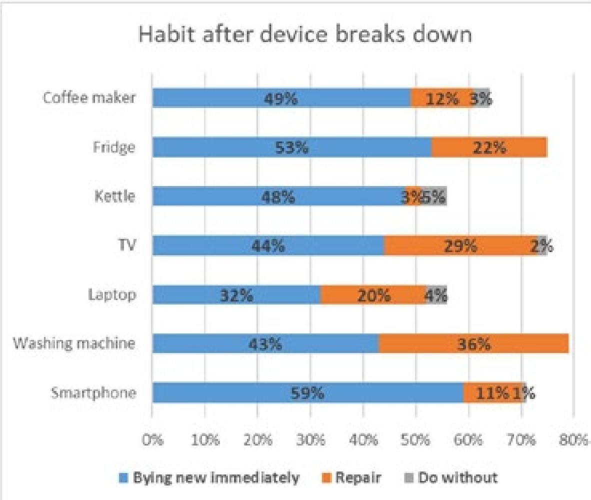

Figure 2: User habits after a device breaks (n = 1.000 participants; other answers like "borrowing a device" or "buy new after some consideration" are not considered in the figure)

This again is a contrast to the attitudes towards repair: About 60% of participants think that is practicable and meaningful to repair a device, two-thirds have the opinion that repair is good for the environment.

3.3 The role of infrastructural and social settings

In order to assess whether participants who are willing to repair get the necessary support from their environment we asked about the perception of the infrastructural and social settings. The survey revealed among other that manufacturers are perceived by half of the participants as not providing enough information about the production of their products. 30 % of respondents indicate that they do not have easy access to repair services. In general the perceived behavioural costs (i.e. the effort and resources that a certain activity requires) of repair are perceived as quite high (see figure 3).

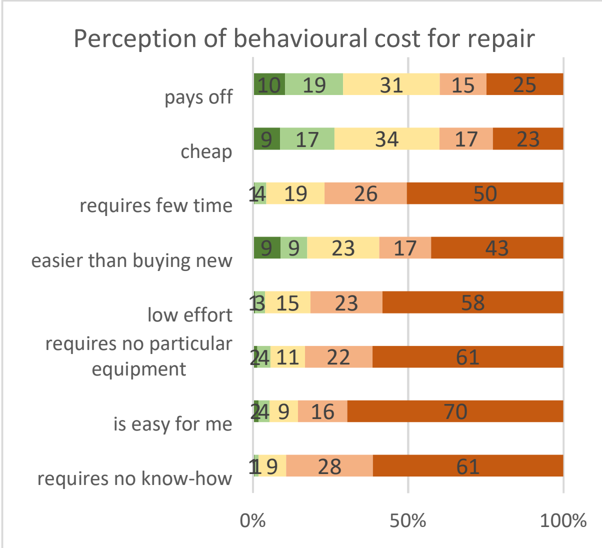

Figure 3: Perception of behavioural costs (red = high disagreement; yellow = neither agree nor disagree; dark green = high agreement)

As we can see in Figure 3, more participants assess repairing as expensive and not worthwhile, than as cheap and a decision that pays of in the end. Furthermore, almost all respondents perceive the behavioural costs in terms of time, effort, equipment and required knowledge as high. Thus, it is no surprise that buying new is seen as much easier than repair.

To compare the influence of different personal or structural aspects on the usetime of the last product as well as the decision to repair, we used multiple regression analysis (see Appendix 1 for the full results). The analysis revealed that the usetime of the last washing machine is higher, if the person is routinely caring for the device and is less attached to the machine. Smartphones are kept longer if a person is less attracted to new products (low novelty seeking) and also has a lower attachment. Repair behaviour is predicted by a positive attitude towards repair and low perceived behavioural costs for both devices. Furthermore, in the case of smartphones if a person feels competent technically and if the product attachment is low, is positively predicting repair.

4. Discussion

How long everyday objects last and why they are replaced early has received considerable attention in obsolescence research. Obsolescence is often generally defined as a process where products "fall into disuse" [6] and is related to a number of factors that can be related to technical and material deterioration (material obsolescence) or lost or outdated functions (functional obsolescence. The early work on obsolescence by

Packard (1960) refers to this as an “obsolescence of desirability”: “In this situation a product that is still sound in terms of quality or performance becomes "worn out" in our minds because a styling or other change makes it seem less desirable.”[7]

What we could find in our survey is that psychological or social factors should not be distinguished from factors that belong to the material arrangement or social and infrastructural setting in which product usage is happening. Our survey has shown among other things that longevity or “keeping products as long as possible” can be seen as an accepted and socially shared norm. However, this norm is not directly translated into practice, as we could see for example in the very low frequency of repair. We we could assume that the high behavioural costs of repair are playing an important role here. Furthermore, we could see that buying new is not only perceived as much easier but also as personally or socially desirable, particularly in the case of an up-to-date product like smartphones.

Product attachment seems to play a somehow peculiar role for longevity and lifetime prolonging practices: Our results indicate that the higher a person feels attached to a product, the less s/he is likely to keep it longer or repair it. We assume that the attachment is not related to the object itself, but more to its performance and functionality. This means that the more a person needs a functioning and well performing product the more s/he replaces a current product if performance or functional problems arise. We also find much evidence for the important role of know-how and competence for product-related practices as well as for the role of caring practices for product longevity.

Thus, a main conceptual conclusion is that product lifetimes are constructed in the dynamic reciprocity between individual agency and structures, which include the object and its design as well as the social and material settings of object-related practices. Strategies to increase product longevity should focus more thoroughly on the conditions for product care and maintenance and on how product-related know-how is appropriated. Policy measures should not only try to foster a general “Right to Repair” but also the capability to repair. However, longevity needs also to be cared for in the re-configuration of material settings as part of current material culture. Currently, material settings facilitate novelty seeking instead of doing longevity and offer more opportunities to acquire something new than to keep the old. We argue that material and social settings for repair are important but would hardly suffice, as long as novelty and innovation remain the more important and dominant meanings in current practices of consumption and production.

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Appendix 1: Results of multiple regressions with SPSS

Lifetime last smartphone (N = 509)	B	SE	Beta	T	p	r
(Konstante)	22,83	6,42		3,56	0,00	
Self repair of smartphones	-3,58	3,67	-0,04	-0,98	0,33	-0,04
Service repair of smartphones	-0,92	2,23	-0,02	-0,41	0,68	0,01
Care practice (smartphone)	-0,56	1,05	-0,02	-0,54	0,59	-0,05
Attraction of newness (phone)	3,70	0,76	0,25	4,89	0,00	0,25
Attachment (phone)	-2,04	0,88	-0,11	-2,31	0,02	-0,01

Usetime last washing machine (N=512)	B	SE	Beta	T	p	r
(Konstante)	2,60	1,93		1,35	0,18	
Self repair of washing machine	-0,25	0,86	-0,01	-0,29	0,77	-0,03
Service repair of washing machine	0,77	0,45	0,07	1,71	0,09	0,12
Care practice (washing machine)	0,50	0,20	0,11	2,52	0,01	0,08
Attraction of newness (washing machine)	0,35	0,19	0,08	1,78	0,08	0,12
Attachment (washing machine)	-0,50	0,22	-0,10	-2,27	0,02	-0,07
Personal norm for longevity	-0,35	0,24	-0,06	-1,47	0,14	-0,12

Repair of Smartphone, (N = 671)	B	SE	Wald	Sig.	Exp(B)
Attitude towards repa(iring smartphones	0,377	0,154	6,016	0,014	1,458
Personal norm for longevity	-0,076	0,180	0,179	0,672	0,927
Attachment (phone)	-0,320	0,161	3,921	0,048	0,726
Attraction of newness (phone)	0,199	0,145	1,889	0,169	1,220
Investment (phone)	-0,076	0,165	0,213	0,645	0,927
Infrastructure for repair	-0,163	0,129	1,595	0,207	0,850
Material for repair	-0,320	0,175	3,323	0,068	0,726
Competence for repair	-0,405	0,185	4,786	0,029	0,667
Social support for repair	-0,067	0,174	0,146	0,702	0,936
Behavioural costs of repair	-0,773	0,200	14,908	0,000	0,462
Social norm for longevity	0,166	0,184	0,816	0,366	1,180

Repair of washing machines (N=512)	B	SE	Wald	Sig.	Exp(B)
Attitude towards repairing washing machines	0,54	0,10	28,75	0,00	1,71
Personal norm for longevity	0,10	0,13	0,62	0,43	1,11
Attachment (washing machine)	-0,15	0,11	1,91	0,17	0,86
Attraction of newness (washing machine)	0,28	0,10	8,59	0,00	1,33
Investment (washing machine)	-0,21	0,12	3,23	0,07	0,81
Infrastructure for repair	-0,31	0,09	12,43	0,00	0,73
Material for repair	-0,15	0,12	1,59	0,21	0,86
Competence for repair	-0,14	0,14	0,89	0,35	0,87
Social support for repair	-0,16	0,11	1,87	0,17	0,85
Behavioural costs of repair	-0,62	0,15	17,87	0,00	0,54
Social norm for longevity	0,12	0,13	0,79	0,37	1,13

Effectiveness of environmental education through Project Based Learning

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Abstract

One of the important missions of Japanese university is to enable students to have practical capability in preparing for graduation. PBL is said to be effective in enhancing self-motivated study. Thus, many Japanese universities are taking PBL in their curriculum. Akita University is also carrying out a PBL program in which students engage on several subjects offered by local companies in Akita prefecture. One of the companies collaborating with program is a recycling company that carries out intermediate processes of recycling of home appliances and small-sized home appliances. The objective of this study is to show PBL is an effective way to find solution for environmental problems and foster students who have knowledge and eagerness to move towards the solution of the problems. In overlooking the processes and the results of the 3 years effort, it was clarified that the success of the project depended on the subject. The subject allows the students to try their own idea in the practical way, was effective in enhancing their motivations and lead to good results. The study lead us to conclude that PBL is effective in fostering students who have "environmental awareness."

1 Introduction

PBL (Project based learning) is said to be effective in enhancing self-motivated study for students. In finding solutions of problems that have no fixed answer, such as environmental problems that have many stake-holders and many trade-offs, this type of education is suitable to let the students think by themselves, investigate, negotiate and find solutions. Akita University is also carrying out a PBL program in which students engage on several subjects offered by local companies in Akita prefecture.

MEXT which is in charge of planning and designing Japanese education has announced a guideline [1] for environmental studies from primary school to high school. For example, in the 3rd and 4th grade, the guideline says they should learn "effective use of water and electricity" and "area where local resources such as natural environment, tradition and culture are preserved and utilized." The expressions are rather concrete compared to the previous guideline. This guidelines are for mentors not for students. Since teachers should have various experiences and rich ideas for mentoring environmental studies, it is difficult to follow the guidelines completely.

This announcement does not say anything about universities. It means that passive study has been finished before entering universities. However, after 12 years passive study, it is difficult to carry out autonomous projects soon. PBL is the necessary step to proceed to practical projects.

The Akita university's program has started in 2016 and project work started from 2017. One of the companies collaborating with program is a recycling company that carries out intermediate processes of recycling of home appliances and small-sized home appliances. The subject from the recycling company have been included every year. The subject focused on promotion of recycling of small-sized e-waste. Since the authors who are in charge of program coordination thought this type of socio-scientific subjects are suitable for PBL, these subjects have been assigned to students every year and the results were basically successful.

The objective of this study is to show PBL is effective way to find solution for environmental problems and foster students who have knowledge and eagerness to move towards the solution of the problems.

2 PBL in Akita University

PBL (Project Based Learning) [2] is a method of education which is defined as "an educational method in which the learning is achieved during the process in understanding and solving the problem." Special features of PBL are summarized to three points. The three points are (A)objective is to solve the problem, (B)focuses on team effort to solve the problem, and (C) students' autonomy is regarded as important. It is a learning method which focuses on daily problems or practical examples and makes team efforts on solving the problem.

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PBL is categorized to 2 major methods. The first one is "Tutorial type" which is to proceed the study based on a virtual story, and the other is "practical experience type" which is to collaborate with real society [3]. Real society includes private companies, municipal government, NPOs, etc. Akita University's program belongs to practical experience type and aims in fostering students' responsibility, practical knowledge, leadership, and other many characteristics. Many universities have introduced PBL in their curriculum, in order to encourage learning motivations.

Since it is a learning method, there is a small difference with practical project work regarding its process and achievement. However, importance of project work and project management of social problem is becoming higher and higher. Thus, significance of this type of learning method which fosters autonomous and practical ability is increasing.

Creative engineering course that belongs to Faculty of Engineering Science, Akita University, also carries out this type of educational program which is named "Practical Study by Project Execution." During the first half of the program, lecture series regarding general methodology of "Design for Manufacturing" were carried out. The contents of the lectures refer ME317 [4, 5] at Stanford University. The lecture covers, Customer Value Chain Analysis (CVCA, [6]) Morphological Analysis, QFD (Quality Function Deployment), Design for Assembly, Cost-worth analysis, FMEA (Failure Mode Effect Analysis), Robust Design, Supply Chain Management, Design for Environment, and so forth.

In the second half of the program, the course collaborated with 6 private companies in 2017 and 6 to 7 companies continuously after that, as shown in table 1. One of the constraints of the university's PBL is that the average number of students in the team differs due to the number of collaborating companies and total number of students.

Table 1 Number of collaborating companies and students engaged.

Year	Number of companies	Number of students
2017	6	28
2018	7	23
2019	6	28
2020	7	29

All the companies locate in Akita prefecture, and project work was imposed to the students. Based on the discussions with the program coordinator, the companies offer projects for students.

In order not to choose unsuccessful projects, preceding discussion is important. Sometimes, first proposals are too difficult for undergraduate students, too specific to foster students' autonomy, or too broad to find-out the way to reach the goal. Therefore, mentors who have practical experiences in PBL or private companies are helpful in deciding the project subjects in advance.

In the middle of the first semester of the program, general descriptions of the subjects were announced. Students choose subjects based on their intention, listening to the brief description of the subjects, considering the company locations, etc.

3 Environmental aspect of the project' themes

Most of the projects are about improvement of manufacturing processes such as quality assurance, improvement of factory environment, enhancement of throughput of a production line, and so on.

However, some of the subjects focus on environmental issues in industry. Throughout 2017 to 2020, Table 2 shows the list of the subjects that have some relations with environmental issues.

Table 2 list of the subjects with environmental aspect

Year	Subject
2017	Promotion of collection of small-sized home appliances
	Proposal of light weight and low cost AGV (automatic guided vehicle)
2018	Proposal of new e-waste collection system to city government
	Improvement of energy efficiency of plating
2019	Design of booth layout in city eco-fair
	Efficient and low-cost inspection of electronic devices
2020	Design of visitors' route layout and exhibition
	Efficiency improvement of heat treatment furnace

Some of the above-mentioned projects were proposed by Ecorecycle Co. Ltd. [7], whose main business is to operate a recycling facility. The authors have been committing to the studies on "Collection of small-sized e-waste based on the consumers' needs," after the legislation of small-sized home appliances was enforced on April, 2013. The authors also joined the students' discussion as advisers utilizing the knowledge from own studies. It is significant to foster the students who belong to the heavy-user generation of small-sized electronics such as mobile phones, portable game machines, etc., to act autonomously and actively in solving the practical problem which has a social necessity.

As for the subject regarding e-waste collection, which has no "right" answer, PBL seems to be a good scheme to propose effective ideas. Since the students are consumers rather than producers or researchers, they are expected to be good at thinking of convenient way for consumers to put e-waste into collection bin.

4 Effect in solving environmental problems

Recycling legislation of small-sized home appliances started to be enforced from April, 2013, in Japan. A social experiment [8] was carried out in several locations in Japan, in advance to the law enforcement. In Tohoku area, Akita prefecture was designated as the area for the experiment, since there is a recycler having technologies for intermediate and final treatment. Designated recycler, Akita prefecture, other municipal government, and Akita university participated in the experiment to promote collection of small-sized home appliances towards the establishment of the legislation.

Even though Tohoku area was one of the advanced areas where collection of small-sized e-waste was tested first, after the enforcement of the legislation, collection of waste has not been carried out effectively. Figure 1 [9] shows the average amount of collection of small-sized e-waste in areas in Japan.

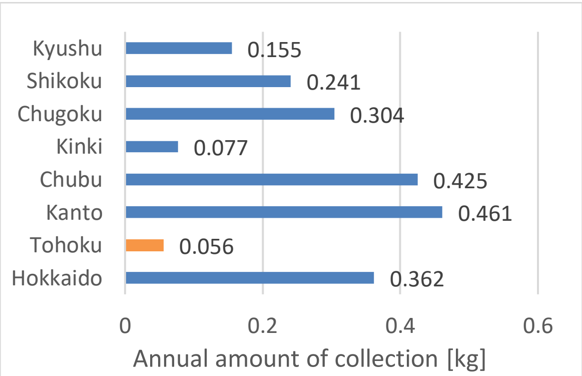

Figure1: Annual amount of small-sized e-waste collection in different areas of Japan

As it is shown in the figure, situation regarding e-waste collection in Tohoku area is far from the ideal state. There might be some barriers such as low population density, relatively large residential space and so on. But, collaborating company and the project team thought the important reasons are insufficient announcement and inconvenient collection system.

Afore-mentioned subjects offered from Ecorecycle aimed to solve these problems by using students' idea. These are the brief explanation of the results of the projects through 2017 to 2019.

- Results of the 2017 project

The previous social experiment was carried out from April, 2012 for about one years, in advance to the law enforcement. There were 3 major ways of collection. 3 methods are (1) pick-up from the waste collected at the collection site, (2) put special recycling bin at various locations, and (3) collection at events such as eco-event, and other events.

Social experiment continues for 11 months, and total amount of collection throughout Akita prefecture was about 13tons. As the result, 68kg of e-waste was collected in Akita university, and 14kg was collected in the first month.

The project team also carried out a social experiment on the campus. The team set 2 recycling bins in the campus for 8 days. The team made some special set-up to promote collection at the collection site. The features of the experiment were detailed information regarding the collection target, attached poster to explain that the recovered metal will be used for Olympic medals, exhibition of historical game machines (Figure 1), using transparent recycling bin (Figure 2) to prevent garbage throw, and so on.

Figure2: Exhibition at the collection site

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Figure 3: Transparent recycling bin

As the result of the new social experiment, the collected amount was 32kg, in total of 2 collection sites. Even though the experiment period was short, the collected amount was 2.3 times of the amount of the first one month of the previous experiment. If the collection period had been 1year, estimated collection amount in the university is 154kg. Thus, it can be concluded that student-to-student promotion was effective in motivating to put small-sized e-waste in the recycling bin.

- Results of the 2018 project

In the 2018 project, the goal was to propose a new e-waste collection scheme to local government. By comparing the situations in different cities in Akita prefecture (Figure 4 [9]), the project team estimated that collection amount differs due to types of waste collection. Because 3 cities that have relatively high collection amount carry out so-called "station collection (Figure 5 [10])," while other 2 cities only carry out "box collection (Figure 6 [11])."

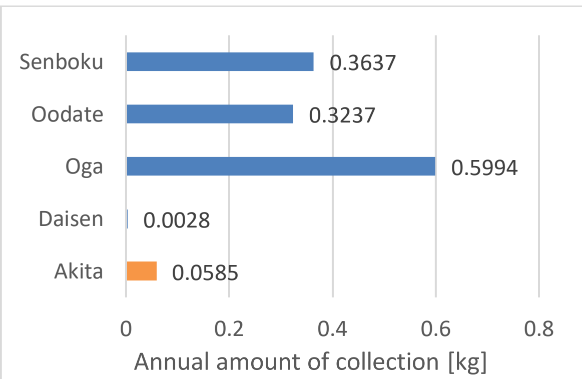

Figure 4: Annual amount of small-sized e-waste in cities in Akita prefecture

Figure 5: Combined waste collection station in Aomori prefecture

Figure 6: Collection box of small-sized e-waste

The statistics of Aomori prefecture (next prefecture of Akita) show that station collection which enables the consumers to bring all kinds of waste including waste papers, plastic bottles and e-waste, may motivate them to sort their waste properly and put into the recycling bins. Thus, station collection system may enhance citizen's recycling behaviour and increase recycling amount of small-sized e-waste.

The team proposed to modify the collection system to the city government. However, they were not positive in changing their way. Collection amount per person in Akita city is a little higher than the average of Tohoku area and they say the amount is the largest in the 6 capital cities in Tohoku. Although the team has also carried out cost-profit analysis, it wasn't enough to change the mind of the city government. In the aspect of social implementation, the project was not successful. The fact suggests that PBL is suitable for bottom-up activity from consumers side rather than top-down activity from governmental side.

- Results of the 2019 projects

This year's subject was to design the booth layout and all the exhibition materials of Oodate city ecofair [12] that Ecorecycle participates every year. Number of the visitors to the company booth is not so large compared to the total number of the visitors of the fair.

All the posters, panels, and so on (Figure 7-9) were designed by students' team and also the team helped the attendee of the fair day. (Figure 10)

Figure 7: Pocket tissue paper destrubited in the fair entrance.

Figure 8: Designed photo frame

Figure 9: Desigened magnet sheet provided for booth visitors

Figure 10: Explanation to booth visitors

As the result of these efforts, number of the visitors to the booth increased drastically as shown in Figure 11. And also the satisfactory level of the visitors was high too (Figure 12).

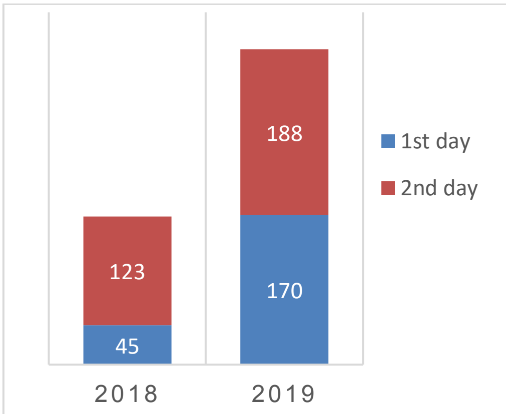

Figure 11: Number of the visitors

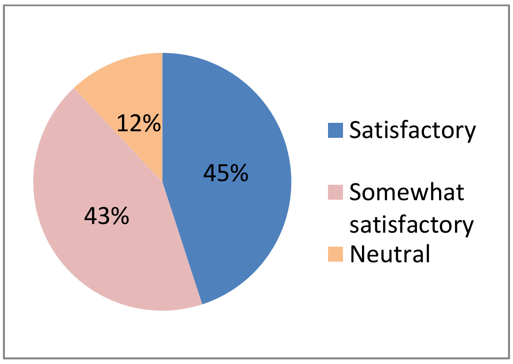

Figure 12: Satisfaction of the booth visitors

As the project result shows, the student's idea was rather successful and it should be noted that by mutual evaluation of students, this subject was selected as the best one (third by mentors' evaluation). Again, this fact suggests this type of bottom-up and autonomous subject can motivate students to engage on the project work and can be successful in terms of the "result."

The problems seen in environmental issues often drastic change of consumer behaviours. In other words, bottom-up approach is necessary. As the authors first assumed, PBL is a suitable approach in finding bottom-up approaches, and such approach is well-applied to environmental problems.

5 Discussion on PBL and environmental studies

Mentors of the PBL program are recommended to have experiences of working outside of the university, or engaged on a project, since it is important to make advices to various questions from students. The questions throughout PBL may include various problems without an answer. On the other hand, the questions in the regular university classes usually have "right" answers. Students are evaluated based on whether their answers are correct, or not. The questions occur during the PBL program are similar to questions that arise in the society rather than academic problems. Therefore, mentors themselves should have various experiences in industries in order to tell suitable ideas to enrich students' thoughts.

Experience in PBL may help students after they graduate, and sometimes when they take interview test as well.

As it was mentioned above, in the PBL program, visualizing method to understand the problem such as CVCA, etc. were lectured during the first 3 months and 4 months project work was carried out. Since this was the first collaborative work with companies, hearing to the students was carried out after the program. Some of the students who engaged the environmental subjects in the PBL also engaged on graduate thesis regarding various environmental problems. These are the examples of the subjects of the thesis.

- Proposal of a configurator enables visualization of environmental impacts of clothing
- LCA based comparison of various maintenance method of wind power systems
- Energy efficient diamond coating process using burning flame
- User experience design of eco-bags

Of course, some of the students' thesis had little environmental aspects. But, even for those students, significance of environmental issues, importance of proper treatment of e-waste, and importance to meet consumers' requirements in recycling activities have been input. Using these subjects as case studies, the paper has explained and discussed the effort in promoting sustainable consumers' behaviours of the students. It also seems effective in encouraging students to engage on environmental studies in their graduate thesis, which will be carried out in the next year of this PBL program

6 Conclusions

As it is mentioned before, for the successful projects, mentors who have enough experiences in industries or practical projects work will be necessary. Such mentors will watch students' works carefully and be able to guide them to the fruitful goals.

Once they have such successful experience in the PBL, it will motivate them to engage on graduate thesis and practical projects in industries positively. Some of the students have set research topics regarding environmental problems. And, even though their thesis topics do not directly intend to reduce environmental impact or enhance process efficiencies, students those who have experienced environmental subjects in the PBL program have obtained environmental consciousness and better consumer behaviours. This can be checked through the interviews to the students after the project end.

Based on the above-mentioned things afterward, it can be concluded that PBL is a good educational method to foster autonomy to students and can be a driving force for the students to have "eco-mind" and right ways as consumers.

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D.3
REGULATION ON MATERIALS LEVEL: ROHS, SCIP, CRM

Review of the List of Restricted Substance (Annex II) of Directive 2011/65/EU (RoHS)

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Abstract

Between 2018 and 2020, Oeko-Institut and Fraunhofer IZM performed a study for the European Commission [1] looking into various aspects of substance restriction in the context of Directive 2011/65/EC (RoHS) on the restriction of hazardous substances in electrical and electronic equipment (EEE).
The study included the revision of the existing methodology for identifying, prioritising and assessing substances for possible restriction, the assessment of seven substances or substance groups and an update and prioritisation of the inventory of substances possibly used in EEE.
This paper provides a short update on changes that have been integrated into the new methodology, followed by a discussion of challenges that arose from the implementation of the revised methodology and the presentation of more relevant results of the study, particularly in relation to recommendations on future restrictions of additional substances and recommendations as to future cycles of assessing additional substance for possible restriction.

1 Background

Directive 2011/65/EU (RoHS 2) restricts the use of certain substances in electrical and electronic equipment (EEE) placed on the European market in excess of maximum tolerated thresholds. The list of restricted substances is specified in Annex II of the Directive and initially listed six substances – four heavy metals and two groups of brominated flame retardants. Article 6 of RoHS 2 requires that the list of restricted substances in Annex II be reviewed periodically and stipulates rules for amending the list, including criteria for justifying the restriction of substances and procedures for the process of updating of Annex II.

In 2013-2014 an initial methodology for identifying, prioritising and assessing substances for possible restrictions under Directive 2011/65/EU was prepared for the European Commission (EC) by the Austrian Umweltbundesamt [2]. A first review of the annex was performed in the course of two studies between 2012 and 2014 [2, 3], resulting in the addition of four phthalates to the annex (the restrictions entered into force as of 2019).

In November 2017 the EC commissioned an update of the methodology along with its implementation towards the assessment of seven substances and the update of the list of substances possibly used in EEE followed by its prioritisation with the view of a short list of substances to be addressed in future revision cycles of annex II of the Directive.

2 The revised methodology for identifying, prioritising and assessing substances for possible restrictions under RoHS 2

The revision was aimed at aligning the methodology with the various stipulations of Recital 10 and Article 6 of the Directive, also ensuring coherence with other Commission legislation and policies and updating various aspects related to the identification, prioritisation and assessment of substances in the context of RoHS.

In general, the methodology continues to refer to three processes related to the update of Annex II of the Directive:

- the *identification* of substances used and/or present in EEE,
- their *prioritisation*, to allow determining which have a higher prioritisation for in depth investigation; and
- their assessment to conclude in line with Article 6 whether they have negative impacts on human health, the environment or resource efficiency during use and/or during WEEE management.

How these processes are prescribed is summarised in Figure 1 below.

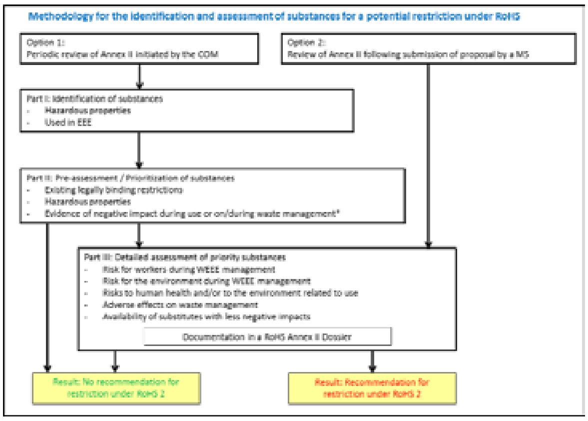

Figure 1: Overview of the methodology [1]; Note: *as specified by Article 6(1) of RoHS2)

In relation to the first version of the methodology prepared by AUBA [2], the current methodology [1] has undertaken thorough revision among others of the following aspects:

- consideration of Article 6 has been revised, particularly in the interpretation of the criterion of "cases where the use of a substance could give rise to uncontrolled or diffuse releases into the environment" (Article 6(1)(b)). To this end, where such impacts occur during use, a restriction may now be justified.
- Detail was added to the methodology as to the relation between the REACH Regulation and the RoHS Directive. This was elaborated based on Common Understanding Paper [4] as to the relation between these two legislations.
- How the precautionary principle is to be applied was elaborated in line with a Commission communication on this issue [5];
- Guidance was added to the methodology on data quality and dealing with data gaps, and on the grouping of substances. In both cases, guidance was based on a revision of documents prepared by the RoHS Substance Working Group.
- Sources to be taken into consideration for performing the various tasks described in the methodology have been updated and elaborated on.
- Consideration of new Union policies and legislation has been added (e.g., the Waste Framework Directive, the Communication on the interface between chemical, product and waste legislation, recent development in the assessment of endocrine disruptive properties);

3 The assessment of substances for future restriction

Following the revision of the methodology, seven substances were assessed with a view to the review and amendment of the RoHS Annex II list of restricted substances. The seven substances were pre-determined by the European Commission and included tetrabromobisphenol-A (TBBP-A); medium chain chlorinated paraffins (MCCPs); diantimony trioxide (ATO); indium phosphide (InP); cobalt dichloride and cobalt sulphate; nickel sulphate and nickel sulfamat; and beryllium and its compounds.

The detailed assessment was carried out in line with the revised methodology (see workflow in Figure 2) and a substance dossier was compiled for each of the seven substances, including recommendations as to the future restriction of the substance or group of substances.

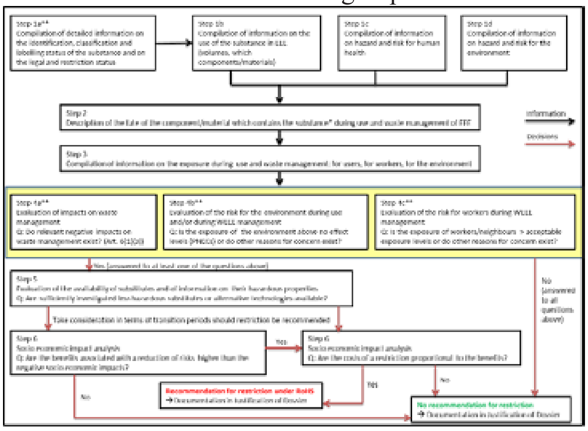

Figure 2: Workflow of the detailed substance assessment [1];

3.1 Challenges of assessment of some of the substances

Though efforts were made to generate a concise and comprehensive methodology for substance assessment, the study encountered several challenges during the work that shall be presented in the following section

3.1.1 Parallel assessment of substances under various legislative frameworks

For some of the substances, it became clear that parallel assessments of the substance were underway under other European legislation, namely Regulation (EC) No 1907/2006 (REACH). For TBBP-A and MCCPs, such assessments were being held as to their properties of concern. Such assessments under REACH are lengthy processes. In contrast, the assessment under RoHS, prepared under the framework of a study undertaken by external consultants, was time constrained. As a consequence, the results from the REACH processes could not always be taken into consideration of the assessment performed under RoHS, consequentially affecting the possible conclusions and recommendations.

MCCPs were under assessment as being a PBT during most of the RoHS process, however the process concluded shortly before the finalisation of the substance dossier and could thus be considered in the final results.

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As a conclusion of the CORAP substance evaluation programme under REACH, MCCPs were generally recognised for meeting vPvB and PBT criteria [6].

In the case of TPPB-A, under REACH, the substance is being assessed for identification as persistent, bioaccumulative and toxic (PBT). In parallel it is also under assessment for identification as being endocrine disrupting (ED), which means that it may interfere with the hormonal system and thereby produce harmful effects in both humans and wildlife.

To illustrate the very different timelines under REACH and RoHS: In March 2017, the European Chemicals Agency (ECHA) requested the provision of further information concerning the endocrine disruptive properties of TBBP-A and the exposure and PBT properties (particularly persistency / environmental fate of transformation products of TBBP-A). The requested information is to be provided until 4 January 2021 [7]. The substance assessment under RoHS was conducted between February 2018 and June 2020.

If a substance is recognized as being endocrine disrupting it is very probable that thresholds in the form of existing guidance values, e.g. derived no effect levels (DNELs) are lowered. Experts assume that thresholds of adversity are likely to exist for EDs but may be very low for individual EDs, depending on e.g. the specific mode of action. A threshold may be particularly low during prenatal development because small changes in hormone levels during development could have permanent serious consequences for the organism.

The REACH assessment processes of TBBP-A are still ongoing at the time of writing of this paper (July 2020).

3.1.2 Lack of conclusive data on hazardous properties of substances

In the case of TBBP-A, the REACH assessment which was still inconclusive at the end of the assessment required a different approach.

As the RoHS Directive in its Article 6 on the review and amendment of the list of restricted substances explicitly notes that the precautionary principle should be taken into account, in the compilation of the human health hazard profile of TBBP-A, a so called read-across approach was applied. Read-across means the use of information from analogous substances as a ‘source' to predict the properties of ‘target' substances. In the case of TBBP-A, a read-across from bisphenol A (BPA) to TBBP-A was proposed because TBBP-A exhibits a notable structural similarity to BPA molecules and furthermore there is “some evidence that TBBP-A can degrade to give bisphenol A under certain anaerobic conditions, and that bisphenol-A is stable under these same conditions”. BPA is a recognized ED. As the current DNELs for TBBP-A do not take account of potential endocrine disrupting properties, it was proposed in the assessment, based on the initial read-across approach, that DNEL values of BPA should be considered. This was done to reflect the potential endocrine disrupting properties of TBBP-A.

The general population is exposed to TBBP-A by house dust ingestion and inhalation. Via estimations on worst case exposure to TBBP-A via house dust (ingestion + inhalation) and by taking the DNEL for BPA for oral exposure, a risk characterisation ratio of > 1 for children into consideration, indicates a risk. This risk was led to the recommendation for inclusion of TBBP-A in Annex II of the RoHS Directive.

3.1.3 Lack of conclusive data as to the volumes of use of substances in EEE

Data on the actual volumes of use of substances in EEE is rarely available publicly in comprehensive form. Understanding the amounts of a substance used in EEE always requires compiling data form various sources.

An important source of information is the website of the European Chemicals Agency. Where data is available from prior assessments prepared in the context of the REACH legislation, it often refers to amounts used for specific applications or sectors. However, in some cases data may only be available through REACH Registration dossiers. Though such data provides a good indication and may also show whether the use of a substance is in increase or decrease in the EU, it only applies to amounts of the substance manufactured and/or used in the EU. Substance volumes contained in imported goods of components are not represented. In so far, indication of the Registration data that use is in decline may also mean that manufacture has shifted outside the EU and is not sufficient to conclude as to the total volumes of use in the EEE sector.

Data thus also needs to be sought through stakeholders. In some cases, the substance or element will have an association that may have access to aggregated data. Sectoral associations may also be able to provide indication as to typical applications of the substance by their members. However, the EEE sector has a complex supply chain, and often without performing a lengthy supply chain survey, data will be limited and uncertain.

In the face of data gaps and depending on the nature of the substance and its hazardous properties, this may require the application of the precautionary principle in some cases.

3.1.4 Defining the scope of substances under assessment

The substances to be assessed in the current study were predefined by the European Commission. Past assessments of substances in the context of RoHS have been contracted by the Commission and by Member States (Denmark, Sweden). Industry has also applied the methodology for substance assessment for e.g., TBBP-A. In such cases, the study commissioner usually determines the substance or group of substances to be investigated in the assessment. However, in the first stages of the assessment, where information is gathered for its various parts, it may become clear that the scope of the assessment may not be efficient in the case that a substance restriction is contemplated. This can have various reasons.

The methodology details the case of an assessment which reveals that a substitute (or a number thereof) for a substance under assessment raises concerns that may also justify a RoHS Restriction. The methodology prescribes subjecting such substances to an assessment and, where justified, their restriction together with the substance addressed under the initial assessment. This is aimed at avoiding "regrettable substitutions" and was for example the case in the past assessment of the three phthalates bis(2-ethylhexyl) phthalate, butyl benzyl phthalate and dibutyl phthalate performed by the AUBA [1] that lead to the further assessment and restriction of diisobutyl phthalate.

In cases of substances used as intermediate or as reactive substances, it may become clear during the assessment that the substance transforms during the process and does not remain in the EEE in its original form. In such cases, restricting the substance under RoHS would not necessarily be affective for preventing its impacts in the use phase and in the waste phase. The question thus arises as to the compounds into which the substance transforms or its derivatives which are contained in the EEE and their possible adverse impacts on the environment and on health. In some cases, the scope of the assessment may be expanded to include such compounds and their impacts, whereas in other cases such compounds may be recommended for further investigation or to be addressed through other legislation. For example, in the case of the assessment of cobalt dichloride and cobalt sulphate, the assessment showed that these salts as well as three additional cobalt salts were applied in metal plating of some materials and components in EEE. All five salts had the same hazard classifications and were considered to have CMR (carcinogenic, mutagenic, reprotoxic) properties with relevant pathways for exposure through the respiratory system, inhalation, contact with skin and through oral exposure. In approval with the Commission it was decided to extend the scope to all five substances. This was also necessary as data available for the first two substances mostly addressed all five substances, making it difficult to discuss use and impacts associated only with cobalt dichloride and cobalt sulphate.

For certain substances the application in EEE may have an interaction with other substances that may need to be taken into consideration when weighing the pros and cons of a restriction. In the case of antimony trioxide, the terms of reference of the study under which this substance was assessed referred to "ATO (flame retardant)". The assessment thus concentrated on the use of this substance as a synergist in combination with halogenated flame retardants. It was shown that the use of ATO allows decreasing the quantities of the latter. Though there was some concern related to possible exposure of workers to ATO during plastic shredding (depending on the facility), this needed to be weighed against the benefit of decreasing the amount of halogenated flame retardant, which ATO was combined with. It was thus recommended to undertake a joint assessment of the system of halogenated flame retardants and the ATO synergist.

3.2 Preliminary results of the assessment of the seven substances

This section provides a short presentation of the main results of the assessment of the seven substances, particularly in relation to recommendations on future restrictions of the substances investigated.

It was not recommended to include *beryllium and its compounds* in Annex II of the RoHS 2 Directive. The risk evaluation concluded that beryllium and beryllium oxide contained in EEE pose medium risks during WEEE treatment and disposal to workers. Nonetheless, the high technological importance of beryllium for the European EEE sector, particularly in bio-medical and industrial monitoring devices, the limitation of available substitutes and the possibility to apply measures for the control of potential emissions, do not support a complete ban under RoHS. This is in line with the recommendation of BAUA [8] that the health hazards of beryllium and beryllium oxide, in particular chronic beryllium disease and beryllium sensitisation "can be regulated through an OEL" (occupational exposure limits). Nonetheless, the use of beryllium in sliding contact brushes in electric motors, which form part of consumers and professional EEE, such as vacuum cleaners and tools, was found to pose a risk to users. A selective restriction of beryllium bearing alloys in abrasive EEE components, such as electric motor brushes, was recommended to be considered, in parallel to performing abrasion tests to determine the range of exposure of EEE-users to particulate copper beryllium alloy debris and the effectiveness of exposure controls (e.g. protective boxes).

As explained in the prior section, the initial assessment of two *cobalt salts* was expanded to address five salts that had been grouped in this way under a proposal for restriction under REACH: *cobalt dichloride and cobalt* *sulphat*e, cobalt dinitrate, cobalt carbonate and cobalt di(acetate). The assessment showed that these substances, used in metal surface treatment, are converted through these processes and do not remain in their original form in the final product, i.e., in relevant EEE and its parts. A RoHS restriction was thus considered to be inefficient as it would not affect substances that do not remain in the final EEE anyway. Along with the pending REACH restriction, it was thus recommended not to include either of the five cobalt salts in Annex II of the RoHS 2.

Diantimony trioxide was investigated as a synergist in flame retardant systems. It was determined from a precautionary principal view that the exposure of workers in some WEEE facilities (open shredding processes) may be of concern in light of ATOs being a carcinogen. Nonetheless, it could also be shown that ATO had certain benefits when applied in such systems with halogenated flame retardants. It allows reducing the volumes of use of the latter while also supporting the separate disposal of plastics containing halogenated flame retardants, as it can be used as a gravimetric parameter in post-shredder sink-float sorting techniques due to its high density. It was thus not recommended to restrict ATO on its own, though monitoring of actual exposure level of workers in shredding facilities was recommended. An additional recommendation suggests a combined assessment of the functional system of flame retardants consisting of halogenated compounds with ATO as a synergist.

The assessment of *indium phosphide* (InP) suggested that the current volumes of use in its main areas of application (optoelectronics, high-speed electronics, displays and lighting as well as photovoltaic applications) do not exceed 100 kg / annum. A possible increase in use to up to 2,000 kg / annum in 2028 could not be excluded. The assessment showed that InP is at least as hazardous as gallium arsenide (GaAs) and has a comparable use and toxicological profile. Based on the 10-100 tons REACH dossier of GaAs, which concluded that risks to human health and environment are irrelevant, the consultants concluded that the same would apply to the use of InP. The limited risk and the further lack of substitutes with better environmental and health performance, lead the conclusion that InP should not be listed in Annex II of the RoHS 2 Directive at present.

The Swedish Chemicals Agency (KEMI) initially prepared a RoHS dossier for *medium chain chlorinated paraffins* (MCCPs) - Alkanes, 14-17, chloro, and proposed its restriction with a 0.1 % by weight threshold as a maximum tolerable concentration in the homogenous material. The function of MCCPs is described as a secondary plasticiser (extender) with flame retardant properties. The use in PVC and in rubber products, particularly electric cables, is confirmed. Despite lacking data as to volumes of use, it can reliably be assumed that MCCPs are used in relevant quantities in EEE mostly as constituents of PVC insulations for electric cables, wires and other soft plastic or rubber components. The assessment concluded that the application areas of MCCPs are likely to result in its release during recycling and disposal treatment of waste EEE. Following the recent decision to identify MCCP with PBT and vPvB properties, it was also considered that releases from WEEE to the environment and releases of MCCPs in house dust would lead to a risk for the environment and for consumers (respectively). An inclusion of MCCPs in Annex II of the RoHS 2 Directive was thus recommended, with an explanatory note that this entry covers chlorinated paraffins containing paraffins with a chain length of C14-17 – linear or branched.

The two nickel salts, *nickel sulphate and nickel sulfamate,* are used in metal surface treatment processes, including electrolytic plating and electroless technologies. The assessment showed that these substances are transformed through the surface treatment processes and do not remain in their original form in the final product, i.e. in relevant EEE and its parts. In the final coating, the nickel salts are understood to be converted into nickel metal. It was therefore expected that a restriction of these compounds in EEE would not necessarily be effective in preventing their use in the processes, as benefits on health and environment would not be expected to incur. To clarify the range of expected impacts of nickel metal and nickel 2+ ions during use and/or waste management as well as the range and nature of possible impacts related to the presence of Ni and its compounds in EEE in the use and waste phases, a future assessment under RoHS of nickel and its compounds was recommended. This should allow concluding as to the range and nature of impacts of the presence of these compounds and the potential of a RoHS restriction of preventing them.

Tetrabromobisphenol A (TBBP-A, flame retardant) was found to be used in relevant quantities in EEE, with the largest share, about 90 %, applied as a reactive component in epoxy resins and the remaining 10 % applied as an additive flame retardant, especially in plastic housings. Releases of TBBP-A were mainly attributed to its second application, the additive use as a flame retardant in housings and encapsulations. This was due to TBBP-A undergoing a chemical transformation when used as a reactive component and – apart from low residual monomer contents –no longer being present in EEE in its original form. Regarding emissions of TBBP-A from WEEE treatment processes, the relevant exposure of TBBP-A by dust in shredding processes of plastic housings and enclosures was assumed to be the most relevant exposure scenario, however monitoring data from recent years was not available and did not allow determining the range of actual impacts. As for risks for human and environmental health, TBBP-A is currently under assessment to conclude whether it has endocrine disrupting (ED) properties or whether it is a PBT. Results of this assessment were still pending during the RoHS assessment and the possibility of the substance being ED was not reflected in its DNEL values. Given the structural similarity of TBBP-A and BPA, it was proposed to take the DNELs of bisphenol-A into account as a precautionary approach in order to reflect the potential endocrine disrupting properties of TBBP-A. Implementing this approach would result in the ECETOC TRA exposure estimation indicating a risk for workers via dermal exposure and a risk characterisation ratio of > 1 for children through ingestion and inhalation of house dust. Evidence in monitoring data of the detection of TBBP-A in the environment would also need to be considered according to the precautionary principle in light of the ongoing PBT assessment. It was thus proposed to restrict the additive application of 2,2',6,6'-tetrabromo-4,4'-isopropylidenediphenol or tetrabromobisphenol A (TBBP-A) (0,1 % per weight) as a precautionary measure. It was further recommended that the final decision on a RoHS restriction of TBBP-A should consider the outcome of the REACH process, i.e. whether TBBP-A is identified as endocrine disrupting and/or PBT properties.

4 The update of the substance inventory and its prioritization

The inventory of substances possibly used in EEE was also updated and prioritised based on the revised methodology [1]. Following the steps defined in the methodology (Figure 3, Part I), the first task was to update the EEE substance inventory created by AUBA in the previous study [2] using a range of sources in addition to requesting information from stakeholders.

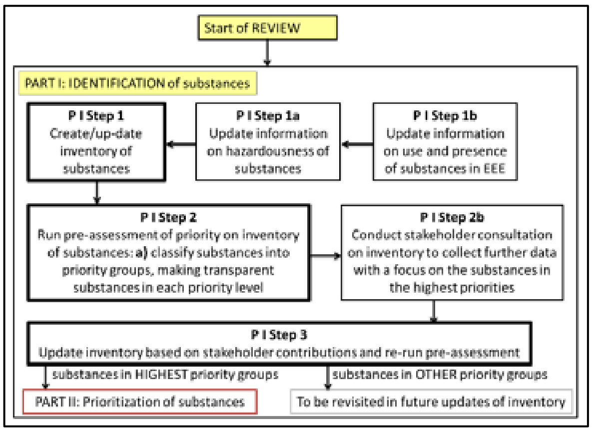

Figure 3: Workflow of the identification of hazardous substances used in EEE [1];

In the next stage, a pre-assessment of the priority of substances contained in the inventory was carried out to identify substances or groups of substances of the highest concern regarding their potential negative impact on human health and/or the environment during use and/or during WEEE management. The following criteria were applied:

- Hazardous properties - Human Health & Environment (including special consideration where substances appear in Annex XIV or Annex XVII of REACH)
- High volumes of use and/or presence in EEE (including special consideration for substances used among others in nano-material form); and
- Possible use of a substance as a substitute for a substance restricted or to be restricted (in transition period) under RoHS.

Using a simple algorithm, the substances listed in the EEE inventory were sorted into ten priority groups (Figure 4).

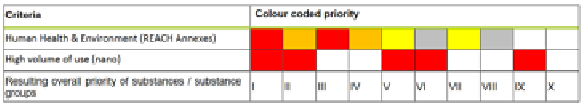

Figure 4: Algorithm used to sort substances in the EEE inventory into 10 priority groups [1];

Out of the 843 substances contained in the final EEE substance inventory, 44 were sorted into the highest priority group. As is shown in Figure 3, only those substances in the highest priority group were subject to a refined prioritisation in the following step (Part II). In this step, additional information on the substances was collected from public sources and requested from stakeholders through online consultation, with a particular focus on quantitative usage data to be used for the refined prioritisation.

4.1 Challenges of the inventory update and prioritisation

Similarly, to chapter 3.1, the following sections illustrate the main challenges encountered during the work on the inventory update and prioritisation.

4.1.1 Lack of conclusive data on the presence of substances in EEE

The objective of the EEE substance inventory was to list those substances and substances groups that are hazardous and that are present in EEE marketed in the EU. Therefore, sources were needed that indicate which substance are present in EEE placed on the EU market.

Examples for sources that were considered to provide sufficiently conclusive data for this purpose are:

- IEC 62474 Database on „Declarable substance groups and declarable substances";
- Material Data Sheets from manufacturers of electronic components; and
- Studies and reports on hazardous chemicals in EEE from reliable sources.

Examples for sources that were considered less useful for this purpose are:

- Reports on hazardous substances in WEEE, as the studied WEEE may have been produced many years or even decades ago, and contained substances may have been phased out since their production;
- REACH registered substances with specific use descriptors, as there is no differentiation between whether the substances are present in EEE or are merely used in the manufacture of EEE (such as certain process chemicals, solvents, etc.)
- SPIN (Substances in Preparations in Nordic Countries) database, for the same reason.

Additionally, several stakeholders pointed out substances listed in the inventory that were not present in EEE according to their knowledge. In a few cases, information provided by several stakeholders on the presence of a specific substance in EEE was contradictive. This reflects the fact that no single organisation or association possesses perfect knowledge on all substances possibly contained in all EEE included in the scope of RoHS.

The described lack of comprehensive and conclusive data on the presence of substances in EEE leads to some remaining uncertainties regarding the relevance of some of the substances listed in the EEE inventory. Naturally, the process of identification of substances should be as precise as possible. However, though not optimal, it may be argued that including a few substances that may not be or may no longer be present in EEE manufactured or used in the EU is not a major issue at this stage of the process. They may still be filtered out from the process in later stages, when more detailed information becomes available (i.e. prioritisation or detailed assessment, see Figure 1), without considerable loss in efficiency.

4.1.2 Lack of quantitative usage data on substances in EEE in the EU

One of the decisive factors for prioritisation of substances for future detailed assessment according to the revised methodology is the volume (in tonnes per annum) of substances present in EEE. The rationale behind this is that the quantitative usage of a substance in EEE is assumed to be one of the factors that determine the potential risk associated with that substance, in addition to the substances inherent hazard properties.

As similarly pointed out in chapter 3.1.3, there was a distinct lack of conclusive data on the quantitative usage of substances present in EEE in the EU. Steps carried out to acquire such data were, among others:

- Assessment of data made available by ECHA;
- Assessment of literature, studies and reports;
- Web search on each individual substance using a variety of relevant search strings;
- Usage volume data was requested in several rounds of stakeholder consultations.

Specific data was retrieved from the ProSUM urban mine platform [9], where amounts of a range of metals used in EEE in the EU are reported.

Several contributions on volumes of use for specific substances were received during stakeholder consultations. Those generally comprised data on usage of substances by a specific company or in a specific sector. While this type of data is useful to confirm the actual presence in EEE and provide an indication regarding the minimum use of the substance, extrapolation to all EEE in the EU is not feasible.

As has been discussed in chapter 3.1.3, data published by ECHA generally have a different scope than data required for the work carried out. Quantitative data from the REACH registration process for instance comprises amounts of a substance manufactured within the EU and/or imported into the EU as such. Amounts of the same substance contained in articles, such as EEE, are not accounted for in the data. However, a major share of EEE is imported into the EU from third countries.

Due to the lack of quantitative usage data, other factors played a more dominant role than expected in the prioritization of substances. This particularly applied to the relevancy under REACH, and a substance's potential to substitute another listed substance (compare section 4.2).

4.2 Preliminary results of the inventory prioritisation

This section provides a short presentation of the main results of the prioritisation. The 44 substances were sorted into five clusters according to the following criteria:

- Hazard group;
- High volume of use and/or use as nano-material;

- Indication that substance is a potential substitute for substances that are listed in RoHS Annex II or are under assessment for possible inclusion in RoHS Annex II;
- Indication that substance is a potential substitute for another substance on the list (to facilitate parallel assessments);
- Indication that substance may possibly not be present in EEE (e.g. based on stakeholder contributions);

The results of the sorting of prioritized substances into clusters is detailed below. It should be noted that the inclusion of a substance in the list does not presume a recommendation for the inclusion in Annex II of the RoHS Directive. The inclusion indicates that a substance is of the highest priority for a detailed assessment according to the methodology manual. Only the detailed assessment (Part III of the methodology manual [1]) may result in a recommendation to restrict a substance for the use in EEE under RoHS Annex II.

Cluster 1 a) contains the following substances:

CAS No	EC No	Name	Rationale
1313-99-1	215-215-7	Nickel monoxide	- highest hazard group - use as nanomaterial in EEE
1314-13-2	215-222-5	Zinc oxide	- highest hazard group - use as nanomaterial in EEE
25155-23-1	246-677-8	Trixylyl phosphate (TXP)	- highest hazard group - potential substitute for MCCPs
68515-42-4	271-084-6	di-C7-11-branched and linear alkyl esters (DHNUP)	- highest hazard group - potential substitute for DIDP
28553-12-0	249-079-5	Di-"isononyl" phthalate (DINP)	- potential substitute for DEHP, MCCPs, DIHP
26761-40-0; 68515-49-1	247-977-1; 2	Di-"isodecyl" phthalate (DIDP)	- potential substitute for DEHP, MCCPs

Table 1: Substances sorted into cluster 1a)[1];

Cluster 1 b) contains the following substances:

CAS No	EC No	Name	Rationale
3864-99-1	223-383-8	2,4-di-tert-butyl-6-(5-chlorobenzotriazol-2-yl)phenol (UV-327)	- highest hazard group
36437-37-3	253-037-1	2-(2H-benzotriazol-2-yl)-4-(tert-butyl)-6-(sec-butyl)phenol (UV-350)	- highest hazard group
3846-71-7	223-346-6	2-benzotriazol-2-yl-4,6-di-tert-butylphenol (UV-320)	- potential substitute for UV-327/350
25973-55-1	247-384-8	2-(2H-benzotriazol-2-yl)-4,6-ditertpentylphenol (UV-328)	- potential substitute for UV-327/350
131-18-0	205-017-9	Dipentyl phthalate (DPP)	- highest hazard group
71888-89-6	276-158-1	1,2-Benzenedicarboxylic acid, di-C6-8-branched alkyl esters, C7-rich = Diisoheptyl phthalate (DIHP)	- highest hazard group
68515-50-4	271-093-5	1,2-Benzenedicarboxylic acid, dihexyl ester, branched and linear (DIHP)	- highest hazard group
115-96-8	204-118-5	Tris(2-chloroethyl)phosphate (TCEP)	- highest hazard group
13674-87-8	237-159-2	Tris[2-chloro-1-(chloromethyl)ethyl] phosphate (TDCP)	- potential substitute for TCEP
13674-84-5	237-158-7	Tris(2-chloro-1-methylethyl) phosphate (TCCP)	- potential substitute for TCEP
10043-35-3	233-139-2	Boric acid	- highest hazard group
375-95-1	206-801-3	Perfluorononan-1-oic-acid (PFNA)	- highest hazard group
50-00-0	200-001-8	Formaldehyde	- highest hazard group

Table 2: Substances sorted into cluster 1b)[1];

Cluster 1 c) contains the following substances:

CAS No	EC No	Name	Rationale
1303-96-4	603-411-9	Disodium tetraborate, anhydrous	
1303-86-2	215-125-8	Diboron trioxide	
335-76-2	206-400-3	Perfluorodecanoic acid (PFDA)	
117-82-8	204-212-6	Bis(2-methoxyethyl) phthalate (DMEP)	
85-42-7	201-604-9	Cyclohexane-1,2-dicarboxylic anhydride	
548-62-9	208-953-6	bis(dimethylamino)benzhydrylidene]cyclohexa-2,5-dien-1-ylidene]dimethylammonium	
123-77-3	204-650-8	dicarboxamide (C,C'-azodi(formamide)) (ADCA)	
106-94-5	203-445-0	1-bromopropane (n-propyl bromide)	
111-96-6	203-924-4	Bis(2-methoxyethyl) ether (Diglyme)	
68-12-2	200-679-5	N,N-dimethylformamide (DMF)	- highest hazard group - presence in EEE doubted
872-50-4	212-828-1	1-methyl-2-pyrrolidinone (NMP)	
25550-51-0	247-094-1	Hexahydromethylphthalic anhydride (MHHPA)	
19438-60-9	243-072-0	Hexahydro-4-methylphthalic anhydride	
48122-14-1	256-356-4	Hexahydro-1-methylphthalic anhydride	
57110-29-9	260-566-1	Hexahydro-3-methylphthalic anhydride	
127-19-5	204-826-4	N,N-dimethylacetamide (DMAC)	
1303-28-2	215-116-9	Arsenic pentoxide; Arsenic oxide	
1327-53-3	215-481-4	Diarsenic trioxide; Arsenic trioxide	

Table 3: Substances sorted into cluster 1c) [1];

Cluster 1 d) contains the following substances:

CAS No	EC No	Name	Rationale
7440-02-0	231-111-4	Nickel	- lower hazard group - high volume of use
68515-51-5	271-094-0	esters or mixed decyl and hexyl and octyl diesters	- lower hazard group

Table 4: Substances sorted into cluster 1d) [1];

Cluster 1 e) contains the following substances:

CAS No	EC No	Name	Rationale
2058-94-8	218-165-4	Henicosafluoroundecanoic acid (PFUnDA)	- lower hazard group - presence in EEE doubted
376-06-7	206-803-4	Heptacosafluorotetradecanoic acid (PFTDA)	- lower hazard group - presence in EEE doubted
307-55-1	206-203-2	Tricosafluorododecanoic acid (PFDoDA)	- lower hazard group - presence in EEE doubted
72629-94-8	276-745-2	Perfluorotridecanoic acid	- lower hazard group - presence in EEE doubted

Table 5: Substances sorted into cluster 1e) [1];

Besides the above shown information, the following data was reported for each substance, where available:

- Known uses and volumes of use, both in EEE and in general;
- Hazardous properties (harmonised classification, endocrine disruptor, PBT/vPvB/PB); and
- REACH status (SVHC, inclusion in Annex XIV or XVII).

To prepare a possible follow-up study, it is recommended to implement a separate study to provide a better data base presence of substances in EEE as well as quantitative usage data. Additionally, further data on presence in articles may become available through the SCIP data base and other future initiatives.

5 Literature

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Flame Retardants for Electronics - Regulation and Future Sustainability Requirements

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Abstract

We encounter flame retardants (FR) in our daily life, and they are used in our surroundings without us often knowing it. They are for example used in electronic devices to prevent the development of a fire, in case of a short circuit. About 30 years ago it was discovered that some brominated flame retardants (BFRs) could form toxic substances (halogenated dioxins and furans) in the event of fire. Furthermore, it was found that some flame retardants can bioaccumulate in organisms and are found in many places in the environment so that the issue of flame retardants has become more prominent in public awareness.
All these findings let to a steadily growing regulatory and environmental pressure: with the European chemical legislation REACH and the European Chemicals Agency (ECHA) firmly established, flame retardants continue to be added to the candidate list for substances of high concern. The directive on Restriction of Hazardous Substances in E&E (RoHS) is again under revision and more substance restrictions may happen. The European Ecodesign Directive will restrict the use of halogenated flame retardants in electronic displays (monitors and TVs) as of 2021. These are just some examples from Europe, other regions are following, although often at a slower pace.
How do flame retardant manufacturers respond? With sustainability initiatives and innovation programs, striving to develop environmentally sound solutions which are future proof. At the same time, increasing performance demands have to be met, often a consequence of further miniaturization and higher signal speeds: low Dk and Df values, temperature and hydrolytic stability, high resistance against arcing (measured by comparative tracking index, CTI) to name just a few. This paper and the presentation will give an overview of the many challenges facing the flame retardants industry and some solutions that are in the pipeline for our customers, the electronics manufacturers.

1 Why are FR used

Due to their versatile and unique properties, plastics are nowadays used in many areas of daily life and it is impossible to imagine life without them. In addition to packaging, construction and transport applications, they are omnipresent in electrical and electronic (E & E) applications. Examples are the use in smartphones, laptops or cables and plugs.

The great extent of the use of plastics can be illustrated by production figures. The worldwide annual production of plastics has continuously increased from 230 Mt to 322 Mt from 2005 to 2015. In 2015, 58 Mt of plastics were produced in Europe alone. This puts Europe in third place worldwide after China and the North American Free Trade Agreement (NAFTA) [1].

Due to their chemical composition, in particular their high carbon and hydrogen content, most plastics, which are also frequently used for electronic applications, are highly flammable. Although there are some plastics, such as polytetrafluoroethylene (PTFE) and phenolic resins, which are intrinsically flame-retardant, flame retardancy is a necessary prerequisite for electronic applications in most plastics [2].

Plastic components that are connected to electrically voltage-carrying metal parts are at risk of catching fire in the event of a short circuit and must comply with strict fire protection regulations. Therefore, electronic devices are protected with flame retardants, which prevent or delay the development and spread of fires in various ways.

2 Which types of FR are used in which polymers?

Figure 1 shows what type of flame retardants were consumed worldwide in 2016 and in what proportion. 85% of all flame retardants are used in plastics, the largest share of the remaining 15% is used in textiles and rubber products. Global consumption of flame retardants is about 2.3 million tonnes per year, worth about USD 6 billion [3].

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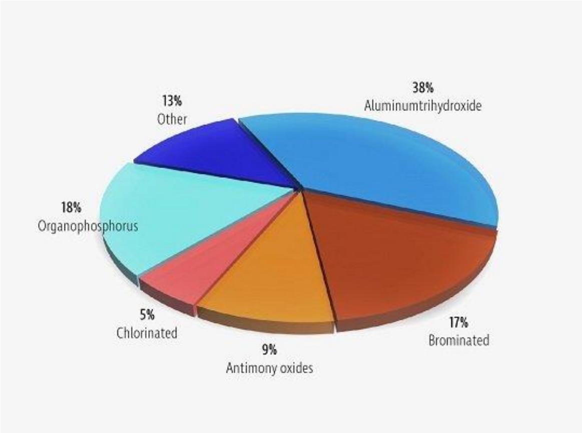

Figure 1: Global Consumption of Flame Retardants by Type, Tonnes (2016) [3, 4].

Chlorinated or brominated FRs are still often used in combination with diantimony trioxide (ATO), which acts as a synergist. They have the second largest share with a total of 31%. Organophosphorus and other flame retardants such as inorganic phosphorus compounds, nitrogen and zinc containing flame retardants make up the rest with 31%. Halogenated and halogen-free organophosphorus flame retardants are mainly used for electronic applications. In recent decades, there has been a trend to replace existing halogenated flame retardants with more sustainable non-halogenated products, thereby increasing their market share [5].

2.1 FR in Engineering Plastics

Glass fiber-reinforced polyamides are increasingly being used for circuit breakers or connectors due to their balanced property profile. Mechanical and electrical properties, good melt flow behaviour and a robust processing window are particularly critical, especially in the electronics industry, where miniaturization plays a decisive role. For electrical properties such as the Comparative Tracking Index (CTI), the selection of the right flame retardant is crucial [6].

Figure 2: Comparative Tracking Index (CTI) test [7].

Compounds containing halogen free organic phosphorus FR such as phosphinates or their synergistic mixtures as FR have a lower density compared to brominated FR and combine good mechanical properties with high CTI values.

2.2 FR in Thermosets

Due to their low shrinkage during curing, high resistance to chemicals and corrosion, high thermal stability, good electrical insulation properties, good adhesion and compatibility with various materials, thermosets such as epoxy resins are used for electronic or high-performance applications. Furthermore, they do not release volatile substances during curing [8, 9].

Glass fiber reinforced composites are used for example for printed circuit boards (PCB). These are widely used in modern electronic devices on which the electronic components are connected. Common application fields are consumer and automotive electronics, or even aerospace and defense. Especially with the upcoming transition to 5G, it is important that their performance is further optimized, with FR taking on a special role.

Depending on where the PCB's are to be used, there are different requirements, for example the possible continuous operating temperatures for the material. For this reason, the National Electrical Manufacturers Association (NEMA) has classified various EP systems that are used especially in these prepregs for PCB’s. FR-4 laminates, which consist of an epoxy resin/hardener mixture, glass fibers and FR, are most frequently used in PCBs in industry [10].

Tetrabromo bisphenol-A (TBBPA), the world's most widely used brominated flame retardant, is still applied mainly as brominated epoxy resins in the electrical industry for PCBs [11]. Nevertheless, more and more halogen-free FR based on phosphorus are being used for this type of resin. Examples are epoxy resins bearing FR properties, based on 9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide (DOPO) or aluminium diethylphosphinate (DEPAL) and its milled types and recently also newly introduced reactive and additive low-viscosity phosphorus-containing FRs [5, 12].

As with engineering plastics, the selection of the right flame retardant is crucial for epoxy resins. Special attention is paid to a low influence on the glass transition temperature (T_g) and a low coefficient of thermal expansion (CTE). In particular with regard to 5G applications also a low influence on the dielectric properties (low Dk, low Df) is of great importance.

3 Increased awareness for Flame retardants

Some 30 years ago FR attracted the attention of environmental scientists and later of environmental legislators.

3.1 Why did flame retardants gain (legislative) attention?

Some halogenated flame retardants have been shown to be toxic or even carcinogenic, accompanied by environmental persistence or the ability to bioaccumulate [5, 15, 16]. Furthermore, some brominated flame retardants (BFR) form toxic substances such as halogenated dioxins and furans in the event of fire. Thus, the issue of flame retardants gained in importance in public awareness. Since the 1990s, brominated flame retardants have been found in the environment [13, 14]. Initially, brominated diphenyl ethers (PBDE) were among the most prominent product groups.

3.2 The NGO view on flame retardants

Due to the above-mentioned hazards of some flame retardants NGOs are often critical about their use. They were generally dissatisfied with U.S. government's inability to regulate "chemicals of concern" (e.g. TSCA – 1976), there was a general distrust of industry (e.g. Chicago Tribune "Playing with Fire" series-2012). They also object to the industry practice of "regrettable substitution", where a regulated substance is replaced by a structurally very similar one. Unfortunately, the subject is very generalized, often no distinction is made between the individual chemical classes and molecules, which can differ massively in their effect on health and environment.

4 Flame retardants and legislation

After long risk assessments and substance reviews, PBDEs are finally restricted in many jurisdictions. In Europe, for example, this is regulated by the directive on the restriction of hazardous substances in electronics (RoHS, [17]), REACH [18]. FR decabromo diphenylether (Deca-BDE) is even regulated by the United Nations Convention on Persistent Organic Pollutants (POPs) [19].

An example which is seen as regrettable substitution in electronics is the replacement of Deca-BDE by the chemically very similar decabromo diphenylethane (DBDPE). The latter was introduced as a non-regulated alternative to Deca-BDE and has already found widespread use in electronics, although it brings up many of the concerns that were the reason to restrict DecaBDE [20].

4.1 Flame retardants on REACH Annex 17 – restrictions

REACH Annex XVII includes all the restrictions adopted in the framework of REACH and previous legislation, Directive 76/769/EEC [21]. The following FR are listed:

- Pentabromodiphenyl ether* (PentaBDE, 0,1% w/w)
- Octabromodiphenyl ether* (OctaBDE, 0,1% w/w)
- Deca-BDE:
  - banned for production or use worldwide by The Stockholm Convention on Persistent Organic Pollutants, April 2017
  - Exemptions were granted for a number of years for specific applications, e.g. in cars and aircraft
- Not allowed in articles for skin contact (e.g. textiles):
  - Tris(aziridinyl)phosphinoxide
  - Tris (2,3 dibromopropyl) phosphate (TRIS)
- Polybromobiphenyls (PBB)
- Inorganic ammonium salts for cellulosic insulation products

Under REACH, all commercially used flame retardants (like all other chemicals > 1 ton consumption) had to be registered in Europe, and the dossiers are publicly available on the ECHA website [22].

4.2 Flame retardants on Annex 14 – List of substances of very high concern for authorisation

REACH Annex XIV contains a list of substances subject to authorization under EU REACH regulation. They are a subset of the REACH Substances of Very High Concern (SVHC). The authorisation process aims to ensure that SVHCs are progressively replaced by less dangerous substances or technologies where technically and economically feasible alternatives are available [23]. The following FRs are listed:

- Hexabromocyclododecane (HBCD) – PBT substance
- Tris(chloroethyl)phosphate (TCEP) – Reprotox Cat. 1b

- Candidates:
    - Alkanes, C10-13, chloro (Short Chain Chlorinated Paraffins) - PBT and vPvB; also added to Stockholm Convention on POPs (2017-04)
    - Boric Acid – Reprotox
    - Trixylylphosphate (TXP) – Reprotox Cat. 1b

4.3 CORAP - Community Rolling Action Plan

The Community Rolling Action Plan (CoRAP) contains substances suspected of posing a risk to human health or the environment. The latest ECHA proposal for the years 2020 – 2022 now lists 74 substances [24]. The Member States submit dossiers on chemicals, which may lead to updated classification and labelling or eventually SVHC proposals. The following FR were listed:

- 2,2-dimethylpropane-1-ol, tribromo derivative
- tris[2-chloro-1-(chloromethyl)ethyl] phosphate (TDCPP)
- 1,1'-(isopropylidene)bis[3,5-dibromo-4-(2,3-dibromopropoxy)benzene]
- N,N'-ethylenebis(3,4,5,6-tetrabromophthalimide
- tris(2-chloro-1-methylethyl) phosphate (TCPP)
- bis(2-ethylhexyl) tetrabromophthalate
- diantimony trioxide (ATO)
- triphenyl phosphate (TPP)
- resorcinol bis(diphenyl phosphate) (RDP)

4.4 RoHS in Europe and additional substance bans

The growing amount of electronic waste and related environmental pollution lead to regulatory action in Europe. The resulting directives on waste separation, treatment and recycling treatment (WEEE [26]) and restriction of hazardous substances in electronics (RoHS [27]) have been in place since the early 2000s in Europe and many other countries have followed with similar legislation. After a "recast" in 2011, currently activities are ongoing about potentially restricting additional substances. So far, the heavy metals Cadmium, Lead, Chromium (VI), Mercury and the FR groups of polybrominated biphenyls (PBBs) and polybrominated diphenylethers (PBDEs) as well as four phthalates are restricted (the phthalates starting from mid 2019).

For potential additional FR, there have been substance reviews and consultations by the Öko-Institute in Germany [28] on ATO, medium chain chlorinated paraffins (MCCP) and TBBPA. In addition to the already discussed ATO and TBBPA, MCCPs are used for other applications, for example as secondary plasticiser in PVC but also as FR for PVC insulations and sheathing for electric cables and wires. ÖkoInstitut presented their proposed conclusions at a webinar 27th April 2020 with a recommended restriction of MCCP and of TBBPA, when not used as reactive component [29]. A general review of RoHS will take place in 2021. For ATO, concerns were identified and a review of the whole combination of brominated FR and ATO suggested.

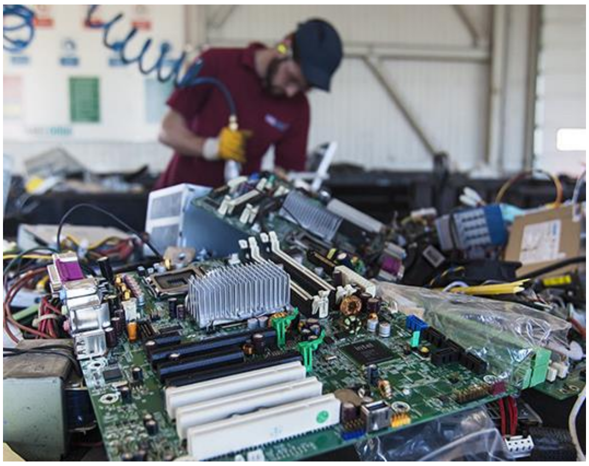

Figure 3: Dismantling of electronic waste for recycling [25].

4.4.1 EU EcoDesign Directive for Electronic Displays - C(2019)2122

The European EcoDesign directive for electronic displays [30] contains a restriction on brominated flame retardants as a broad substance group in the enclosures of monitors and displays, entering into force in 2021-03. While industry groups oppose this approach because it sets a precedent for regulating chemicals in another legislative area beyond REACH, some equipment manufacturers are not against the rule as such, because they have substituted these flame retardants already. For easier recycling, indicating the polymer and flame retardant type on the product is mandatory.

- Annex (4): "The use of halogenated flame retardants is not allowed in the enclosure and stand of electronic displays."
- Annex (2b): "Components containing flame retardants shall additionally be marked with the abbreviated term of the polymer followed by hyphen, then the symbol "FR" followed by the code number of the flame retardant in parentheses. The marking on the enclosure and stand components shall be clearly visible and readable."

5 The development of more sustainable products

Not only hard legal restrictions can drive change and the move away from legacy chemicals, but also voluntary measures and incentives like ecolabels. Prominent examples are “Blue Angel”, EPEAT or TCO. Some of these labels have restrictions on halogenated flame retardants and TCO in addition introduced a list of approved halogen free flame retardants (white list) [31].

Figure 4: Clariant’s ecotain label identifies products with a preferential environmental and health profile [32]. Many phosphorus based FR pass the stringent assessment and achieve the label.

There are already FR manufacturers who have created their own label to screen their portfolio and to make it even more sustainable. One example is the EcoTain® label [32], which sets a benchmark for sustainable products. In addition, more sustainable products are being developed. Examples are FR using renewable hydrocarbons which are derived from sustainably produced bio-based raw materials such as waste and residue oils, so they help in reducing consumption of fossil resources and fossil-based carbon emissions to the atmosphere [33].

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How to collect and prepare the data for SCIP database reporting

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Abstract

The upcoming requirement to provide information to the SCIP database on all articles and complex objects (products) supplied to the EU market with an SVHC content of > 0.1% w/w (weight by weight) from January 5th, 2021, proves to be quite a challenging and complex task for companies.

The tightness of the timeframe and extent of data to be considered stipulates that everyone affected by the new requirement gets started now. This includes analysing the product data already available, determining data gaps, collecting missing data, and finally creating SCIP reporting dossiers.

In order to keep efforts to a minimum – not only for the initial submission to the SCIP database, but also for the following updates required –, it is highly recommended to have an IT tool at hand for the collection, analysis, and reporting of data. In most cases where a high number of articles or complex objects have to be reported, a solution offering a system-to-system interface to the SCIP database is necessary to allow for the bulk processing of data.

1 What is the SCIP database?

In 2018, the revision of the European Waste Framework Directive (EU) 2018/851 [1] entered into force. In article 9, the directive tasks the European Chemicals Agency ECHA with establishing a database for the reporting of articles as such or in complex objects. The obligation concerns products supplied to the EU market containing a substance of very high concern (SVHC, also known as Candidate list substance) above 0.1% w/w (weight by weight). This new requirement covers the articles and complex objects already referenced by the supply chain communication obligation defined by REACH article 33(1). The information gathered in the new SCIP database – short for **S**ubstances of **C**oncern **I**n articles as such, or in complex objects (**P**roducts) – shall be made available to waste operators and the general public.

The intention of this new reporting requirement is to support Europe's development towards a more circular

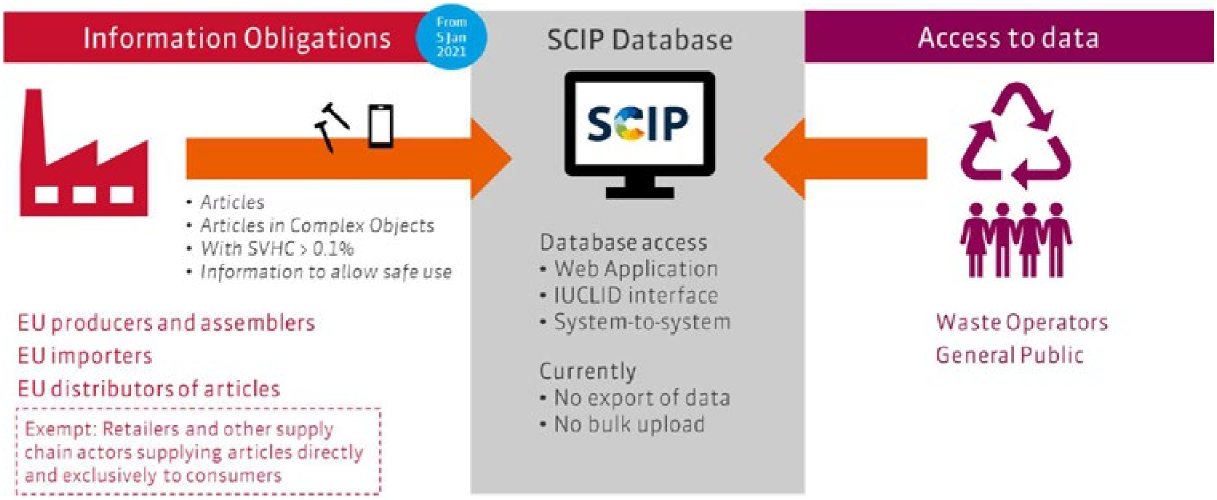

Figure 1: Basic overview of the SCIP database.

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economy[2] by allowing for the separate consideration of waste streams containing SVHCs by ultimately reducing articles containing hazardous substances in our lives.

The legislative act which is the basis of the SCIP database is a directive. As such, it has to be transposed into individual national laws by the EU member states by July 5th, 2020, to finalize the legislative framework and specify enforcement actions.

2 Are you a duty holder?

The goal of the SCIP database is to give waste operators an overview of all the products on the EU market containing an SVHC > 0.1% w/w. Therefore, the range of duty holders is rather broad, covering every company supplying articles to the EU market.

Duty holders include:

- EU producers and assemblers of articles,
- EU importers of articles, and
- EU distributors of articles and other actors in the supply chain placing articles on the EU market.

An exemption only applies to retailers and other supply chain actors supplying directly and exclusively to consumers. Further exemptions, e.g. in the interest of defence, are in the hand of the EU member states upon transposition of the revised Waste Framework Directive into national law.

3 Which timeframe do you have to stick to?

The Waste Framework Directive has set a rather ambitious timeframe for the establishment and commencement of reporting to the SCIP database. Dossiers must be submitted from January 5th, 2021, and ECHA intends to have the first version of the database up and running by October 2020, with the dissemination of data due in the first half of 2021. Access to the database will thus be later than initially intended by the legal act: Article 9(2) of the Waste Framework Directive set the date to January 5th, 2020.

Looking at the timeframe set by both the Waste Framework Directive as well as the SCIP database development, it becomes apparent that the data collection and set-up of a process for dossier submission is an urgent requirement, particularly when considering that the option to report will exist with the release of the first version of the SCIP database expected in October 2020, although reporting is only mandatory from January 5th, 2021.

On the plus side, affected companies usually already have available quite a lot of data required to compose a SCIP report, e.g. due to the information requirements deriving from REACH article 33(1). A good starting point for SCIP reporting is leveraging existing compliance data and enriching them first with internally available data to fill all the mandatory fields of a SCIP dossier (see Figure 4).

Using a software solution for material compliance proves advantageous here, since it considerably reduces manual labour and prevents errors.

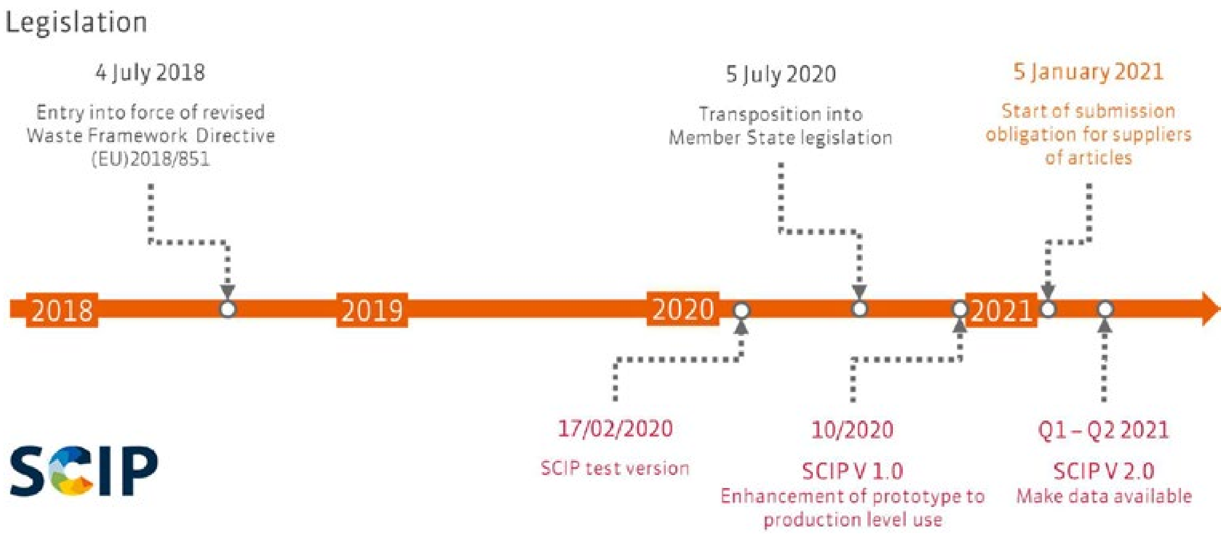

Figure 2: Timeframe set by the Waste Framework Directive and the European Chemicals Agency for the establishment of the SCIP database.

4 How to deal with all the data

With the multitude of products and articles in a company, which can be purchased or an in-house production, it can be a daunting task to select those of your sales products that need to be reported to SCIP database.

When taking a closer look at the legal obligations it becomes clear that a structured step-by-step selection is the most promising approach:

Figure 3: Step-by-step approach for the selection of articles for SCIP database reporting.

In a first step, only those sales-relevant articles (as such and in complex objects) are selected that are supplied to the EU market – since reporting obligations exist solely for these. In case the SVHC content for these products is already known, dossiers can be prepared for those with a content of a Candidate list substance > 0.1% w/w.

If there are data gaps that prevent an evaluation at this stage, a risk assessment might be useful, in order to help select those articles which pose a high risk of containing SVHCs, e.g. due to the materials used. Then you can request more information from your suppliers specifically for these components.

This will finally lead to the selection of your sales products that need to be reported to the SCIP database from January 5th, 2021

. Please bear in mind that – based on the current stage of discussion – the real products brought onto the market must be reported. This means e.g. that in the case of multi-sourced parts, a "worst-case" reporting is not viable.

ECHA is working on ways to simplify notification and to support duty holders. This includes the possibility to group notifications of products into one dossier if the products are similar enough. However, the determining factors for grouping the products still need to be finalised.

Another simplification method includes the so-called simplified notification and referencing. Intended for distributors or assemblers/manufacturers respectively, they allow to reference SCIP dossiers of purchased articles on the basis of their SCIP dossier ID. However, these options require you to collect the SCIP dossier ID of your purchased articles – outside of SCIP.

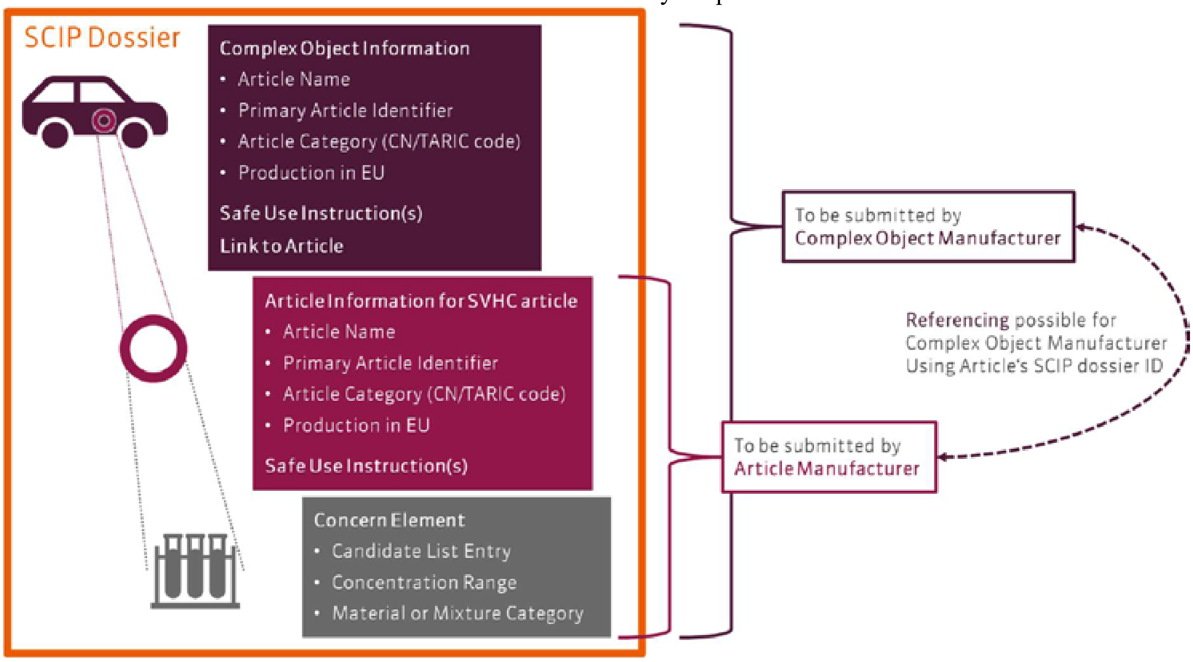

Figure 4: Step-by-step approach for the selection of articles for SCIP database reporting.

Both grouping and simplified notification / referencing will be possible with ECHA's release of SCIP version 1.0 in October 2020.

The data required for the submission of a SCIP dossier is defined by the "Detailed information requirements for the SCIP database"[3] which ECHA published in September 2019 and further detailed in the SCIP IT User Group[4]. The mandatory data described there goes beyond the information requirements defined by REACH article 33(1), therefore making it necessary to gather additional product data to the available compliance information.

This additional data includes the definition of the article category via the integrated Tariff of the EU (TARIC) including the Combined Nomenclature (CN) codes, a statement on the production in EU (EU produced/EU imported/Both EU produced and imported/No Data), the concentration range of the SVHC content, and the material or mixture category of the article containing the Candidate list substance (from a picklist).

Since this adds up to quite a lot of data that needs to be gathered for a multitude of products, an IT solution to collect, analyse, and finally also report the data is highly recommended. This holds particularly true with regards to the fact that not only an initial SCIP reporting is required, but that updates will have to be carried out with modifications to the products, for new products being brought onto the market as well as with the semi-annual updates of the Candidate list. The more information on products is available in an IT system, the easier it will be to carry out this repetitive task.

5 Data gaps and how to close them

Today, REACH article 33(1)[5] requires informing the supply chain in case an article contains a substance of very high concern (SVHC) above 0.1% w/w. The reporting requirements for the SCIP database centre on this information but also ask for more data (see Figure 5).

5.1 Specifics of the Electronics Industry

In addition to the challenge of gathering the additional data, the electronics industry exhibits a few specifics.

Electronics components in general exhibit a high risk of containing SVHC such as lead which has been included on the candidate list in 2018.

For small standard electronics components, full material declarations (FMD) are often available (in contrast e.g. to mechanical components). Additionally, existing standards in the electronics industry like IPC-1752B or the new IEC 62474 are adjusted to meet the new data requirements from the SCIP database. But despite this, there are still significant information gaps and barriers in collecting the relevant information required for the successful creation of a SCIP dossier.

Standard components in electronics are mainly produced outside the EU and supplied by distributors. Although information on SVHC content should be made available by suppliers (and distributors) on the basis of REACH article 33(1), in most cases the information has to be collected directly from the manufacturer and therefore is not readily available. In addition, small building blocks such as resistors are usually sourced

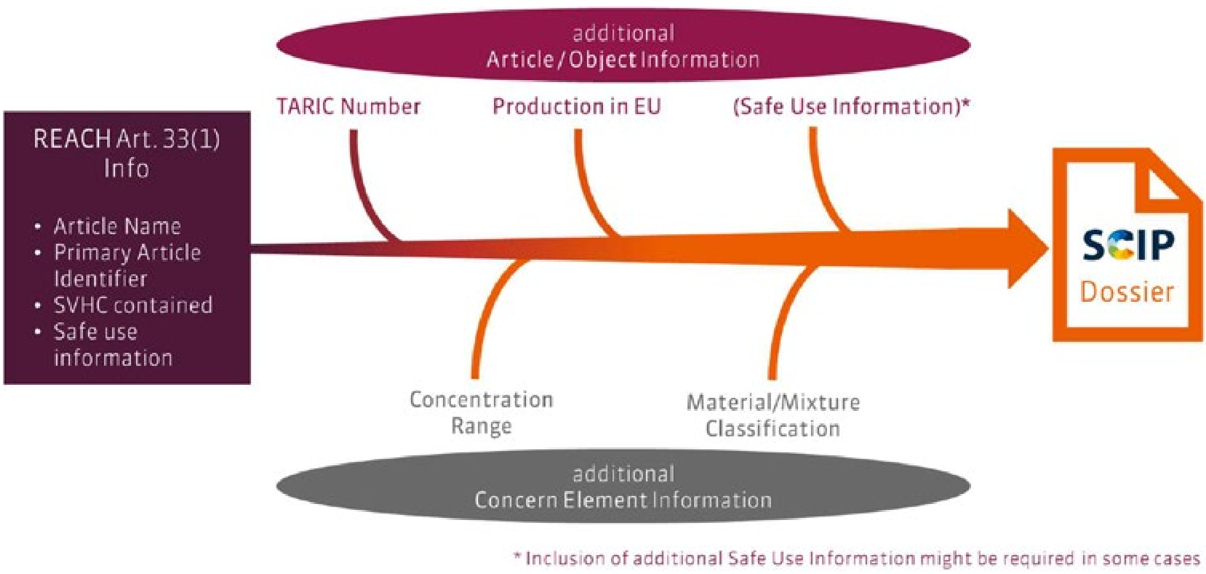

Figure 5: Information requirements for the creation of a SCIP dossier starting from REACH Article 33(1) information.

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from various suppliers and included into products in an interchangeable and non-traceable fashion. Consequently, it is impossible to say which (potentially SVHC containing) building blocks are present in an individual final assembly, which is why reporting is limited to a so-called "worst case scenario".

In case of a lacking FMD, partial or negative declarations as well as Certificates of Conformity (CoC) only provide limited information about SVHC content and run out of date the moment new SVHCs have been identified and published on the Candidate list to fulfil SCIP reporting requirements This poses a particular challenge in all industry sectors where FMDs are not widespread.

Ultimately, this leads to an increased effort in data collection since each change in regulatory requirements will necessitate an additional round of compliance data collection from the supply chain for anything that has not been declared to full content.

Given these limitations, how can a successful SCIP reporting routine be established?

5.2 Additional data sources

A first step can be building SCIP data collection on existing business processes, e.g. starting from the data already gathered within a company to fulfil information requirements according to REACH article 33(1). Based on the type and quality of available data, the process has to run as a compliance circle (cf. Figure 6), ensuring that any relevant change (with regards to product composition, supplier, or legal requirements) is considered at an early stage and new or updated information is requested from the supply chain or data sources.

Further information can be gathered by leveraging RoHS compliance information. As most electronic products or components have to comply with the requirements of the the Restriction of Hazardous Substances (RoHS) Di rective 2011/65/EU, information on RoHS compliance can be used as an indicator for the potential presence of an SVHC.

Several SVHCs are also regulated under RoHS (e.g. lead, CAS# 7439-92-1 or various phtalathes) are either restricted above the threshold of 0.1% w/w or subject to an exemption. The knowledge about an applied exemption under RoHS provides helpful information on the presence of an SVHC that has to be reported to the SCIP database

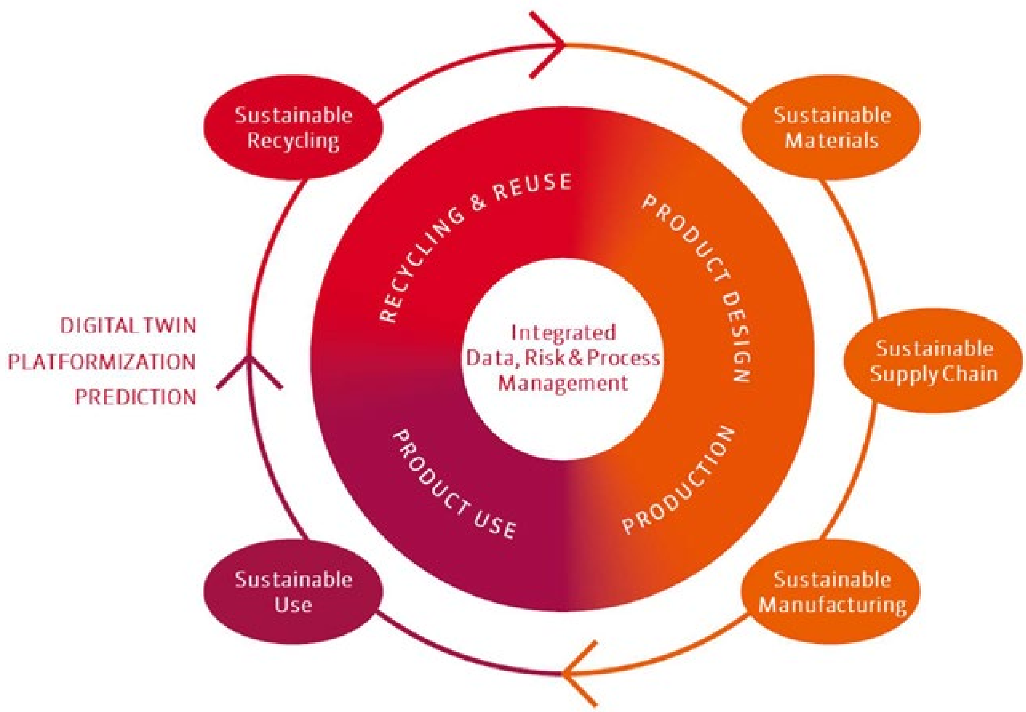

Figure 6: Compliance Circle

Providing the material category (which is also required by SCIP) might be a challenge for complex articles and commodities. Checking the RoHS statuses that have an applied exemption (e.g. RoHS 6c: Lead in copper alloys) can help in quickly assessing the SCIP relevance and the associated material category. Since a SCIP dossier requires information exceeding product composition information, data has to be taken from additional sources.

The so-called "article category" requires the CN/TARIC tariff code on each article level, which is handled by the customs organization or has to be provided by the supplier.

These additional sets of information – on product level – need to be added to the product composition data for successful SCIP submission. Ideally, this mapping of data is carried out in an automated way to avoid errors and high manual and maintenance efforts.

5.3 Leveraging Default Settings

In case there is no detailed information on the SVHC concentration, the SCIP dossier offers the possibility to declare the widest concentration band (> 0.1% to 100%), which ideally is pre-set as a default.

Setting defaults is a useful way forward, particularly for initial SCIP reporting, where the tight timeframe does not allow to collect all of the missing data from the supply chain.

Further administrative data is required for SCIP reporting, e.g. if the article is produced in or outside the EU. For SCIP reporters that do not have this information available or do not want to disclose, "no data" can be selected.

Information on safe use has to be provided but might not be relevant – in that case, the system offers to choose that there is "no need to provide information".

Another mandatory information required (exceeding REACH article 33(1) obligations) is the declaration of the CN/TARIC tariff code on each article level. This information, if not present, needs to be collected from the supply chain and has to be administered in a SCIP solution. Working with default CN/TARIC code, even if just used to fill initial data gaps, can increase efficiency and save time.

It is apparent that it is necessary to combine information from various sources and beyond material compliance data.

Leveraging compliance data from various sources, adding available data e.g. on customs codes and completing them by prudent selection of defaults allows to compile SCIP dossiers for the initial reporting on the basis of available data and sets the basis for further dossier refinement upon update.

SCIP reporting thus also follows the compliance cycle illustrated in Figure 6. Starting off on the basis of available data, more detailed information can be collected from the supply chain in further steps and included into the SCIP dossiers upon update.

This follows what we call the CARE principle, i.e. the **c**ollection, **a**nalysis, and **r**eporting of data, followed by various ways to **e**volve towards a refined reporting with every submission of a SCIP dossier. This establishes due diligence and showcases continuous improvements. iPoint is currently developing such a solution in close cooperation with the European Chemicals Agency ECHA[6]. The solution will of course meet all requirements for initial reporting, such as bulk upload functionality of SCIP dossiers and covering all mandatory data. But it will also ease the burden of reporting by e.g. making it possible to leverage default values as far as desired and will support iterative refinement of dossiers upon update.

6 What could a solution for SCIP reporting look like?

For basically all companies affected, solutions for handling large amounts of data are required, with estimations of SCIP dossier numbers for single companies ranging between thousands to several tens of thousands. This does not even include reporting requirements for one and the same product for different legal entities of large companies

Any SCIP solution has to meet a number of requirements. It must allow for the analysis of existing data, determination and collection of missing information, and enrichment of data from various sources. For the upload of a large number of dossiers to the SCIP database, a system-to-system transmission is the only option.

Ideally, a solution also allows the administration of data and makes repetitive analyses straightforward, since updates of SCIP dossiers submitted will be required both in case of product changes as well as Candidate list updates. To save both time and manual effort concerning repetitive tasks, any solution offering automation as well as integration into existing systems is beneficial.

Therefore, the solution of choice should be IT based, since this provides reliable, reproducible, and fast handling of large amounts of data.

Key features to look out for are:

- Communication with multiple data systems and formats
- Automated request and collection of data from suppliers
- Automated identification of SCIP relevant products
- Generation of SCIP submission format
- Handling and submission of data in bulk
- Verification and validation of submissions
- Management of your company's REACH IT UUIDs required for submission
- Options for settings of defaults allowing easy initial SCIP reporting on the basis of existing data.
- Management of product details and setting of SCIP relevance

7 Conclusion

Fulfilling the reporting requirements concerning the SCIP database poses a challenge to almost all companies affected, which is additionally enhanced by the tight timeframe given.

For the initial creation of SCIP dossiers it is therefore of particular importance to be able to leverage existing data as far as possible.

This means that the best approach for SCIP reporting is choosing a solution that will integrate data from diverse sources and systems, allow for the identification and filling of gaps by pre-set values, and of course allow for bulk handling and upload of data. This is best achieved by an IT-based solution with its inherent power of automatization, fastness, and reproducibility[7].

By choosing a solution that also has an in-built supply chain communication option, this allows to evolve in SCIP reporting by refining dossier information as needed.

Handling SCIP relevant data in a software system also allows to expand compliance to other relevant restrictions and thus supports a company's way forward on the compliance journey.

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The SCIP Database under the Waste Framework Directive – Challenges, Strategies and Recommendations

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Abstract

Almost all manufacturing companies are affected by the latest revision of the Waste Framework Directive (WFD). Under the directive the SCIP Database is being developed by the European Chemicals Agency (ECHA). The reporting obligation to submit Substances of Very High Concern (SVHC) information for a company's products poses significant challenges. The submission deadline for Product Notifications is January 5th, 2021. All products that have been placed on the EU market and contain substances of concern need to be submitted to the SCIP Database by this deadline, which means companies need to start taking action soon to remain compliant. This paper provides insights and recommendations on how companies can set up a SCIP strategy that is tightly integrated into their core business processes and allows them to manage their obligations as efficiently as possible.

1 Legal Background and Requirements

1.1 The Waste Framework Directive

Starting point of the legal requirements is the Waste Framework Directive (Directive 2008/98/EC), which has the overarching objective to support the transition to a circular economy. The measures aim to prevent or reduce the harmful effects of waste generation and management on the environment and human health. At the same time, the efficiency of resource use shall be improved.

The amended Waste Framework Directive entered into force in July 2018 and assigns the European Chemicals Agency (ECHA) the task of establishing a database with information on articles containing substances of very high concern on the REACH Candidate List – the SCIP Database ("**S**ubstances of **C**oncern **I**n articles as such or in complex objects (**P**roducts)").

1.2 The SCIP database

1.2.1 Information requirements

Referring to the information obligation under Article 33 of the REACH Regulation, suppliers of articles containing a Candidate List substance in a concentration above 0.1% w/w must submit the following information to the database:

- Information to allow the identification of the article
- Information on the concern element, i.e. the name, location and concentration range of the Candidate List substance(s) present in the article
- Information to allow the safe use of the article, particularly in the waste stage

In accordance with the ruling of the European Court of Justice of 10 September 2015 [1], the limit value of 0.1% by mass applies to articles that are part of another article, known as the O5A principle ("**O**nce **A**n **A**rticle **A**lways **A**n **A**rticle").

As indicated in the title of the database, its requirements apply to both articles as such and complex objects (products). An article in this context is defined as an "object which during production is given a special shape, surface or design which determines its function to a greater degree than does its chemical composition"[2] by REACH Article3(3). A complex object describes an object consisting of more than one article [3].

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As shown in Figure 1, the information to be provided to the SCIP database differs between articles as such and complex objects:

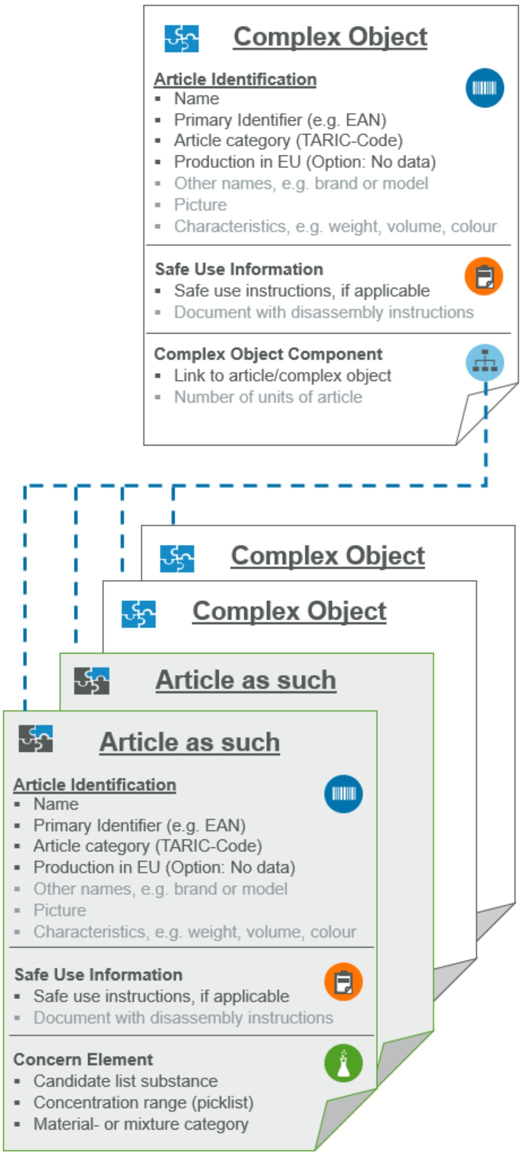

Figure 1: Complex objects and articles as such

The information obligations include EU producers and assemblers, EU importers and distributors, as well as other actors in the supply chain placing articles on the EU market. Retailers and other supply chain actors that supply articles directly and exclusively to consumers are exempted by the obligation, and Member States may define additional exemptions related to matters of defense.

1.2.2 Objectives

The objectives pursued by the SCIP database are derived from the Waste Framework Directive. The generation of waste containing dangerous substances shall be reduced, waste management facilities shall be provided with information to help sort and recycle products containing substances of very high concern, and end-users shall be enabled to make more informed choices on how best to use and dispose such products. Authorities should be empowered to monitor the use of substances of very high concern throughout their life cycle and take appropriate measures. The database shall contribute to the gradual replacement of substances of concern in articles and the development of safe alternatives.

The fact that consumers will have access to the database will probably have a significant market impact. Experiences with similar topics showed that especially NGOs are likely to utilize the data to raise public awareness on the SVHC content. Brands and companies with high public visibility will pay close attention to the information that are going to be published and will demand similar efforts from their suppliers.

1.2.3 Timeline

The notification obligation for affected products will enter into force on 5 January 2021. When the obligation to notify comes into effect, a notification must be available in the SCIP database for all products that are on the market on this date. Notifications are possible with the first productive database version, which is to be published in October 2020.

After the start of the notification obligation, all articles containing SVHCs that are newly placed on the market must be notified. Updates of existing notifications or new notifications may also be necessary, for example if new substances are added to the candidate list that are contained in the article, or SVHC substances are introduced into an existing product due to design changes or change of supplier.

1.2.4 Ways to notify

For the preparation and validation of data for the SCIP Database ECHA provides the IUCLID software (**I**nternational **U**niform **C**hemica**L** **I**nformation **D**atabase) in a cloud version for online editing and in a stand-alone version that can be installed on a local PC or in a company's network. A dossier that contains all data that belongs to a single notification can then be manually submitted into the SCIP Database through the ECHA Submission Portal.

It is also possible to prepare the data in a third-party system that supports the IUCLID format and submit the dossiers to ECHA via the system-to-system (S2S) interface.

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Figure 2 summarizes the available options for preparing and submitting SCIP notifications.

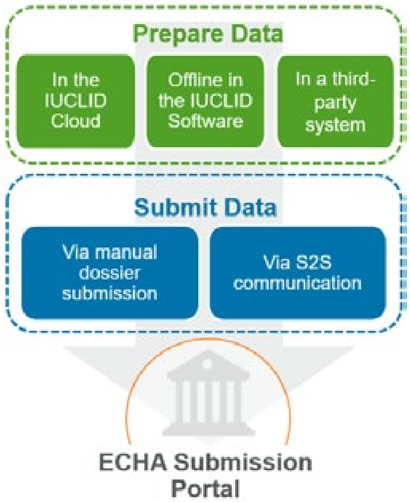

Figure 2: Complex objects and articles as such

2 Strategical considerations

2.1 System-to-System Interfaces

Manual submissions by using the ECHA IT tools described in the previous chapter will not be a viable option for many companies, considering the size of their portfolio and/or the complexity of their products in conjunction with the amount of manufacturing, purchasing, sales, and supply chain driven updates to their products.

An estimation published by Zentralverband Elektrotechnik- und Elektronikindustrie (ZVEI) estimates the effort for a typical article supplier in mechanical engineering with about 2,500 products at 23 additional full-time employees for manually preparing and submitting the initial notifications for to ECHA – not considering any potential updates to the submissions. [4]

The S2S interface is intended to facilitate the SCIP notification processes by providing the opportunity to prepare and submit notifications to the SCIP database outside of ECHA tools and allows for automated notification processes. This is especially of interest for companies with many notifications, frequent updates and an already existing system in place for managing products and articles that can be extended or complemented with a suitable S2S solution. [5].

The IUCLID tool which forms the basis for the SCIP format has been developed by ECHA in collaboration with the OECD for a wide range of different application areas worldwide, within the EU e.g. for substance registration according to REACH Art. 7(2), for the Biocidal Product Regulation (BPR), and for Poison Centre Notifications under the CLP regulation.

The flexibility of the format that is required for suiting the many different use cases comes with many challenges in regard to S2S interfaces.

In particular, SCIP Notifications share a many similar requirements and challenges with Poison Centre Notifications. Our experience in managing Poison Centre Notifications has shown that the first hurdle for many companies is the complexity of the format, with its multiple XML files that have to be generated. This makes the development of own 'home-grown' solutions by duty holders difficult. However, the frequent changes to the format pose the biggest problem for companies. Continual half-yearly updates to the IUCLID format make it a moving target that requires timely updates to the S2S interface solution. In light of this, companies should pay close attention to the aspect of maintenance to ensure an ongoing support when looking for potential S2S communication solutions.

In conjunction with the information requirements described in chapter 1.2.1, this highlights the unique nature of the Waste Framework Directive's requirements for companies in comparison to the requirements of REACH Art. 33 or RoHS due to the high level of formalization.

2.2 Confidential business information

Since the SCIP database requires detailed product information to be disclosed, it is naturally a concern for many duty holders how their confidential business information (CBI) can be protected.

The central element in this context is to avoid the disclosure of links between the actors in the supply chain and information on supply sources. Therefore, ECHA is not going to publish the link between a SCIP notification and its submitter, i.e. the legal entity. In case of submissions for complex objects, only the identifiers and names for the top-level article, i.e. the complex object, will be disclosed. For its complex object components, only the name and the article category are disclosed. [6]

Figure 3 illustrates the CBI concept in the SCIP database:

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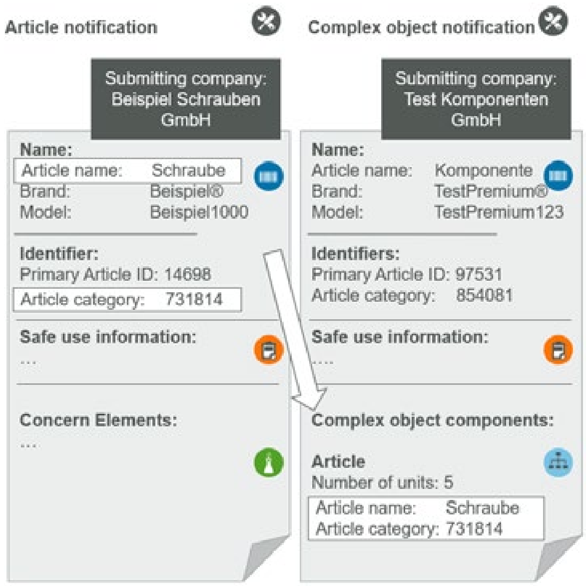

Figure 3: CBI and the SCIP database

2.3 Data exchange in the supply chain

2.3.1 Challenges

Besides the technical considerations, the high level of detail of the data required for reporting to the SCIP database is demanding for duty holders. This is true especially for complex objects where detailed information is required on the specific components that contain the Candidate List substance(s). Therefore, companies need to develop strategies for how this data is obtained from the suppliers and how it can be used for the creation of own product notifications.

2.3.2 Re-use of data

Since almost all companies will be obliged to provide information about SVHC substances in the SCIP database, it is obvious to refer directly to the notifications of their own suppliers. Concepts for referencing and simplified SCIP notifications are currently being implemented by ECHA and are planned to be available in the productive version of the SCIP database.

The referencing of articles allows the sharing and reuse of article information, thereby helping to avoid submitting the same article multiple times. The concept is applicable to assemblers that do not alter the shape and composition of the referenced product. After the submission of the SCIP notification the supplier can provide the references ("SCIP Numbers") for their notifications to their customers. Customers can use these references when creating their own complex objects instead of re-creating the article data for the supplied parts. [7]

For companies who are acting as distributors and companies with intra-party agreements, for example 'sister' companies within a multi-national corporation, the concept of Simplified SCIP Notifications (SSN) can be applied. In this case the complex objects and article data is directly submitted without any further changes. For a Simplified SCIP Notifications the original supplier of the article needs to submit the SCIP notification first and then, like in the concept of referencing, to provide the SCIP Number to the distributor. The distributor indicates in his notification that he is redistributing an existing notification.[8]

These concepts provide the advantage that the time and effort for data maintenance is reduced significantly. In addition, the referenced submissions are automatically kept up to date in the SCIP database. On the other hand, the fact that it is currently not possible to see the complete dataset of the referenced article represents a major disadvantage as a company does not have full insight into the data they are referencing in their submission.

2.3.3 Data exchange standards and platforms

As a standardized way to communicate compliance information within the supply chain, various standards have been developed in recent years, with IPC1752A and IEC 62474 being the most widespread ones. IPC1752A is an XML-based exchange format for material declarations. The IPC Committee is working on a new version of the standard (IPC1752B) that should also cover the additional information requirements for reporting to the SCIP database. Publication is planned for July 2020. The IEC 62474 standard has also been revised and the new version was published in March 2020 [9]. The two formats have the advantage that in addition to the REACH SVHC requirements of the SCIP database, other substance-related requirements can also be exchanged. A software solution is required to enable the processing of these data formats. Unfortunately, the availability of material declarations in IPC1752 and IEC 62474 format in high quality is not yet large. Additionally, it remains to be seen how quickly companies can implement the new adaptations to the formats.

Other possibilities include the use of data exchange platforms like BOMCheck or CDX. Since the obligation to provide SVHC information according to REACH Article 33(1) remains and exists in parallel, another possible way would be to include the SCIP number in those REACH Article 33(1) declarations.

With all approaches, it must be considered that the SCIP database does not support the handling of several suppliers for one product (multi-sourcing). Since in practice not all possible variants of a product can be mapped in the SCIP database, companies should consider aggregating the information from all possible suppliers.

2.4 Change Management

2.4.1 Triggers for submissions and re-submissions

Although not obvious at the current stage of preparing for the obligation to kick-in, potentially the biggest challenge with regards to SCIP notification will be keeping the submissions up to date. Scenarios such as engineering redesigns, changes within the supply chain, new market introductions for existing products, and updates to the REACH SVHC Candidate List with new substances subject to reporting being added typically two times per year all need to trigger a re-evaluation and possible (re)submission to the SCIP database.

The manufacturing, purchasing, sales, supply chain, and regulatory driven change management can lead to an extremely high level of effort (or worse, non-compliance). Figure 4 shows an overview of potential triggers. and resulting requirements.

Figure 4: Possible triggers and decision tasks for SCIP notifications

2.4.2 Change Management scenarios

2.4.2.1 Supply-chain and purchasing driven changes

Two scenarios need to be considered with regards to supply-chain driven changes. In case a supplier is replaced, or an additional supplier is added, the REACH SVHC content of the purchased component needs to be evaluated, the affected products need to be identified and required update submissions need to be sent to the SCIP database.

In case a supplier updates an article, first step is to determine if ECHA´s referencing option described in chapter 2.3.2 has been utilized by the affected suppliers, as this removes the necessity for updates in that case. If not, it needs to be checked if an updated REACH SVHC declaration has been provided by the supplier and if it requires an update submission for the products where the purchased component is contained.

2.4.2.2 Engineering driven changes

In terms of manufacturing driven changes, an engineering re-design decision for a product can cause changes to its SVHC content which might require an update submission for this product. In addition, the changes in the BOM structure of the product due to the re-design decision can lead to different complex objects and articles as such having to be reported to SCIP.

2.4.2.3 Sales driven changes

In terms of sales-driven changes, three main different scenarios need to be considered.

If a new product is intended to be sold in the EU market, a SCIP notification needs to be prepared prior to placing the product on the market. The same is true if an existing product is introduced to the EU market

In case different sales companies for specific countries exist within a corporation, this includes identifying the appropriate Legal Entity for submitting the notification to the SCIP database. Introducing an existing product to an additional EU country might then also require an additional SCIP notification by the responsible Legal Entity. In this context, potential scenarios for utilizing Simplified SCIP Notifications (SSN) as described in chapter 2.3.2 needs to be evaluated and the required information, i.e. the applicable SCIP number, needs to be submitted.

2.4.2.4 Regulatory driven changes

The half-yearly updates of the REACH SVHC Candidate List require a comprehensive re-assessment of a company's product portfolio following the steps described in chapter 2.5.1 for the initial evaluation.

For components where the material composition is known, an own re-assessment is possible. For components without existing full material declarations, the steps for supplier-induced article updates described in chapter 2.4.2.1 apply.

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2.5 Process implications

2.5.1 Preparation

Due to the many challenges involved, it is crucial for companies to develop a comprehensive strategy for managing the requirements of the SCIP database.

The first element of an effective strategy is the preparation. This includes the analysis of the company's product portfolio to identify products affected by the legal obligation. An efficient way to do this is by starting from the component (i.e. lowest article) level.

For purchased components, companies need to evaluate if REACH SVHC information of the suppliers exist to identify the ones which contain Candidate List substances above the legal threshold of 0.1% w/w. For components that are manufactured in-house, the raw materials used need to be examined for their SVHC content and their weight share in the components.

Based on this, a where-used analysis for the identified components utilizing the bill of material (BOM) structures of all products sold in the EU helps to identify those products which require a SCIP notification.

In a next step, the existing data for those products needs to be checked for potential gaps. ERP systems can play a crucial role in filling those information gaps due to their deep integration into all the core processes of a company. Their extensive integration and continuously updated data view also represent a powerful response to the challenges of change management.

2.5.2 Family declarations

Having collected all necessary data, companies should pay close attention to developing a manageable concept for family declarations with regards to ECHA´s concept for handling quasi-identical complex objects that is displayed in Figure 5.

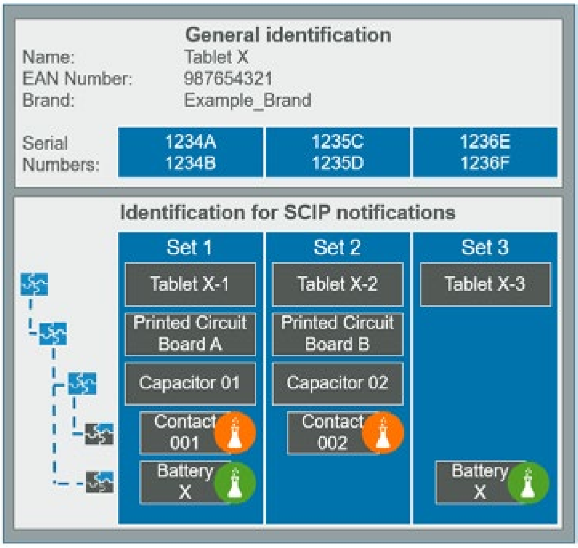

Figure 5: Quasi-identical complex objects. Adapted from European Chemicals Agency, SCIP IT User Group 11.06.2020

Besides the numerous triggers, the concept of quasi-identical complex objects adds yet another layer of complexity to the change management, as every change needs to be evaluated in terms of its impact on the defined sets.

2.5.3 Process integration

Another important task is the integration of SCIP requirements into related processes. This may involve the inclusion of SCIP requirements in

- Quality gates
- Product development processes (to trigger new submissions)
- Product change management processes (to trigger update submissions)
- etc.

It may also lead to measures for establishing REACH SVHC information as a mandatory element of the purchasing process.

3 Conclusion

Almost all manufacturing companies are affected by the latest revision of the Waste Framework Directive. The requirement of submitting information about Candidate List substances in their articles and products poses significant challenges to companies to efficiently comply with their reporting obligations due to the high level of formalization and technical requirements of the notification process, the level of detail of the information required, and the public accessibility of the data.

The setup of a comprehensive strategy that is tightly integrated into a company's core business processes is therefore essential for a successful management of the Waste Framework Directive´s legal obligations.

Companies should not underestimate the challenges related to SCIP notifications. The effort for the initial data maintenance and submission and especially for the change management is high, and the format for SCIP reporting is demanding both technically and content wise.

The requirements of the SCIP database are currently a dynamic situation with frequent changes on the part of ECHA. The recommendations provided in this paper refer to its status as of June 2020. Future changes to the requirements and associated tools can have far-reaching consequences with effects on a company's SCIP strategy.

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Make Use of Your Compliance Data for SCiP Reporting

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Abstract

The EU Waste Framework Directive (WFD) mandates manufacturers and importers to enter product registration information into a centralized substance database (“SCiP Database”) for all articles and complex products that contain REACH Candidate List substances above 0.1% w/w, starting January 5th, 2021. It becomes obvious that only with a systematic approach to collect, analyse, and report substances relevant under the REACH regulation companies will be able to comply with the requirements of SCIP reporting, on top of other relevant aspects of REACH and other European regulations.

DXC is the world’s leading independent IT services company, serving nearly 6,000 private and public-sector clients from a diverse array of industries across 70 countries. For over 20 years DXC manages the International Material Data System (IMDS) for the global automotive industry and has a proven track record in the area of material compliance and sustainability.

Compared to IMDS for the automotive industry, the Compliance Data Exchange (CDX) is available for all manufacturing industries to manage material data collection, analysis and reporting for regulatory compliance and sustainability purposes. CDX supports partial and full material reporting with reference to almost all common legislations. Right from the beginning the team was closely involved in the SCiP database discussion; SCiP reporting is a MUST and is available for testing already.

1 SCIP Reporting Preparation

A SCiP project at least must follow the following steps:

Create an overview of the chemical content for all purchased and/or produced materials / components in your company. You may think about to shorten this exercise by collecting information only if an SVHC is included (the existence of an SVHC – defined by REACH – grants the reporting need). But with the next SVHC update (per default, two updates are published per year), you must go thru the complete lists of your parts/components again. So finally, it would be more efficient to start with a full repository of chemical content up from the beginning.

Select those parts that contain SVHC above the threshold of 0,1% for your initial SCiP upload. More details of how the SCiP interface works in detail, will be described later in this text.

As an ongoing responsibility each company must monitor a) changes in the material composition of all parts and b) changes in the REACh SVHC list (bi-annual updates will be provided by ECHA). Whenever the criteria for a SCiP upload are impacted, an updated SCiP dossier has to be submitted. All these requirements should be supported by an IT system as automated functions, e.g. they all are available in CDX.

2 How to provide the SCiP interface

Several IT vendors will provide a SCiP S2S interface that identifies all relevant parts and that is fully aligned with ECHA’s reporting requirements. Upload confirmation has to be maintained as well.

And the availability of the relevant SVHC information per article is key as well. Relevant material data must be collected in a structured way: centrally or – as recommended by DXC – directly from the supply chain.

2.1 Scenario 1

Your suppliers’ material information may be available in reports based on the IPC 1752 format or the IEC62472 format. It is not possible to directly upload these common formats to the SCiP database, but services like CDX offer interfaces to import/export these standard formats and therefore enables the SCiP upload.

2.2 Scenario 2

Material information is managed in any in-house system, but the vendor of this system, or your IT department in case the inhouse system is an individual development, is not able or willing (e.g. due to budget and/or time restrictions, or missing know-how) to offer an own SCiP interface. In this case, with the data transfer e.g. to CDX's by using its standard web-services, in-house data can be assembled there and then loaded into SCiP.

2.3 Scenario 3

If your in-house system can provide "SCiP-ready" data sets but does not offer a S2S interface, again a material management system like CDX can be used as the intermediary for SCiP upload, with or without redundant data in both the in-house and the "in between" system.

Although this is a massive reduction of the functionality of such a material management system like CDX, it can be used as a pass-thru functionality for the in-house system's communication with the SCiP database, with all interface development and maintenance work done by the system provider. Finally, it is a cost driven make or buy decision to identify the most efficient business case.

2.4 Scenario 4

Scenario 3 will become even more attractive if further functionality of the material management system will be used, in particular the material data collection from the supply chain or the use of the IPC 1752 / IEC62472 interfaces.

3 SCiP interface functionality in detail

The ability to properly report substance information to ECHA depends on the availability of such data in our company in a structured form. This sounds trivial but the devil is in the details.

Assumed that your company has already started to collect information about substances in supplier parts and own produced parts in a structured way, e.g. by using an IT service like CDX, the process to create and submit SCiP dossiers would be as follows:

3.1 Where-used Analysis

Identify all components or parts with articles that contain substances of high concern (SVHC) above 0.1%.

The "Where-Used Analysis" in CDX is a powerful function to run this analysis in a structured way – e.g. per product family – with reference to the "REACH Candidate List" filter integrated in CDX.

3.2 Validate against SCiP reporting requirements

ECHA has created specific new reporting content that has to be maintained first before a SCiP dossier (commonly: the SCiP report) can be submitted.

On the top level of the component or part in scope this information should be available, but for supplier parts the provision of this information most likely needs the involvement of your suppliers. We recommend not to start guessing, instead to contact the suppliers, but in parallel to continue to prepare an initial dossier with the information available and to update it in a second turn as soon as further supplier information is available.

Nevertheless, for the incremental dossier all top-level information should be provided.

The following fields are for text input or based on small catalogues:

3.2.1 Input fields

- Primary Identifier: in CDX this is the part-number by default
- Other Identifiers: the EAN should be used as primary identifier, if provided
- Article Name should be a standard field
- Other Names: optional
- Produced in EU e.g. in CDX implicitly available by "Country of Manufacturing"
- Safe Use Instruction: requires specific information or default text.
- Concentration Range: recommended to use ECHA default concentration range.

The most discussed entries are the "Article Category" and the "Material Category", both based on newly introduced ECHA pick lists.

3.2.2 Article Category

The Article Code is a subset of the TARIC (Customs) Code that is compulsory to clarify all goods imported into the EEA. Article categories are a mandatory identifier for every article subject to SCIP reporting.

This even includes articles that never directly placed on the market but just used as production parts. The challenge for the supply chains is significant, as TARIC Codes are an unknown for non-exporting companies. These SMEs typically form the base in article production on all supply chains.

CDX will provide means for setting a default TARIC Code for articles in products, which will be used in SCiP dossiers for articles without TARIC Code in each given product.

Apart from direct setting the TARIC Code, CDX offers a convenient assistant for identification of the appropriate code.

3.2.3 Material Category

For every "concern element" (SVHC) the SCiP dossier requires at least one material category or mixture category to be provided. Material categories are beyond the scope of REACh Art. 33 and thus introduce a new requirement and potential source of supply chain resistance.

Especially, supply chains that already have collected REACh Art. 33 data to the required extend, will suffer from a need of a full revision cycle in the supply chain.

Moreover, ECHA decided to introduce a newly devised nomenclature for material categories not allowing reuse of material categorisation information in their material category 11/other. Material category 11 may only be used in such situations where the material properties do not match any of the ECHA material categorizations.

For example: Using a JAMP category M-119 (other ferrous alloys / nonferrous steels) expresses material properties which can be easily expressed by one of the proposed metal categories of ECHA. Unfortunately, a default mapping cannot be established in this and many other cases, requiring intense consultation with the supply chain.

Other classification schemes – such as IMDS – will provide a mapping scheme usable for dossier creation. CDX already has means providing auto-mapping capabilities for material categories / classifications.

4 Simplified Notification

As distributors typically do not alter the physical product nor its business properties, ECHA has proposed a means for simplified notification.

Provided that the distributor will only forward the product for which he has received a SCiP reporting number, he may create a new dossier that only needs to refer to the supplied data set. Upon dissemination the SCiP database will provide the original data structure with supplier identification replaced by distributor identification.

This is analogous to the CDX system functionality of "forwarding" a material data sheet (MDS). CDX will automatically create a simplified notification if a forwarded MDS is based on supplied information that include a SCiP number.

5 Referencing

On the first glance the "Referencing" seems to be a huge help to reduce redundancy and responsibility in preparing a dossier.

Assumed that a supplier makes the SCiP Article Id available to his customer, this can be included as a reference in the submitted SCiP dossier instead of the full drill-down of all data.

The advantage of this mechanism is that data redundancy is avoided on the ECHA level and the workload is reduced for those companies that manually provide dossiers.

But this approach bares some risk and the submitter should be aware of it.

Updates of SCiP dossiers are not automatically notified to referencing companies. Moreover, the current dissemination schemes of the SCiP database do not allow for insight into referenced dossiers, rendering them a "black box".

This will lead to situations where dossiers will contain unexpected data. Nevertheless, the submitter is responsible for these data.

If using systems such like CDX, there is no perceivable advantage in effort when using referencing. Therefore, we recommend providing a full dossier.

6 Outlook

The IUCLID application as the ECHA tool for dossier preparation and submission is a good showcase to understand the ECHA data requirements. Nonetheless, it is not a feasible approach for the creation of complex and/or mass data submissions.

The WFD has created requirements that need insight into very complex supply chains. Communication, data management, and data insight in these contexts can reasonably be established only by using IT tools like CDX that support big data analytics of material compliance information and provides the means for processing mass data.

The creation of SCiP dossiers may be the starting point to implement tools like CDX, but SCiP reporting is only one small aspect in a far wider scope of material compliance and risk management. Transparency about supplier goods allows active management of purchase decisions under the aspects of sustainability and environmental responsibility. Using tools like CDX supports turning risk management into value creation.

7 Literature

[1] CDX Homepage provides by DXC, Page “MATERIAL REPORTING”:
CDX Extends Support for Waste Framework Directive "Substances of Concern in Products (SCIP)" Database Reporting
https://public.cdxsystem.com

[2] ECHA Homepage “The Waste Framework Directive”
https://echa.europa.eu/understanding-wfd

[3] ECHA Homepage “SCiP Database”
https://echa.europa.eu/scip-database.

IEC 62474 (EN IEC 62474) Declarations for EU SCIP Database Reporting

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Abstract

The International and European Material Declaration Standard (IEC 62474 / EN IEC 62474) was revised in 2018 and the data exchange format was updated in March 2020 to meet emerging requirements for communicating material and substance information through the manufacturing supply chain. IEC 62474 provides declaration requirements/format and includes several EEE sector lists, including the Declarable Substances List (DSL), Material Classification List (MCL), and exemption lists to support global harmonization within the industry.

New capabilities to address upcoming regulatory obligations, user needs and requirements to report an expanded range of substances/materials (such as Critical Raw Materials, CRMs)) were added. The new capabilities include enhanced supply chain information to meet the requirements of the upcoming EU Substances of Concern in Products (SCIP) database. In this paper, we discuss the IEC 62474 capabilities and how supply chain declarations may be mapped into a SCIP dossier for submission.

1 Introduction

Material declaration through manufacturing supply chains has become a vital tool for manufacturers to inventory material and substance information in their products and to assess compliance to environmental regulations. It is also becoming increasingly important in providing information for environmentally conscious design (ECD) and various circular economy initiatives.

The upcoming EU requirement for manufacturers, importers, and distributors to submit product content information into the Substances of Concern in Products (SCIP) database [1] is a particular challenge. Collecting data to meet the prescriptive reporting requirements will be difficult for many companies in the EEE industry. Information gaps and concerns over confidential information will weigh heavily on how suppliers, manufacturers, importers and distributers move forward. They will need to work with and educate their suppliers to collect data that hasn't been traditionally communicated through the supply chain. The fact that REACH Candidate List SVHCs [2] are still needed in several EEE applications and that SVHCs are sometimes incorporated at multiple levels within the product build hierarchy creates complex reporting scenarios.

In this paper we discuss and examine:

- capabilities of IEC 62474 [3] in supporting industry needs;
- how the IEC 62474 standard is used by suppliers and solution providers to report SCIP information, using: (1) the composition declaration module which allows reporting of product parts, materials and substances in a hierarchical structure; and/or (2) a declaration for compliance module for reporting against a DSL.
- use cases, including scenarios when SVHCs are incorporated or applied to the product at different points in the build hierarchy; and
- how material declarations may be mapped into the ECHA IUCLID data fields for submitting into the SCIP database.

1.1 Evolution of an International material declaration Standard

Effort in developing an International Standard for material declaration in the electrotechnical industry was launched in IEC/TC111 (Environmental Standardization) [4] in 2005 when the need for international harmonization was becoming evident. A few industry initiatives made significant progress in consolidating the large number of forms and systems that companies were using but given the prescriptive requirements from regulators and the complexity of global supply

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chains, an International Standard recognized by the WTO would be needed. The initial version of IEC 62474 was published in 2012 [5].

A revision of the standard was published in 2018, introducing several new capabilities based on emerging regulatory requirements and user feedback. Several countries have started to use the standard for a broader range of products – this led to changes enabling the use of IEC 62474 in other sectors and support for alternate substance lists. Reporting of critical raw materials (CRMs) has also become a priority with European Standard EN 45558:2019 (General method to declare the use of critical raw materials in energy-related products) [6] building upon the IEC 62474 standard for reporting CRMs. Given technology convergence, harmonization and the ability to support the needs of other industries was particularly important.

The IEC 62474 Standard provides declaration requirements, an XML-based data exchange format (DXF) and the EEE industry's Declarable Substances List (DSL), Material Classification List (MCL), and exemption lists.

In March 2020, an update of the data exchange format (DXF) was published to provide a few additional data fields to support information needed for the upcoming EU Substances of Concern in Products (SCIP) database. The additional support for SCIP was implemented in a generic manner to help future-proof the DXF, anticipating requirements from other jurisdictions that could be supported by the new data fields.

A key driving principle for IEC 62474 has always been that a material declaration conforming to the standard must declare sufficient information for a downstream manufacturer to be able to assess regulatory compliance. Information needed for EU REACH compliance received significant attention in the revision.

1.2 Global harmonization improves efficiency and compliance assurance

IEC 62474 has been gaining worldwide adoption as an International Standard. It is the European standard for material declaration (EN IEC 62474) and has been adopted as the national standard in several other countries. In Japan, the standard is utilized in a government sponsored program to drive harmonization in material declaration across multiple industries. The Japanese Ministry of Economy, Trade, and Industry (METI) found that there was significant inefficiency and cost overhead for suppliers to support multiple declaration systems within and across industries. In 2014, they launched a program to develop a common declaration tool using IEC 62474 as the basis.

2 What is in the standard?

The IEC 62474 standard specifies material declaration data exchange requirements (this includes the data requirements and the format) and a set of reference lists that are specific to the electrotechnical industry, including the DSL, MCL, and exemption lists.

The exemption lists were added to the standard in 2018 with two objectives. The first objective was to provide organizations and solution providers with a consistent method to reference regulatory exemptions that are continuously evolving. Unique and consistent identity codes are needed for reliable supply chain communication, but are often not provided by regulators. The second objective was to allow regulators around the globe who are implementing RoHS-like regulations and intend to align with the EU RoHS exemptions, to reference the exemptions in IEC 62474 instead of having to compile and maintain their own regulatory lists.

IEC 62474 is implemented in two parts: (1) a traditional standards document and (2) an online database containing parts of the standard that need regular updates.

The document portion of the standard contains the stable parts of the standard. This includes the declaration framework and the key information that must be included in a declaration. It also specifies rules for creating and maintaining the parts of the standard that are maintained in the online database.

The IEC 62474 database [7] contains the parts of the standard that may need to be quickly updated in response to market needs. This includes the DXF (including the XML schema) and the DSL, MCL and exemption lists. The lists may need to be updated several times a year – whereas the traditional standards development process would not be quick enough to meet the market needs.

To achieve the timely updates, the IEC 62474 Validation Team (VT62474) leverages IEC's expedited procedures for standards in database format. This has enabled the DSL to be updated on the same day (or within a few days) of the REACH Candidate List updates and the rapid deployment of new data fields for SCIP.

2.1 The Data Exchange Format (DXF)

The current IEC 62474 data exchange requirements includes new capabilities based on emerging regulatory requirements, user feedback, and the needs of a broad range of industries. It provides significant flexibility for suppliers to provide material declaration information while ensuring that critical information for downstream manufacturers to assess product compliance is always available.

The data exchange uses a modular structure by providing an overarching framework and declaration modules to plug into the framework. The information in a material declaration is organized hierarchically with high-level information at the top and progressively more detailed information at each lower level. The overall structure is illustrated in Figure 1.

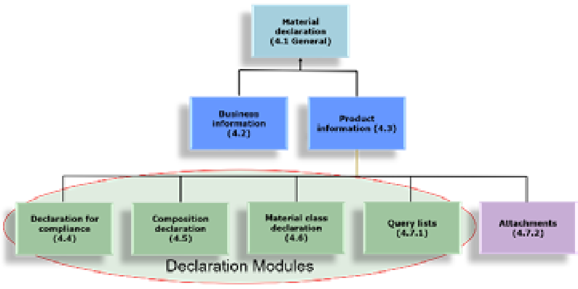

Figure 1: Material Declaration Hierarchy

Business information and product information is part of the framework near the top of the declaration hierarchy.

The business information identifies details about the request such as the type of declaration requested and contact information for the requester. It also includes details about the responder such as contact information, date of declaration and who authorized the declaration.

The product information identifies the product and key characteristics about it. This includes product name and mass, but may also include other identifiers such as model number, EAN, UPC, catalog number, article identifiers, category, and SCIP number.

3 Declaration modules

The material and substance information are organized into declaration modules (green boxes in Figure 1). The number shown in each box refers to the subclause in the standard that specifies the high-level requirements for each module. Additional details about data format for the modules are provided in the XML schema and developer's table.

The declaration modules that may be included in the IEC 62474 declaration are:

- Composition Declaration;
- Declaration for Compliance;
- Material Class Declaration;
- Query Statement Declaration (QueryList)

An IEC 62474 declaration needs to include at least a Composition Declaration or a Declaration for Compliance (it may also contain both).

3.1 Composition Declaration

The Composition Declaration is used by a responder (supplier) to provide a hierarchical declaration of substances within materials and/or product parts that make up the product. A conceptual illustration of a composition declaration is shown in Figure 1. Product parts may be declared to simplify the interpretation of the declaration by associating materials with the build hierarchy of the product. The Composition Declaration also supports the identification of articles (as per EU REACH) for SVHC reporting.

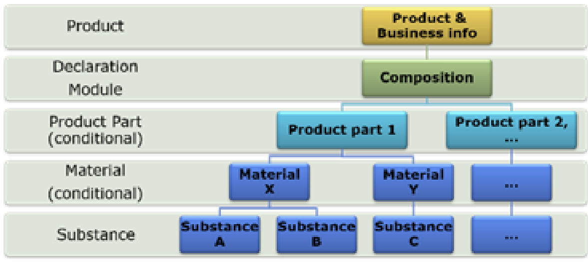

Figure 2: Hierarchical structure of a composition declaration

IEC 62474 requires that at least DSL substances present in the product be declared, but other substances, up to and including a full material declaration (FMD) may be declared.

An FMD flag is available for a supplier to indicate that the declaration includes all substances in the product. An increasing number of manufacturers are requesting their suppliers to provide FMDs to reduce the need for suppliers to update their declaration each time a regulatory change occurs. In this way, manufacturers can screen newly regulated substances against an existing FMD declaration to identify any additional obligations.

3.2 Declaration for Compliance

The Declaration for Compliance was added to IEC 62474 during the 2018 revision. It is a simplified product-level declaration against a DSL. If a declarable substance (DS) or declarable substance group (DSG) is present in the product above the reporting threshold, the supplier reports aboveThreshold='true' for the DS or DSG; otherwise, 'false' is reported.

The Declaration for Compliance is intended to include sufficient information for the downstream manufacturer to be able to assess compliance against the regulations covered by the DSL. It does not typically include information about parts or materials, but there is an exception when a regulatory requirement imposes reporting obligations about the part or material containing the substance. This is the case for reporting REACH Candidate List substances into the SCIP database. A new element 'ProductPartInformation' was added to allow suppliers to provide information about the part and material containing the substance.

3.3 Material Class Declaration

The material class declaration is a simple summary of the types of materials that are in the product and the mass percent of each type. This information may be useful to downstream manufacturers for Environmentally Conscious Design (ECD), Life Cycle Assessment (LCA), or determining the recyclability of the product.

4 Supplier declarations for SCIP

EU REACH and the Waste Framework Directive (SCIP database) impose challenging requirements on product manufacturers to identify and locate REACH Candidate List SVHCs in their products. Some of this information is not typically communicated through the supply chain and requires additional information from suppliers. IEC 62474 material declarations are well suited for meeting this need, but it still requires suppliers and manufacturers to expand their substance management programs and systems to provide and process additional data.

The IEC 62474 DXF released in March 2020 (version X8.10) includes all data fields needed for suppliers to report the mandatory SCIP information to downstream manufacturers. It also supports some of the optional SCIP information for data fields that already existed or a broad benefit was identified for a new data field. Either the composition declaration or the declaration for compliance may be used – the SCIP data is compatible between both types of declarations.

4.1 The declarable article

IEC 62474 uses the term 'declarable article' to refer to the article (as defined by REACH) to which a Candidate List substance is first added. Depending on the manufacturing steps, this may be an 'article as such' or a 'complex object'. Declarable articles need to be reported in the IEC 62474 declaration if the SVHC is present above 0.1%. This requirement is based on IEC 62474 subclause 4.5.2 which requires the product part to be declared when a substance with a reporting threshold based on a product part (e.g. an article) is present.

4.2 Mass percent of the article

When a substance is reported in a declaration it includes mass information – this may be either the mass of the substance or a mass percent (the mass of the substance divided by the mass of the material or product part). However, the recipient of the declaration may not know enough about the manufacturing of the product (or its parts) to identify the declarable article associated with each SVHC in the declaration.

To address this dilemma, the supplier uses the isArticle flag to identify product parts in the declaration that meet the definition of an article (per EU REACH) . In most circumstances a product part will be an article, but there are use cases where a part on the bill of materials may not meet the article definition. The isArticle flag provides certainty for downstream manufacturers reviewing the data.

Note: in some cases (for simple products), the product may be the declarable article (e.g. the product provided by a supplier may be a single piece of molded plastic) or the product may be a mixture (e.g. wet paint) and there is no article.

4.3 When multiple SVHCs are added at different manufacturing stages

There may be products that include more than one SVHC. In some cases, the SVHCs may be applied at different stages during manufacturing, resulting in a complicated declaration hierarchy. A hypothetical example is illustrated in Figure 3.

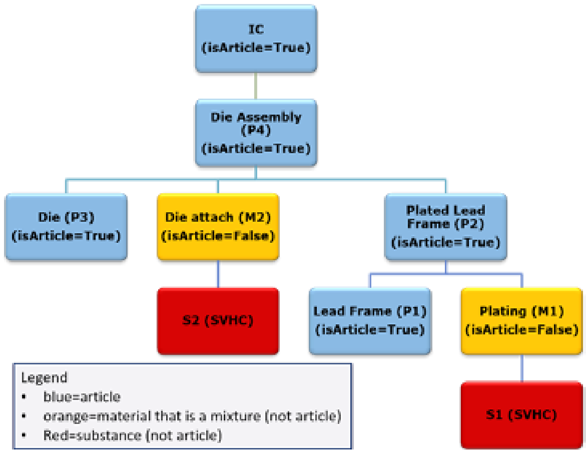

Figure 3: Electronic component with two SVHCs included at different levels of build hierarchy

The substance S1 (an SVHC) is included in a plating material (M1) which is applied to a lead frame (P1) which then becomes a plated lead frame (P2).

- P2 is the declarable article that includes S1, therefore the mass % of S1 in an article is the (mass of S1) / (mass of P2).
- If this mass % is above 0.1%, then S1 has REACH/SCIP obligations.

The substance S2 (another SVHC) is a constituent of die attach material that is applied to the die (P3) and the plated lead frame (P2) to become the die assembly (P4).

- In this case, P4 is the declarable article for substance S2 and is used as the basis of the mass % calculation to compare to 0.1%.

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Overall, in this declaration hierarchy of the IC, product parts P4 and P2 are both declarable articles for different SVHCs, creating a complex declaration.

4.4 Material Declaration vs. ECHA SCIP data model

The above scenario with multiple SVHCs applied at different levels within the BOM hierarchy is complex but is well supported by IEC 62474 for supply chain communication. During the initial SCIP prototype testing in late January 2020, one of the authors attempted to map this scenario to the SCIP database. However, a direct mapping was not possible given that the SCIP data structure was not designed to support both a substance declaration and a component article at the same declaration node. ECHA proposed an alternate approach to declare each SVHC path separately. This highlights that a set of mapping rules are needed to transfer typical EEE supply chain data into the IUCLID format needed for SCIP submission.

4.5 Mapping supply chain data to a SCIP declaration.

A submission into the SCIP database requires that certain minimum information about the product being manufactured, imported, or distributed in the EU and its contents is reported. This includes the article name, primary article identifier, article category (i.e. CN customs code), and production in the EU. The same information needs to be provided about all declarable articles that include a Candidate List SVHC above 0.1%. Information about the SVHC and its constituent material or mixture also needs to be reported.

In a Composition Declaration, declarable articles are reported as product parts. ProductPart, in turn, includes elements and attributes for ProductID, Material, SafeUse instructions, and Substance, all of which provide information that is needed by downstream manufacturers in compiling the Article and Concern Element for SCIP.

Product and declarable articles

The top-level product information is already known to the manufacturer and is easily compiled for SCIP. The information about the declarable article (or other intermediate assemblies) should be provided from the supplier in the material declaration. The information for SCIP can be found by traversing the declaration for SVHCs and identifying the first product part above the substance in the declaration hierarchy with isArticle set to true – this will be the declarable article. The information for SCIP will be contained in the ProductID element of the declarable article and the corresponding Material and Substance elements (Note: for simple product, there may no product parts and the product is the declarable article). A graphical representation of the ProductID element is shown in Figure 4. The green ovals highlight data fields that provide information that is mandatory for SCIP; the dashed ovals highlight optional information.

Figure 4: SCIP Data Fields in ProductID

The identifier and safe use information for SCIP is mapped from the Product, ProductPart, and ProductID elements as shown in Table 1.

Table 1: Mapping product/article to SCIP

IEC 62474 maps to (⇨) SCIP data field
ProductID name ⇨ Article name **Note:** Free text
ProductID Identifier ⇨ Primary article identifier ProductID Identifier ⇨ Other article identifier **Note 1**: If multiple Identifier elements are reported, then the first one is considered to be the Primary article identifier. **Note 2:** Identifier includes a ListID and EntryID. • ListID ⇨ Article identifier type • EntryID ⇨ Article identifier value
ProductID ProductCategory ⇨ Article category (i.e. CN customs code) **Note:** ProductCategory includes a ListID and EntryID. The ListID should correspond to ECHA picklist PG6_60768.
Product SafeUse ⇨ Safe use instructions ProductPart SafeUse ⇨ Safe use instructions **Note:** SafeUse may be a free text string or an entry from a list. If entry is from list, needs to be converted to text string in initial SCIP format.

IEC 62474 maps to (⇨) SCIP data field
ProductID countryOfManufacture ⇨ Production in the EU **Note**: if countryOfManufacture is provided by the supplier, it needs to be mapped to the options for Production in the EU. If countryOfManufacture is not provided, "no data" may be selected for SCIP submission.

Note: The data field name 'Identifier' is used instead of 'article identifier' and 'ProductCategory' is used instead of article category. IEC 62474 uses generic names for data fields wherever possible to remain agnostic of specific regulations and provide flexibility in the use of the data fields.

Information about the material

Some of the information required for the SCIP submission is derived from the Material element in the IEC 62474 Composition Declaration (see Table 2).

Table 2: Mapping material/mixture to SCIP

IEC 62474 maps to (⇨) SCIP data field
Material MaterialClassID ⇨ MaterialCategory **Note 1**: if the IEC 62474 MCL is used, the material class code needs to mapped to an appropriate ECHA material category (VT 62474 is investigating a standardized mapping table) **Note 2**: If supplier has used the ECHA material category list, ListID should be: authority=ECHA; identity= PG6-60753; version =v1.2
Material UseDescriptor ⇨ MixtureCategoryEUPCS value **Note**: If supplier has used the ECHA EUPCS list ListID should be: authority=ECHA; identity= PG6-60567; version =v2.1

SCIP requires that either a material category or a mixture category associated with the SVHC be reported. MaterialClassID is used to indicate the Material Category (the ListID identifies whether the IEC 62474 MCL or the ECHA material category list is used). A new UseDescriptor element has been added to indicate the mixture category. ECHA has indicated that reporting of material properties will be optional, but if desired, the supplier may report these in the newly added data field for MaterialProperty.

When reporting SafeUse instructions, the SafeUse element in ProductPart should be used.

Information about the SVHC

Typically substances and not substance groups are declared in composition declarations. If the REACH Candidate List entry is a substance group, then the supplier may identify the declarable substance group in the DsgID data field that is provided under the Substance element – this allows easy mapping to the Candidate List entry. If the supplier hasn't provided the substance group ID, a lookup in a substance reference list may be necessary to identify the Candidate List entry.

Mapping data types into SCIP

Most of the SCIP data fields have expectations or constraints on the values that may be provided. Suppliers should be made aware of these data requirements and communicate sufficient information in the material declaration so that the information can be mapped into the SCIP submission.

Many of the SCIP data fields are based on picklists (provided by ECHA) – these constrain the options that may be used. Several SCIP data elements are implemented as a data set that consists of both a data type and a data value. One example is the Primary Article Identifier – it includes the data elements PrimaryArticleIdentifierType and PrimaryArticleIdentifierValue. PrimaryArticleIdentifierType, in turn, is constrained to a list of options (e.g. EAN, GTIN, GPC, SCIP number); 'other' is an option and, if selected, the supplier needs to specify the alternate type of identifier.

It's necessary for suppliers to communicate this 'data type' information down the supply chain to ensure that duty holders are able to submit valid data into SCIP. A manufacturer that receives an article identifier value but no information as to whether it represents an EAN, GTIN, GPC, etc. will be in a difficult position to interpret the data and to make a meaningful submission into the SCIP database.

To ensure that a material declaration does not result in such data gaps, the IEC 62474 data elements that correspond to SCIP data requirements are typically of type UniqueEntry, for which the supplier indicates the authority, list identity, and a value.

For example, for the primary article identifier the following IEC 62474 data fields can be easily mapped to the corresponding SCIP requirements.

- Identifier ListID authority = "EAN (European Article Number)"
- Identifier ListID Identity = "66299" (this is the ID for EAN in the ECHA picklist)
- Identifier ListID Version = "v2.0" (version of ECHA picklist)
- Identifier EntryID entryIdentity = "1234567890123" (the EAN number)

Suppliers and solution providers will need to use the applicable picklists to ensure that downstream duty holders can correctly map the article, material, and substance information into their SCIP submissions.

Declaration for Compliance -> SCIP

Given that the Declaration for Compliance is intended to be a simple, product-level declaration, it's not a natural fit to declare information about the articles containing SVHCs. Never-the-less, some organizations prefer to use a Declaration for Compliance, especially if their product is very complex. To support these use cases, a new element "ProductPartInformation" was added as an element under the DSL entry. This allows the supplier to report the declarable articles that contain the SVHC.

5 Summary

Standardized material declaration systems will play an important role in the industry's ability to exchange article, material, and substance data that meets SCIP reporting obligations while continuing to address other current and emerging substance, ECD, and Circular Econom requirements worldwide.

The IEC 62474 International Standard for material declaration provides the data fields needed for suppliers to declare information that duty holders need to make to meet their compliance obligations and sustainability initiatives, including submissions into the SCIP database. Suppliers will, never-the-less, need to be aware of the SCIP data requirements so that downstream manufacturers can correctly map the supplier data into their SCIP submission. Obtaining the complete information from suppliers improves data quality and reduces effort and risk compared to mapping the data afterwards.

IEC 62474 is actively maintained to remain current with regulatory developments and user needs. Use of the standard will continue to grow, especially as the standard is referenced by other standards, purchasing specification and regulations worldwide.

6 Literature

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Towards a multi-sectoral material declaration data-exchange standard

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Abstract

The IEC 62474 standard for materials declaration helps electrical and electronic companies to comply with substances regulations like RoHS, REACH and CRMs. It also contributes to environmental conscious design and LCA assessments, supporting the reduction of environmental impact of products through their whole life cycle. The new IEC 62474 edition 2 is also able to manage alternate DSLs that are declarable substances lists from other sectors.
Today we see that the number and complexity of requirements for product chemical legislations is increasing. These requirements are steadily affecting more and more product sectors. There is, therefore, a strong need for harmonized data exchange formats applicable to multiple sectors. Here we will show how a single (overarching) international standard, covering multiple product sectors and different types of generic and sector specific requirements will be developed. This is intended to be a ISO-IEC dual logo Material Declaration Standard. It will guarantee that substances compliance remains feasible in terms of complexity and costs. This new multi-sectoral data-exchange standard will be based on open, modular, architecture having a generic part, applicable to all sectors, as well as the possibility to plug-in specific requirements by different sectors such as process chemicals or sector-specific exemptions lists.
Additionally, we want to show our long-term vision managing chemical substances. In the future, we envisage increasing automation of data exchange, promoting systems-to-systems automatic data exchange for both the material declarations as well the reference data used to establish them. Such services exist today, but they are proprietary with different protocols that do not facilitate interoperability between IT systems.
Establishing standard formats and services will allow manufacturers to automatically collect data needed for compliance and have their employees focused on managing special cases to ensure good quality reporting. Data and tool providers could also subscribe to notification services for automatically updates, improving their service.

1 Needs for data exchange

There are more and more chemical-related laws and policies impacting numerous product sectors as shown in Figure 1.

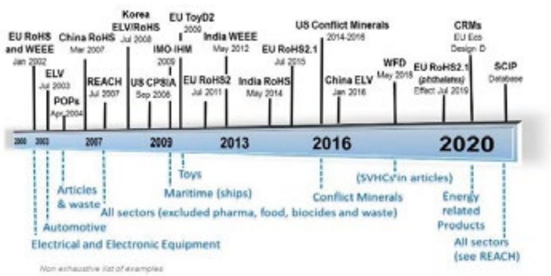

Figure 1: Legislations on hazardous substances in products

Chemical substance restriction and reporting regulations and requirements started in the automotive and electronic product sectors, with regulations such as the EU RoHS and WEEE directives in 2002 and end-of-life vehicles directive (ELV) in 2003. More and more chemical legislations are starting to apply to other product sectors. Since then, RoHS and WEEE types of legislation spread throughout the world.

Later, a number of of regulations appeared applying broadly to all products or to other product sectors. Examples include:

- the European REACH regulation that came into force in 2007; Similar legislations are now spreading to other countries and regions;
- the US Conflict Minerals rule in 2014;
- the EU Waste Framework Directive (WFD) in 2018;
- reporting of critical raw materials (CRMs) in energy related products; and
- starting in 2021, reporting of substances and materials into the ECHA Substances of Concern in Articles and Products (SCIP) database under the WFD.

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Another development are the convergence of technologies in a multitude of different products, where electronics are becoming part of many products used outside of the electronics industry. Here are just some examples: wearable electronics, medical electronics, smart glasses, augmented reality games, sensors and heating/cooling in clothing, tracking tags in food, etc. This development increases the need for cross-sectoral data exchanges on materials and substances in products.

The increased complexity of regulations means that organizations need more detailed information about substances contained in their products, and not only a high level concentration of a substance in the full product, but substance information at article and homogeneous material levels.

The EU Court of Justice ruled that reporting and restrictions associated with REACH are based on articles and not products. The concept is that:

once an article, always an article

So the article starts as small parts and components.

Many products are complex, with deep supply chains. Examples are medical devices such as Magnetic Resonance (MR), Computer Tomography (CT), and Ultrasound equipment's. Other complex products with thousands of parts include the aerospace and automotive industries. Such products contain > 100,000 different parts and components (articles).

All of these considerations are becoming even more important with the new ECHA SCIP database requirements.

2 Data exchange process

Many different product sectors need to be able to get material declarations from suppliers, and to provide material declarations to their customers.

A material declaration contains materials and substances data related to a given product, typically identified by its part number or its serial number, and their manufacturer information; optionally it also contains products parts. The material declaration process is either based on a request-response or a self-declaration between suppliers and manufacturers as illustrated in Figure 2.

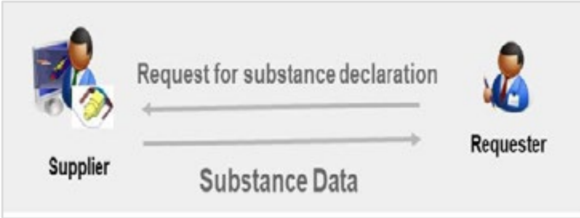

Figure 2: Material declaration process

The substance and material data must be able to flow through the full supply chains for each applicable product. The supply chains of complex products may go very deep, at heights of ten or more; and the more complex the supply chain, the more of a challenge it is to get the needed data.

Even if the end-product is in the aerospace, automotive or electronics sector, the supply chain usually starts within several other non-electronic product sectors, such as chemicals, textiles or machinery, as shown in Figure 3.

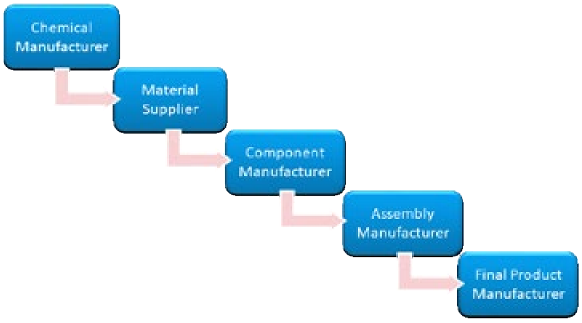

Figure 3: Cascading data request within the supply chain

3 Drivers for harmonized data exchange formats

3.1 Too many custom forms

Many product suppliers are faced with the challenge regarding how to meet all of the different reporting requirements of their customers.

In the past, each customer seemed to have a different requirement for what to report, how detailed the data needed to be, and how it was to be submitted. Many customers have their custom forms and formats for this reporting. This can be time consuming and very challenging when one has thousands of customers. This also represents duplicative work, to take the same information and to enter it into different report formats.

The multiple requirements from customers and the manual entries may lead to errors, whether from manual entries or misunderstandings of requirements.

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Every time a customer changes its requirements for what to report and the format to report in, this causes suppliers to obtain the new information or spend more time with new formats.

Figure 4 below summarizes this view.

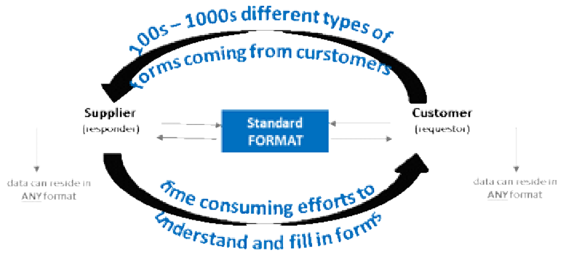

Figure 4: Custom vs. standard data exchange format

Standardization is needed so that the supply chain has a minimum of different types and detail of information requested with a single method to exchange this data.

3.2 Several existing industry standards

Today, besides IEC 62474, few other industry standard data exchange formats exist. These include the IMDS automotive sector-proprietary format, the IPC 1752A standard designed to meet the needs of the electronics sector, and the IPC 1754 standard designed for the aerospace and defense sectors. See Table 1 for more complete overview.

Those standards define "HOW TO DECLARE" the relevant materials and substances data for single product or group of products sharing the same declaration. They could be used with different regulatory or sector specific substances lists, considered as "WHAT TO DECLARE".

IEC 62474 is an international material declaration standard designed for the electrotechnical industry. Although it focuses on the electrotechnical sector, it can be used with substance lists from any other product sectors.

It is a flexible standard that allows for rapid update of substances to report and their data exchange methods, so that it meets the industry needs.

There are many drivers that demand a common material declaration standard for all product sectors. This includes:

- The increasing number of requirements and the complexity of both the regulations and products;
- More and more product sectors are being asked to provide this data, either due to regulations or customer requirements;
- As product technologies merge, one may be selling one's product into multiple product sectors;
- The anticipated regulations on circular economy will add to the need to know what substances are contained in one's products.

Table 1: Sectoral data exchange formats and substance lists

Sector	Data Exchange Formats	Substance Lists
Automotive	IMDS (sector proprietary format)	GADSL: Global Autom. Declarable Substance List) GLAPS: Global List of Autom. Process Substs.)
EEE	IEC 62474 (International)	IEC 62474 DSL (Declarable Substances List) Capable to manage alternate DLS's (from other sectors)
Electronics	IPC-1752A (USA)	Legislation lists (E.g. RoHS, REACH) COCIR list: Medical Devices related (used in BOMcheck)
Aerospace	IPC-1754 (USA)	AD-DSL: Aerospace and Defence Declarable Substances List
Child Care	---	ENPC: Merge of regulatory requirements
Railway	---	RISL: UNIFE Railway Industry Substances List
Cosmetics	---	COSING: annex II and annex III
Ship Industry	---	IHM: Inventory of Hazardous Substances for end of life of ships over 500 GT (by IMO)

Today, there is no International Standard that covers multiple product sectors or to all the different requirements that product sectors have. This causes much extra effort and costs.

The need for an international multisector standard on material declaration to verify hazardous substance compliance, environmental conscious design (ECD), life cycle assessment (LCA), and circular economy are:

- Need for harmonized data exchange formats for cross-sectors data exchanges;

- Increased need for data quality, effectiveness and efficiency of the reporting process;
- Need to reduce costs for manufacturers and their supply chains by increasing interoperability between existing tools and standards;
- Given the complexity and cost considerations, it is highly needed to have a single (overarching) international standard, able to cover multiple product sectors and different types of general and also sector specific requirements!

4 The current IEC 62474

The IEC 62474 material declaration standard edition 2 is implemented in two parts as shown in Figure 5:

- a traditional standard document and
- an online database containing specifications that need regular updates.

The document part contains the procedure and the fundamental rules for requesting and responding with a material declaration. It also contains rules for creating and maintaining the specifications that are in the online database.

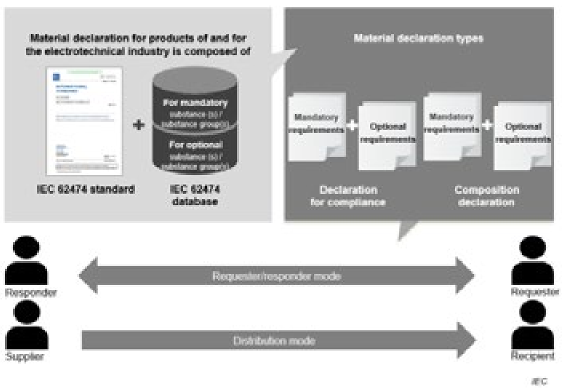

Figure 5: IEC 62474 content

In the current IEC 62474, the database also contains several electrotechnical sector specific lists such as a consolidated Declarable Substance List (DSL) relevant to electrotechnical products, exemption lists and a material classification list.

Going forward, the electrotechnical specific specifications will be segregated from the ISO-IEC common specifications and separately managed by IEC TC111.

The information in a material declaration is organized hierarchically with high-level information at the top and progressively more detailed information at each lower level, as shown in Figure 6.

Near the top of the declaration we have business information and product information.

The business information identifies details about the request such as the name and contact information of the requester – this is in the case of a downstream manufacturer making at direct request to the supplier - - and the details about the responder such as the supplier who manufacturers the parts or materials. The responder information may include contact info and who authorized the declaration.

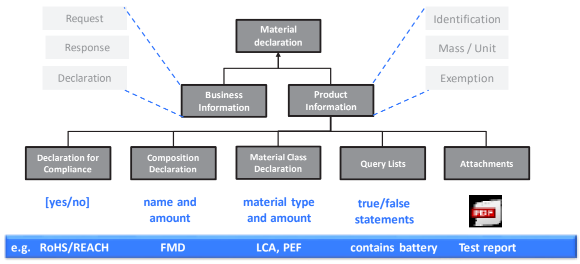

Figure 6: IEC 62474 edition 2 standard on material declaration

The product information identifies the product and key characteristics about it. This includes product name, but may also include other identifiers such as model number, universal product code, catalog number, article identifier, etc. It also includes the mass of the product. Units is the basis for the mass, such as one manufactured item (e.g. car) or litre in the case of paint or metre in the case of a length of string.

The material and substance information in the material declaration are organized into declaration modules underneath "product". Each declaration module is a different type of declaration. Four declaration modules are currently specified in IEC 62474:

- Composition Declaration;
- Declaration for Compliance;
- Material Class Declaration;
- Query Statement Declaration (Query List).

The **Composition Declaration** is used by a responder (supplier) to provide a hierarchical declaration of substances within materials and/or product parts that make up the product.

The **Declaration for Compliance** is a simplified product-level declaration of presence of substance or substance group against a declarable substance list (DSL).

The **Material Class Declaration** is a simple summary of the types of materials that are in the product and the mass percent of each type.

The **Query Statements Declaration** (Query List) include several query statements that are answered by the responder with a true or false statement. E.g. "Does this product has a battery?" and "Does it contain a Critical Raw Material (CRM)?".

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Any of these declaration types could be provided with attachments as supporting material needed for the declaration as shown in Figure 6; e.g. an analytical test report.

5 The new dual logo "Material Declaration for Products" standard

5.1 The vision

The dual logo IEC 62474 will cover most of the needs of all sectors for reporting substances and materials in products, parts or articles.

This fits the blue box in Figure 7.

The dual logo standard provides document (PDF), data model, schema, developers table and web services (WS). It offers a modular and extendable architecture for other standard development organization (SDOs) to complement specific features needed for declaration

Specific sectors (authority) could use their own reference data and extend the standard data models and schemas for their specific needs.

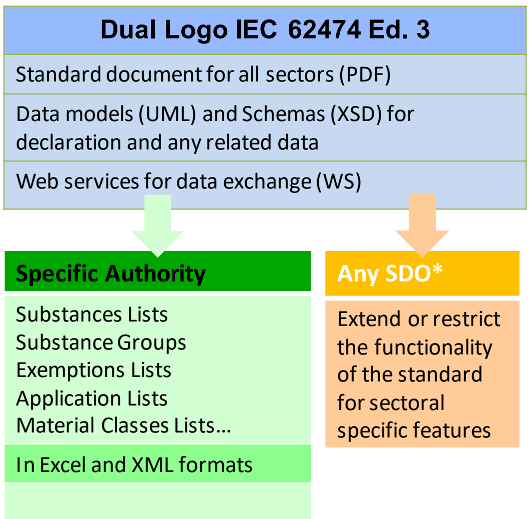

Figure 7: The new ISO-IEC dual logo Material Declaration Standard

5.2 Modular and open architecture

The dual logo standard will continue to cover the business information (requester, supplier, product ID…) as the foundation of the architecture.

It will include the four types of material declaration: Compliance, Composition, Material Classes and Queries that already exist in edition 2.0 of IEC 62474 and shown in Figure 8.

It allows sector specific features to accommodate their needs, such as:

- The aerospace and defense "process chemicals" that is also of interest for the textile sector.

Specific authority (sector, regulator) can define their own reference data (substances lists), for instance:

- IEC: DSL and Material Classes for EEE sector
- IMDS: GADSL, GLAPS and Material Classes
- IAEG: AD-DSL, Query Lists, and Descriptor lists
- ZDHC: RMSL substances list for textile sector
- ECHA: REACH Candidate List

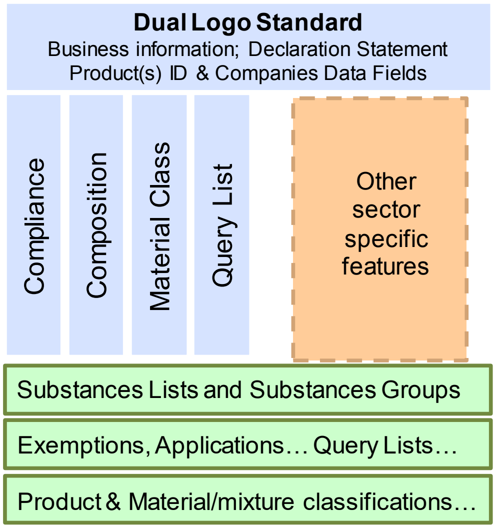

Figure 8: Open and modular architecture

5.3 The plan

The development of the new international, multisector ISO-IEC dual logo standard for Material Declaration is planned to start based on the current IEC 62474 edition 2.

This would require the following steps:

- Approval of the plan for collaboration between the two ISO and IEC technical committees: the IEC TC 111 / MT&VT 62474, in charge of developing the current IEC 62474 standard and ISO TC 207 / SC1.
- Upon approval, a Joint Working Group (JWG) with members from both, ISO TC 207 and IEC TC 111 will be created. The members from both committees have the same duties and rights in the development and balloting processes. The new JWG will operate under the leadership of IEC.

- The standardization activities can start, with a duration of approximately 3 years before the new dual logo standard can be published.

The existing IEC 62474 edition 2.0 includes a data exchange formats and reference data. New responsibilities would be established:

- Data exchange formats will be the responsibility of overarching ISO-IEC joint team
- Reference data will be owned by sectoral teams; typically IEC TC 111 VT team will continue to maintain the IEC 62474 declarable substance list (DSL) and other lists specific for the electrotechnical sector.

6 Summary and conclusions

The new ISO-IEC 62474 dual logo standard will be designed to serve all sectors currently under the scope of ISO and IEC and facilitate cross-sectors data exchange.

The ISO-IEC dual logo standard for Material Declaration will include (to be define by the ISO-IEC joint working group):

- Extend product scope from electrotechnical to the broad ISO product scope
- Build a data exchange format that supports a variety of reference data (e.g. hazardous substances, critical materials, process chemicals, etc.)
- Modular approach that enables additional sector specific features
- Specification for web services for system to system data exchange

The new dual logo standard will not include sector specific reference data such as substances lists (DSL/RSL), material classification and sector specific exemptions lists that remain under the sector responsibility.

7 Literature

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Conflict Minerals — U.S. Lessons Learned and European Efforts

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Abstract

Various electronic products contain "conflict minerals," named for the armed conflict and human rights abuses in the eastern Congo and neighbouring countries that the mining of these minerals perpetuate. While investors, institutional purchasers, and consumers increasingly want greater transparency on products that support increased environmental protection and human rights, efforts to curtail the supply of conflict minerals have proved challenging. These minerals – tin, tantalum, tungsten, and gold – are part of a global supply chain which involves many actors and transfers on their path from raw mineral extraction to final products. This paper examines the U.S. experience with conflict minerals legislation, specifically the Dodd-Frank Act Section 1502 and the Act's ensuing "Conflict Minerals Rule." Also discussed is European Union Regulation (EU) 2017/821 (17 May 2017) that institutes supply chain due diligence obligations to support the responsible sourcing of conflict minerals from high-risk areas. The author examines whether the U.S. experience with legislating conflict minerals offers any insights for European efforts.

1 Dodd-Frank Section 1502

The United States Security and Exchange Commission (SEC) was instituted to protect investors, facilitate capital formation, and maintain fair and efficient markets. As early as 1971, the SEC promulgated disclosure rules that required companies to consider their environmental and civil rights impacts [1]. However, Congress's passage in 2010 of the Dodd-Frank Wall Street Reform and Consumer Protection Act [2] ("Dodd-Frank") Section 1502 created a new role for the SEC, that of regulating to prevent human rights abuses [3]. Section 1502 was designed to prevent the funding of military and paramilitary groups operating in the Democratic Republic of the Congo (DRC) and adjoining countries, which together are referred to by the SEC as "covered countries" [4].

"Conflict minerals" symbolise a host of historic human rights abuses perpetrated within the DRC that began as early as the 1870s [5]. This legacy of brutality and violence continues today as armed militia in the DRC, and adjoining countries, gain access to valuable mineral resources by means of violence towards other armed militia groups and the civilian population. Civilians are subjected to brutality, extortion, sexual violence, and forced into labour to extract minerals that fuel continued warfare and violence.

To prevent these abuses, the U.S. Congress chose to use securities disclosure laws to enact supply chain requirements to "bring greater public awareness of the source of issuers' conflict minerals and to promote the exercise of due diligence on conflict mineral supply chains…" and "inhibit the ability of armed groups to fund their activities… and thereby put pressure on such groups to end the conflict" [6]. Dodd-Frank, Section 1502, amends the Securities Exchange Act of 1934 [7], Section 13, and adds section (p), which directs the SEC to promulgate regulations requiring publicly-listed companies to annually disclose their use of conflict minerals [8] that "are necessary to the functionality or production" of a manufactured product [9].

The SEC's final "Conflict Minerals Rule," adopted 22 August 2012, regulates columbite-tantalite (coltan), cassiterite, wolframite, and their commonly extracted derivatives, respectively – tin, tantalum, and tungsten [10] – which along with gold are referred to as "3TG." The rule applies to each publicly traded domestic or foreign company that is required to file investor reports with the SEC [11] (i.e., an "issuer"). An issuer must, first, determine whether their company manufactures or contracts to manufacture products for which conflict minerals are necessary to product functionality or production. There is no *de minimis* exception, so the rule applies to the use of even small amounts of conflict minerals [12].

Second, an issuer subject to the rule must conduct a "reasonable country of origin inquiry" to identify all conflict minerals in their supply chain [13]. Such inquiry must be reasonably designed to determine whether the issuer's conflict minerals did originate in a "covered country" or originated from recycled or scrap sources, and the inquiry must be "performed in good faith" [14]. If the conflict minerals in a product

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originated from recycled or scrap sources, the products containing these minerals are considered "DRC conflict-free" [15].

Third, if, as the result of the inquiry, an issuer knows or had "reason to believe" that a product contained, or may contain, conflict minerals from a covered country, the issuer must "exercise due diligence on the source and chain of custody of its conflict minerals" [16]. If, following the due diligence investigation, an issuer still had reason to believe that a product contained conflict minerals from the DRC, or other covered country, the company was required to submit a Conflict Minerals Report to the SEC that included a description of the measures the company took to perform due diligence on the minerals' source and chain of custody [17]. The Exchange Act, Section 13(p), mandated that the "due diligence" measures include an independent private sector audit of the Conflict Minerals Report, conducted in accordance with established standards [18].

Section 13(p) also prescribed that the Conflict Minerals Report include "a description of the products manufactured or contracted to be manufactured that are not "DRC conflict free" [19], the facilities used to process the conflict minerals, the conflict minerals' country of origin, and "the efforts to determine the mine or location of origin with the greatest possible specificity" [20]. The Conflict Minerals Rule introduced a new specialised disclosure report, Form SD, that allowed an issuer to provide their conflict minerals disclosure and, if needed, attach their Conflict Minerals Report as an exhibit [21]. The rule also required issuers to disclose annually the relevant conflict minerals that originated in the DRC, or adjoining countries, and to make their disclosure publicly available on their website [22].

2 The Legal Challenge

Rather than making it outright illegal to source conflict minerals from covered countries, Section 1502 is viewed as a "name and shame" law. Such public disclosure laws are intended to amplify investor, institutional purchaser, and consumer concerns about human rights abuses to heighten public pressure on named companies to motivate, or shame, them into rooting out socially unacceptable practices [23]. Dodd-Frank's strategy rests on three premises: (1) by increasing public awareness about conflict minerals; and (2) requiring manufacturers to implement due diligence practices; then, (3) the use of conflict minerals from the DRC and its adjoining neighbors will diminish, thereby impairing the funding of armed conflicts [24]. Therefore, without public transparency as a requisite, the foundation for achieving Section 1502 objectives is dismantled.

Within two months of the Conflict Minerals Rule's final promulgation, manufacturing industry representatives and the U.S. Chamber of Commerce challenged the SEC rule on a variety of legal grounds. Over the course of litigation, the manufacturers narrowed their challenge to a constitutional First Amendment argument, which the D.C Circuit Court of Appeals, eventually, decided. In August 2015, the majority on a three-judge panel held in *National Association of Manufacturers v. Securities Exchange Commission* that a rule requiring issuers to publish on their company websites that their products were not "DRC Conflict free" violated corporations' First Amendment rights against compelled commercial speech.

The court reasoned that the SEC was unable to show that a "forced disclosure regime will decrease the revenue of armed groups in the DRC and [that] their loss of revenue will end or at least diminish the humanitarian crisis there" [25]. Citing the principle that in commercial speech cases the government's interest in compelling speech "cannot rest on 'speculation or conjecture,'" [26] the court dismissed the idea linking disclosure to reduced armed conflict as "entirely unproven" and resting "on pure speculation" [27].

The majority then considered a second basis for finding that the SEC's Final Rule violated the First Amendment. Compelled disclosures must be "purely factual" and "uncontroversial" information [28]. The court opined that requiring regulated companies to disclose on their websites that a product was not "DRC conflict free" metaphorically "conveys moral responsibility for the Congo war" [29]. Requiring issuers to inform consumers that its products were "ethically tainted, even if they only indirectly finance armed groups," was forcing an issuer to "confess blood on its hands" [30]. With this analysis, the court struck down as unconstitutional the requirement that regulated entities report to the SEC and declare on their website that any of their products were not "DRC conflict free" [31].

The court's ruling left in place the rest of the Conflict Minerals Rule. Thereafter, the SEC reconsidered the rule's implementation [32]. By 7 April 2017, the SEC issued a public statement that staff would not undertake enforcement actions against companies that failed to complete an independently audited Conflict Minerals Report [33]. Instead, an independent private sector audit is required only for a reporting company that voluntarily claims that its products are "DRC conflict-free" [34]. In an odd twist that lightly grazes Section 1502 goals, issuers are subject to disclosing and making publicly available on their websites their unaudited reasonable country of origin inquiry only for conflict minerals that they determined either did not originate in a covered country, or that originated from recycled or scrap sources [35].

3 Dodd-Frank Section 1502 Implementation and Findings

In 2016, Schwartz conducted an empirical review of over 1,300 Dodd-Frank Section 1502 corporate disclosures [36]. Schwartz found that far fewer companies needed to file reports than the SEC originally estimated, and those that filed complied "in a largely superficial manner suggestive of minimal effort" [37]. Schwartz observes that the filings did not contain enough information about the conflict minerals supply chain for the law to operate as intended. Importantly, Schwartz contends that "[t]he overarching problem with the reports is that reading them does not provide insight into which companies ought to be praised and which condemned" [38]. Therefore, as a "naming and shaming" law, Section 1502 notably misses the mark.

Schwartz points to several structural issues. Most reporting companies are using simple supplier surveys to conduct their country of origin inquiry [39]. Therefore, suppliers must be willing to cooperate. However, a "name and shame" law disincentives suppliers, especially those engaged in wrongful conduct, from making relevant information easy to obtain [40]. Additionally, Section 1502 provides minimal penalties for companies that fail to comply or that are evasive [41]. Further, lack of clear SEC guidance to manufacturers resulted in "muddled, redundant" reports that were difficult to compare [42]. Finally, companies interpreted the final rule's language to maximise opacity and frustrate the goal of transparency [43].

The Responsible Sourcing Network (RSN), a project dedicated to ending human rights abuses associated with everyday products, also has analysed Section 1502 corporate compliance, and companies' 3TG due diligence activities and public reporting. In its 2019 annual review, RSN reports that company due diligence "falls short from the intent of the law and the expectations of stakeholders" [44]. Average compliance scores in 2019 declined, which RSN noted showed "the lack of efforts of a large number of companies" [45]. RSN also noticed another "new and concerning trend" [46]. Companies were providing to the SEC the exact same disclosures from the year before [47]. RSC described this trend as "disconcerting" because it demonstrates "a blatant disregard to implement U.S. federal legislation" and that 3TG due diligence has diminished as a corporate concern [48].

The most recent U.S. Government Accountability Office's (GAO) review of the Conflict Minerals Rule's performance, issued in September 2019, shows little change from prior years' reporting. GAO reports that the 1,117 conflict minerals disclosures filed with the SEC in 2018 were similar in number and content to those filed in the prior two years [49]. Of these reporting companies, GAO's sampling methodology indicates that almost 100 percent of the companies that filed conflict minerals disclosures in 2016 through 2018 reported having conducted countries of origin inquiries [50]. Of the companies in 2018 that conducted countries of origin inquiries, an estimated 56 percent reported on whether the minerals in their products came from covered countries—a slight increase over 2017 (53 percent) [51]. However, many companies reported difficulty in determining conflict minerals' country of origin, in part because of a lack of access to suppliers within complex chains that involve many suppliers and processing facilities [52].

Almost all reporting companies in 2018, an estimated 94 percent, had conducted their required due diligence inquiries [53]. Having conducted these inquiries, 35 percent of the companies reported that they were able to determine that their conflict minerals originated in covered countries or from recycled or scrap sources [54]. Yet, some 61 percent of the reporting companies could not definitively confirm the source of the conflict minerals in their products [55].

Importantly, regarding the legislation's impact on advancing its stated policy aim to reduce conflict minerals fueled violence, the GAO report provides no analysis. Data from the United Nations shows that violence worsened in the DRC between 2016 and 2019 during the lead-up to presidential elections [56]. International Peace Information Service (IPIS), an independent research institute, reports: "Despite significant growth and investment in minerals certification and traceability programmes, data on the impact of due diligence for miners and communities remains scarce" [57].

4 European Union Conflict Minerals Legislation

The European Union (EU) adopted the final text of its conflict minerals regulation ("EU Regulation") on 17 May 2017 [58]. As one reason for this legislation, and within its recitals, the EU Regulation references European Parliament resolutions that called for the EU to "legislate along the lines of the US law on conflict minerals, [Dodd-Frank] Section 1502…" [59]. Like Section 1502, the EU Regulation relies on heightening public concerns about human rights abuses by requiring supply chain due diligence and public disclosure. However, unlike Section 1502, the EU Regulation establishes a *de minimis* threshold below which 3TG conflict minerals are exempt [60]. These minimum thresholds are set to regulate at least 95 percent of the 3TG imported into the EU [61]. Also exempt are stocks existing prior to 1 February 2013 [62], and recycled metals, which are subject to public disclosure requirements only [63].

The EU Regulation, which came into force on 8 June 2017, takes full effect on 1 January 2021. The legislation requires importers of 3TG into the EU to implement supply chain “due diligence” requirements [64] in alignment with the Organisation for Economic Cooperation and Development (OECD) Due Diligence Guidance [65]. The regulatory scope applies only to upstream companies which, according to human rights researchers at the Business & Human Rights Resource Centre, captures smelters, refiners, traders, banks, and manufacturers that import these minerals and metals into the EU [66]. EU companies downstream, which includes dealers and manufacturers, are encouraged to make voluntary disclosures [67] but are only subject to the legislation if directly importing a 3TG metal [68]. Therefore, if an imported product or component already contains 3TG, such as a computer chip or mobile phone, it is not subject to the EU Regulation [69]. The European Commission estimates that the Regulation will directly affect between 600 and 1,000 EU importers and indirectly about 500 smelters and refiners of 3TG, whether EU based or not [70]. Member States are responsible for enforcing the EU Regulation’s requirements [71].

Importer due diligence obligations include: establishing management systems [72]; conducting 3TG source inquiries [73]; identifying and addressing risks linked to conflict-affected and high-risk areas to reduce the adverse impacts of sourcing activities [74]; independent third party audits of supply chains [75]; and making certain disclosures [76]. The EU Regulation’s disclosure scheme goes beyond Dodd-Frank’s Section 1502. An importer’s annual public disclosure duties includes reporting on their website their supply chain due diligence policies and practices for responsible sourcing, the steps taken to implement their regulatory obligations, a summary of their third-party audits, and whether the importer can “reasonably conclude” that their metals are derived only from recycled or scrap sources [77]. Surpassing Section 1502 disclosures, the importer has additional obligations to “make available to their immediate downstream purchasers all information gained and maintained pursuant to their supply chain due diligence with due regard for business confidentiality and other competitive concerns” [78].

Because 3TG can be in mineral or metal forms, the Regulation covers both importers who supply ores or unrefined minerals to EU smelters, and refiners or importers who import 3TG metals processed outside the EU [79]. The EU Regulation identifies the important role smelters and refiners play in the global mineral supply chain as they are "typically the last stage in which due diligence can effectively be assured by collecting, disclosing and verifying information on the mineral's origin and chain of custody" [80]. After metals transformation, it becomes unfeasible to trace the origins of minerals. Therefore, the EU Regulation empowers the Commission to adopt and implement acts to establish a “list of global responsible smelters and refiners” [81].

5 Assessing Section 1502

Dodd-Frank Section 1502 has been sharply criticised. Woody argues that the law was “ill-conceived in substance and form” [82]. She points to three key reasons. First, Section 1502 represented “an unmitigated extension” of securities law disclosure rules “to pursue a foreign policy goal” [83]. Second, the law was purported to have led to “global arbitrage in the world market for minerals and a de facto embargo by the United States” [84]. Supposedly, companies were reluctant to source minerals in the region for fear of not being able to confirm the minerals origin [85]. This de facto embargo, purportedly, then resulted in job losses and increased poverty, which harmed the DRC people and led to regional social-economic instability, but did not curtail the international and black markets for minerals or reduce the demand for illicit products [86]. Third, in terms of rule of law, Section 1502 was “doomed” because “there was no penalty attached to the use of conflict minerals” [87]. Other critics note that the legislation consumed significant SEC resources in rulemaking and litigation and created private sector confusion [88]. U.S. industry claimed that Section 1502 implementation was costly and burdensome [89].

Some of these criticisms have been challenged. The claims of a *de facto* embargo have been contested, and disclosures filed in 2013 pursuant to Section 1502 counter the notion that U.S. companies are leaving the DRC [90]. The legislation’s high compliance cost has, likewise, been challenged. Schwartz’s empirical analysis shows that most companies had “little cost” and the burden was “relatively insubstantial” to comply with Section 1502 [91]. Paradoxically, despite its flaws and detractors, Section 1502 does appear to have achieved its aim of influencing human rights’ advancement. The Act’s mere existence raised public awareness for conflict minerals and their link to human rights, caused normative shifts in company behaviors and consumer expectations, and catalysed other legislation, including the EU Regulation [92].

6 Dodd-Frank, Section 1502 — Lessons Learned

Whether seen as a policy failure, or not, the U.S. experience with its Conflict Minerals Rule has already provided valuable lessons for EU policymakers. According to Koch and Burlyuk, key advocates learned from the U.S. Conflict Minerals Rule's "unintended consequences" [93]. Consequently, advocate pressure resulted in the EU Regulation differing from Section 1502 in four primary ways: 1) geographic scope; 2) range of applicability to companies; 3) compliance versus a risk-based approach; and 4) enforceability [94]. Whether the EU Regulation will prove to be effective in achieving its stated purpose of reducing armed conflicts funded by minerals is a question for the future. However, as promulgated, the EU Regulation both broadens and narrows the regulatory scope from that covered by the U.S. Conflict Minerals Rule.

First, the EU Regulation's geographic scope is more expansive. Dodd-Frank Section 1502 applies only to the DRC and neighbouring countries. By contrast, the EU Regulation applies to any "conflict-affected and high-risk areas," defined as "areas in a state of armed conflict or fragile post-conflict as well as areas witnessing weak or non-existent governance and security, such as failed states, and widespread and systematic violations of international law, including human rights abuses" [95].

Second, the EU Regulation narrowed the set of covered companies. The U.S. rule applies to any domestic or foreign publicly listed companies in which the use of conflict minerals is necessary to the functionality or production of their product. The EU Regulation, by contrast, is constrained to 3TG importers into the EU, and smelters and refiners that process 3TG from conflict-affected and high-risk areas. Therefore, downstream manufacturers and sellers are eliminated from the EU legislation's scope.

Third, the EU Regulation avoids, altogether, the U.S. rule's experience with attempting to mandate manufacturer disclosure on products that were not found to be "DRC Conflict free." Instead the EU Regulation requires covered companies to show due diligence by implementing the OECD-recommended risk management approach for minerals sourced from conflict-affected and high-risk areas, and then publicly disclosing their due diligence policies and practices. Finally, as previously noted, whereas the U.S. rule did not recognise a *de minimis* level that exempts manufacturers from compliance, the EU Regulation does exempt importers that are below a specified threshold.

There are other areas where the U.S experience with Section 1502 can inform the EU. As discussed, Section 1502 was not actually enforced. As a result, companies' compliance with the U.S. law has waned and increased company due diligence and transparency has suffered. Therefore, for the EU to safeguard its due diligence and transparency framework and incentivise compliance, each Member State should carefully consider what agency within their government is most appropriate to effectively enforce the EU Regulation. Member States should work together to implement enforcement activities evenly and consistently across the EU. Member States should also work together to develop clear, standardised guidance and reporting formats to minimise confusion, compliance costs, and the reporting burden for companies subject to the legislation.

Finally, for the EU Regulation's scheme to be credible, third party auditors certifying companies to the requirements must perform their work scrupulously. If verification audits are deemed suspect, stakeholder confidence and, thereby, the legislative scheme, will be undermined. A review of the disclosure performance of 3TG smelters or refiners (SORs) by Development International (DI), a nonprofit global development organisation, highlights this danger [96]. DI's report concludes: "…the [SORs] audit results presented to stakeholders have the appearance of full conformance on industry standards, even where the required due diligence standards are in large part absent. It is critical that verified SORS implement the standards in their entirety (including the disclosure requirements) or else not be awarded verification" [97].

Furthermore, lack of public disclosure generates "additional questions about the existence, thoroughness, and effectiveness of the SORs' own due diligence programs" [98]. Therefore, as this example shows, to maintain stakeholder confidence, it will be in the best interest of a 3TG supply chain to encourage due diligence, public disclosure, and verification integrity.

7 Conclusion

The U.S. experience with using securities law to address conflict minerals and their link to human rights abuses in the DRC, and neighbouring countries, is sharply criticised by its detractors as both flawed and a policy failure. Objectively, the effectiveness of Dodd-Frank Section 1502 in reducing armed conflict and violence in the DRC region cannot be shown. However, in at least one regard Section 1502 is a clear policy success. Section 1502 catalysed similar actions, including the European Regulation, aimed at curtailing the regional violence. Thus, Section 1502 established normative expectations that companies will pursue due diligence in sourcing conflict minerals and publicly disclose their efforts.

Although the EU Regulation was crafted to avoid Section 1502's major pitfalls, additional lessons from the U.S. experience still lie ahead. As such, implementation of the EU Regulation will benefit from consistent enforcement, clear and standardised guidance for regulated companies, and the credible validation of companies' due diligence and disclosure activities. Importantly, companies that issue transparent and reliable public disclosures that reflect accurate, timely, and verifiable information show that they are exercising due diligence and continuous improvement earnestly to, thereby, safeguard stakeholder confidence.

8 Literature

[1] Jena Martin, "Hiding in the Light: The Misuse of Disclosure to Advance the Business and Human Rights Agenda," 56 Colum. J. Transnat'l L., p. 537, 2017.

[2] Public Law No: 111-203 (07/21/2010).

[3] Marcia Narine, "From Kansas to the Congo: Why Naming and Shaming Corporations through the Dodd-Frank Act's Corporate Governance Disclosure Won't Solve a Human Rights Crisis," 25 Regent U.L. Rev., p. 538, 2012-2013.

[4] Defined as "…a country that shares an internationally recognized border with the Democratic Republic of the Congo [DRC]." Section 1502 (e). "Covered countries" include the DRC, Angola, Burundi, Central African Republic, the Republic of the Congo, Rwanda, South Sudan, Tanzania, Uganda, and Zambia.

[5] *See* Sabrina Reyes, "Conflict Free DRC," 17 Santa Clara J. Int'l L., pp. 2, 5-9, Feb. 6, 2019. Discussing the history of the DRC's violence.

[6] Conflict Minerals, SEC, 17 CFR pts. 240-249b, p. 8, Aug. 22, 2012. [Online] Available: https://www.sec.gov/rules/final/2012/34-67716.pdf.

[7] 15 U.S.C. 78m.

[8] Sec. 1502 (b) [amending 15 U.S.C. 78m by adding subsection (p)].

[9] *Id.* [amending 15 U.S.C. 78m by adding subsection (p)(2)(B)].

[10] *See* 77 Fed. Reg. 56275, fn. 6, and 56285, Sep. 12, 2012. [Online] Available: https://www.federalregister.gov/documents/2012/09/12/2012-21153/conflict-minerals.

[11] *Id.* at 56287.

[12] *Id.* at 56298.

[13] *Id.* at 56299.

[14] *Id.* at 56312.

[15] *Id.* at 56333.

[16] *Id.* at 56320. Conflict minerals from recycled or scrap sources have alternative due diligence and reporting requirements. *See Id.* at 56313.

[17] *See* Exchange Act Section 13(p)(1)(A)(i). *See also, Conflict Minerals*, SEC, 17 CFR pts. 240-249b, p. 10, Aug. 22, 2012. [Online] Available: https://www.sec.gov/rules/final/2012/34-67716.pdf.

[18] *See id.* [requiring in the Conflict Minerals Report a description of the due diligence measures taken on the source and chain of custody of conflict minerals, including independent private sector audit of the report]. For established standards, *see,* for example, Organisation for Economic Co-operation and Development, "OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas," 3rd ed., OECD Publishing, Paris, 2016, [Online]. Available: http://dx.doi.org/10.1787/9789264252479-en [hereinafter "OECD Due Diligence Guidance"].

[19] The SEC determined that "DRC conflict free" refers only to "conflict minerals" defined in Dodd-Frank, Section 1502(e)(4). *See* SEC, "Conflict Minerals,"17 CFR pts. 240-249b, p. 11, fn 25, Aug. 22, 2012. [Online]. Available: https://www.sec.gov/rules/final/2012/34-67716.pdf [hereinafter "SEC, Conflict Minerals"]. The Final Conflict Minerals Rule defined "DRC conflict free" as a product that "does not contain conflict minerals necessary to the functionality or production of that product that directly or indirectly finance or benefit armed groups" in the DRC or an adjoining country. Conflict minerals from recycled or scrap sources are considered "DRC conflict free." 77 Fed. Reg. 56364, Sep. 12, 2012.

[20] *See* Exchange Act, Section 13(p)(1)(A)(ii).

[21] SEC, Conflict Minerals *supra* note 19.

[22] *See* Exchange Act Section 13(p)(1)(E) (stating that each issuer "shall make available to the public on the Internet website of such [issuer] the information disclosed under" Exchange Act Section 13(p)(1)(A)).

[23] *See*, for example, Kevin Kolben, "The Consumer Imaginary: Labor Rights, Human Rights, and Citizen-Consumers in the Global Supply Chain," 52 Vand. J. Transnat'l L., p. 839, Oct. 2019.

[24] Sabrina Reyes, Conflict Free DRC, 17 Santa Clara J. Int'l L., pp. 2, 20, Feb. 6, 2019 [citing "Understanding Conflict Minerals Provisions," Enough Project, Aug. 8, 2010. [Online]. Available: https://enoughproject.org/one-pager/understanding-conflict-minerals-provisions.

[25] National Ass'n of Manufacturers v. S.E.C., 800 F. 3d, p. 526, 2015.

[26] *Id. at* 527 [citing Edenfield v. Fane, 507 U.S. 761, 770 (1993)].

[27] *Id. at 526.*

[28] *Id.*

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[30] *Id.*

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[32] Acting Chairman Michael S. Piwowar, Reconsideration of Conflict Minerals Rule Implementation, Jan. 31, 2017. [Online]. Available: https://www.sec.gov/news/statement/reconsideration-of-conflict-minerals-rule-implementation.html.

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[34] *See* SEC, Dodd-Frank Wall Street Reform and Consumer Protection Act, Frequently Asked Questions, Conflict Minerals, Question 15. [To qualify products as "DRC conflict free," an issuer must obtain an Independent Private Sector Audit] [Online]. Available*:* https://www.sec.gov/divisions/corpfin/guidance/conflictminerals-faq.htm.

[35] SEC Division of Corporation Finance, Updated Statement on the Effect of the Court of Appeals Decision on the Conflict Minerals Rule, Apr.7, 2017. [Online] Available: https://www.sec.gov/news/public-statement/corpfin-updated-statement-court-decision-conflict-minerals-rule. [Requiring disclosures only under the provisions of Form SD Item 1.01 (a) and (b), and not (c)].

[36] Jeff Schwartz, "The Conflict Minerals Experiment," 6 Harv. Bus. L. Rev., p. 129 (2016).

[37] *Id.*

[38] *Id.*

[39] *Id.* at 132.

[40] *Id.* at 161.

[41] *Id.* at 162-163.

[42] *Id.* at 164.

[43] *Id.* at 165.

[44] Responsible Sourcing Network, Mining the Disclosures 2019: An Investor Guide to Conflict Minerals and Cobalt Reporting in Year Six, p. 4, 2019.

[45] *Id.*

[46] *Id.*

[47] *Id.*

[48] *Id.*

[49] U.S. GAO, Report to Congressional Committees, Conflict Minerals, 2018 Company Reports on Mineral Sources Were Similar in Number and Content to Those Filed in the Prior 2 Years, p. 9, Sept. 2019 (GAO-19-607).

[50] *Id.* at 10.

[51] *Id.*

[52] *Id.* at 11.

[53] *Id.* at 12. Of these, an estimated 89 percent used the OECD Due Diligence Guidance to determine the source and chain of custody of the conflict minerals in their products. *Id. See* OECD Due Diligence Guidance *supra* note 18.

[54] *Id.*

[55] *Id.*

[56] *Id.* at 20-21.

[57] IPIS, Assessing the Impact of Due Diligence Programmes in Eastern DRC: A Baseline Study, p. 5, Apr. 2019. [Online] Available: https://www.academia.edu/39602450/ASSESSING_THE_IMPA

CT_OF_DUE_DILIGENCE_PROGRAMMES_IN_EASTERN_DRC_A_BASELINE_STUDY.

[58] EU Regulation (EU) 2017/821 of the European Parliament and of the Council of 17 May 2017 laying down supply chain due diligence obligations for Union importers of tin, tantalum and tungsten, their ores, and gold originating from conflict-affected and high-risk areas [hereinafter "EU Regulation"].

[59] *Id.* at Recital 9.

[60] *Id.* at Art. 1 (3).

[61] *Id.*

[62] *Id.* at Art. 1 (7).

[63] *Id.* at Art. 1 (6).

[64] *Id.* at Art. 1 (2).

[65] *See*, for example, *Id.* at Recital 4, 14, 16, Art. 5(1)(a), 5(1)(b)(ii), 5(3), 5(4). *See* supra note 18 for OECD Guidance.

[66] Business and Human Rights Resource Centre, Advice Note to Companies, Member States, and the European Commission: Implementation of the EU Regulation, p. 4, Mar. 2018.

[67] The EU Commission is launching a platform where downstream companies can voluntarily share information on their due diligence activities. *See* European Commission, Combating Conflict Minerals, at https://ec.europa.eu/trade/policy/in-focus/conflict-minerals-regulation/.

[68] European Commission, Directorate-General for Trade, Conflict minerals, the regulation explained [hereinafter "Conflict Minerals Explained"], "Why are there different requirements for different companies?" [Online]. Available: https://ec.europa.eu/trade/policy/in-focus/conflict-minerals-regulation/regulation-explained/index_en.htm.

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[70] Conflict Minerals Explained, *supra* note 68, "How many companies does the regulation affect?"

[71] EU Regulation, Art. 10 (3), Art. 16.

[72] *Id.* at Art. 4.

[73] *Id.* at Art. 4 (f).

[74] *Id.* at Art. 2 (d), Art. 5.

[75] *Id.* at Art. 6.

[76] *Id.* at Art. 7.

[77] *Id.* at Art. 7 (3), (4).

[78] *Id.* at Art. 7 (2).

[79] *Id.* at Recital 17; Art.1 (1).

[80] *Id.* at Recital 16.

[81] *Id.* at Art. 9.

[82] Karen E. Woody, "Can Bad Law Do Good? A Retrospective on Conflict Minerals Regulation," 78 Md. L. Rev., 291 (2019).

[83] *Id.* at 302-303.

[84] *Id.* at 303.

[85] The Unintended Consequences of Dodd-Frank's Conflict Minerals Provision, Hearing Before the Subcomm. on Monetary Policy and Trade of the House Comm. on Financial Services, 113th Cong., pp. 4, 6, 11 (2013) [hereinafter "Unintended Consequences"].

[86] *Id.* at 11; Woody, *supra* note 82 at 308-309.

[87] Woody, *supra* note 82 at 303, 310-311.

[88] Harold S. Bloomenthal and Samuel Wolf, 3 Sec. & Fed. Corp. Law, Sec. 1:615, 2d ed., Dec. 2019.

[89] Unintended Consequences *supra* note 85.

[90] Schwartz, *supra* note 36 at 171-172.

[91] *Id.* at 131, 141-142, 158.

[92] Woody, *supra* note 82 at 318-321.

[93] Dirk-Jan Koch & Olga Burlyuk, "Bounded policy learning? EU efforts to anticipate unintended consequences in conflict minerals legislation," Journal of European Public Policy, p. 18, 2019, DOI: 10.1080/13501763.2019.1675744.

[94] *Id.* at 1-2.

[95] EU Regulation, Art. 2 (f).

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[97] *Id.* at 2.

[98] *Id.*

Products, Technologies, and Normative Requirements for Recycling of Valuable and Critical Raw Materials

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Abstract

Recycling rates of most critical raw materials (CRMs) as defined by the EU are close to zero, while the demand for many CRMs is growing in various sectors. the recycling contribution is largely insufficient to meet the demand.[1] Recycling is considered a risk-reducing measure.[2] The EU-funded H2020 project CEWASTE (www.cewaste.eu) contributes to improve the recycling rates of CRMs from e-waste and batteries by producing and pilot testing requirements for collection, transport and treatment of products containing sufficiently high concentrations and amounts of critical raw materials. In a first step, these products – the Key CRM Equipment (KCE) – were identified, and current normative requirements analyzed for stipulations that could be referenced. This paper describes the approaches and results of these activities, which form the base for the development of KCE-specific CEWASTE-requirements (c.f. paper of Sonia Valdivia, World Resources Forum, "Sound recycling and transboundary movements of WEEE containing critical raw materials - CEWASTE Requirements"). To enable certifications of operators working according to these requirements, an assurance and verification system will be created (c.f. paper "CEWASTE Assurance and Verification System for the certification of waste management operators with CRM focused requirements" of Yifaat Baron, Oekoinstitut). This system and the requirements will be pilot tested with several treatment operators (ongoing) and then be finalized taking into account the collected experiences.

1 Introduction

The 2017 EU-list of critical raw materials (CRMs) includes 27 materials. [2] Their recycling rates from waste products are, however, low. [1] Since recycling is one approach to mitigate the criticality of CRMs, the CEWASTE project aspires setting up and establishing requirements for a standard and a verification system for the collection, transport and treatment of products containing CRMs to enable their recycling and to create a level-playing field for the operators along the end-of-life (EoL) chain. At the same time, the requirements shall – besides the recycling of palladium listed as CRM – also improve the recycling of other valuable materials.

2 Product scope and selection of waste products for CRM recycling

The volumes of electrical and electronic equipment (EEE), waste batteries from EEE and end-of-life vehicles (ELVs), and engines of electrical ELVs are growing rapidly, and it is foreseeable that this trend continues. At the same time, these products use many CRMs while the recycling rates are very low. E-waste, waste batteries and engines of electrical vehicles were therefore selected to further evaluate from which from those devices and their components recycling of CRMs might be feasible. For the evaluation, the consortium set up conditions which waste products have to meet in order to qualify as Key-CRM-Equipment (KCE).

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2.1 Criteria for KCE

Waste products need to match with the following criteria to qualify as KCE:

1. The final treatment must be technically feasible. This is considered to be the case if a processing technology has achieved a (technology readiness level (TRL) [3] of at least 7) so that an adequate industrial scale final treatment is possible already or verifiable in the near future.
2. Collectors and pre-treatment operators must be able to provide the input which the end treatment processes require for the recycling of the CRMs. In most cases, this will imply that the pre-treatment, with support from collectors e.g. by sorting of KCE, yields a fraction with sufficiently high concentrations of CRMs in a form from which the end treatment operator can recycle CRMs.
3. The product or at least one component (CRM source component) contains relevant concentrations and amounts of CRMs. If CRMs are concentrated in components, they can be separated from the KCE prior to further pre-treatment steps to avoid CRM dilution and to maintain or achieve a sufficient concentration which enables the CRM recycling in the final treatment.
4. The economic feasibility under the current economic framework conditions is no obligatory criterion to be met since economic conditions can be changed. Prior to the enactment of the WEEE Directive, for example, the sound treatment and disposal of e-waste was economically not feasible in many cases. The WEEE Directive ensured the proper financing by introducing the extended producer responsibility (EPR) thus installing a stable financing mechanism. Increasing the recycling rates of CRMs will require political decisions improving the economic conditions of collection, transport and treatment of KCE if recycling of CRMS shall actually be achieved.
5. Despite of the above criteria no. 3. and 4. , CRM-containing products must have relevant concentrations and contents of CRMs to keep a reasonable balance between benefits and efforts/costs for CRM recycling. E-waste with very small CRM-containing components which have to be separated from a printed circuit board (PCB) to enable the recycling of the small CRM content therefore cannot qualify as KCE as long as it causes excessive costs to obtain tiny amounts of CRM. E-waste containing tantalum in capacitors could, for example, not qualify as KCE for this reason.
6. CRM recycling shall not be conflicting with precious metal (PM) recycling. PMs are the economic backbone of the e-waste recycling business, and they generally have a huge environmental backpack affecting the overall environmental impact of EEE and other products.[4] Sacrificing PMs for the sake of CRM recycling thus would be an economically and ecologically questionable decision. The case of tantalum capacitors exemplarily can illustrate the economic situation and the conflict with PM recycling. PCBs may contain very small tantalum capacitors as well as relevant contents of PMs (gold, silver). Tantalum and PMs require different final treatment processes to enable their recycling. Tantalum recycling would thus be possible if the entire PCB went into tantalum recycling resulting in the loss of the PMs. An alternative scenario would be separating the tantalum capacitors from the PCB. This alternative was found to be inadequate due to the economic imbalance of the separation efforts on the one hand and the very small yield of tantalum on the other hand at the current state of technolgy. PCBs with tantalum capacitors therefore could not qualify as KCE/source component for tantalum.

2.2 Key CRM Equipment

For the CRM concentrations and contents in the selected product groups, the consortium could revert on data from the ProSUM [5] and SCRREEN [6] projects as well as the database of Umicore Precious Metal Recycling.

The below table 1 lists the KCE identified according to the above criteria and the CRMs in their source components.

Table 1: KCE and source components

Source Component	KCE	CRMs	Current Economic Feasibility
Fluorescent powders	Fluorescent lamps	Eu, Tb, Y, Ce, La	No
	CRT monitors and TVs	Y, Tb, Eu, Gd,La, Ce	
Nd-magnets	Temperature exchange equipment (compressor)	Nd, Pr, Dy, Gd, Tb	No
	Household appliances other than temperature exchange equipment (motors/drives)		
	Laptops (HDD)		
	Desktop Computers, prof. IT (HDD)		
	BEV, (P)HEV (electro engine)		
PCBs	Desktop computers, prof. IT	Au, Ag, Bi, Pd, Sb	Yes
	Laptops		
	Mobile phones		
	Tablets		
	External CDDs, ODDs, devices with internal CDDs/ODDs		
Screen	Mobile phones	In	Yes
Li-ion batteries	Laptops	Co	Yes
	Mobile phones		
	Tablets		
	Li-ion batteries in other WEEE		
	BEV, (P)HEV		
NiMH battery	NiMH batteries in WEEE	Co, (Ce, La, Nd, Pr)	Yes (Co) / No (REEs)
	HEV		
Lead acid batteries	Lead-acid batteries	Sb	Yes

2.3 Current KCE treatment practices and abilities

Recycling of palladium and other PMs from printed circuit boards is daily practice in e-waste treatment. Further, cobalt is recycled from lithium-ion batteries in industrial scale.

Recycling of fluorescent powders from fluorescent lamps had been practiced until 2016 before the operations were stopped for economic reasons. The price decrease of REEs after the peak in 2011 undermined the economic base of these recycling operations.[7] These past recycling activities prove, however, that the recycling of REEs from fluorescent powders is technically feasible with an established technology. Since the operations had been stopped, it could not be clarified whether the previously installed commercial REE recycling process would have been appropriate for CRT fluorescent powders as well. Another operator reports to run a plant which could process 400 t per year [8] of fluorescent powders from CRTs and from fluorescent lamps for REE recycling in case the financing would be ensured.

Different from other CRM-components, the TRL of NdFeB-magnet recycling is lower than 8. REE recycling from NdFeB-magnets thus is technically feasible, but the economic feasibility may be critical under the current economic conditions.

Hitachi Metals has developed a pyrometallurgical method in Japan using molten Mg as an extraction medium to recycle Nd and Dy from NdFeB-magnets. Santoku Corporation is said to have started in 2012 a recycling route for neodymium and dysprosium from magnets of air conditioner motors and magnet production scrap.[9] Details about the actual status of these processes are not available.

Another process for recycling of REEs from NdFeB-magnets is Momentum's hydrometallurgical MSX technology process. The MSX technology was reported to be capable of recycling more than 99 % of the rare earth content from HDDs dissolved in acid while operating at room temperature and pressure.[10] Finally, the Ames Laboratory acid-free dissolution recycling technology is described as having the potential to recycle Nd from shredded HDD samples without pre-concentration of the magnet contents, even though a pre-concentration is desirable to reduce the amounts of chemicals needed.[11] Both processes produce mixed REE-oxides, which are less favorable for NdFeB-magnet production than separated ones. Several EU-projects address recycling of REEs from magnets, e.g. REE4EU (pilot scale plant [12], REEcover [13], and others [14]).

Besides recycling REE from NdFeB-magnets, waste NdFeB-magnets can be used to produce new NdFeB-magnets. A US-based company claims to have commercialized its process for producing recycled sintered NdFeB-magnets with their patented Magnet-to-Magnet process [15]. In the EU, the SDS-process [16] (Shaping, Debinding and Sintering process), another process to produce new NdFeB-magnets from waste ones, was developed in the ReproMag [17] project. The development is being continued in the SusMagPro [18] project.

Further principle alternatives are the reuse of NdFeB-magnets from HDDs in applications others than HDDs, or the reuse of NdFeB-magnets from HDDs in newly produced HDDs.[19] HDDs are, at least in consumer products, more and more replaced by SDDs, which do not use NdFeB-magnets, but they still seem to have a future in the increasing numbers of datacenters around the world.[20, 21].

The CEWASTE consortium expects that the current technological status and ongoing development of recycling processes will soon allow industrial scale operations once the financing is secured and the feeds for these processes are available in sufficient volumes. The commercial application can be assumed to boost the development of recycling more effective and efficient recycling processes so that, in combination with competition in the market, the treatment of NdFeB-magnets may become cheaper over time.

3 Mapping and analyses of normative requirements

To avoid setting up requirements which are already established in other regulations, the consortium identified 55 normative requirements – mainly pieces of legislation and standards - with potential relevance for collection, transport, treatment and disposal of the KCE. Additionally, six verification schemes were found to be potentially useful for the setup of a CEWASTE verification scheme, or to take over the verification of the CEWASTE requirements. The 61 items were analysed for stipulations that could be referenced in the CEWASTE requirements document.

In order to qualify for further consideration, the verification schemes had to comply with the ISEAL principles and the ISO 17 000 series [22] since they represent the core values on which effective sustainability standards are built:

- Sustainability,
- Improvement,
- Relevance
- Rigour
- Engagement
- Impartiality
- Transparency
- Accessibility
- Truthfullness
- Efficiency

Each verification scheme has been contacted in order to assess whether they conform to the ISEAL principles and the CENELEC ISO/IEC 17 000:2004 standards. Three verification schemes have confirmed their compliance: EPEAT, WEEELABEX and JAZ-ANS, the organization who introduced the AS/NZS 5377:2013 standard in Australia and New Zealand.

The WEEE-, ELV- and Battery-Directives, and the CENELEC EN 50625 standards series are the most important normative requirements in the EU. Since the CEWASTE requirements shall also be pilot-tested outside the EU, non-European normative requirements like R2 and e-Stewards were included as well. While many environmental, health and safety as well as documentation and tracking requirements can be adopted from the analyzed normative requirements, in particular specific technical requirements for CRMs generally and for the KCE in particular are largely missing.

A large non-technical gap is the lacking financing of sound collection, and treatment of most KCE, which the EU has to fill if CRM recycling is to happen as one pillar of CE to mitigate CRM criticality.

Further details about the selection of KCE and the analysis of normative requirements are available in Deliverable D1.1 on the CEWASTE webpage.[23]

4 Outlook

The identified requirement gaps for the sound collection, storage, transport and treatment of the identified KCE have been filled in the past weeks, and the development of the assurance and verification system is under way. For further information c. f. the papers and presentations of Sonia Valdivia, World Resources Forum, et al. ("Sound recycling and transboundary movements of WEEE containing critical raw materials - CEWASTE Requirements"), and "CEWASTE Assurance and Verification System for the certification of waste management operators with CRM focused requirements" of Yifaat Baron, Oekoinstitut, et al.).

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The CEWASTE Assurance and Verification System for the Certification of Waste Management Operators with CRM Focused Requirements

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Abstract

Recycling rates of most critical raw materials (CRMs) as defined by the EU are close to zero, while at the same time recycling is considered as one mean to mitigate the criticality. The EU-funded H2020 project CEWASTE (www.cewaste.eu) contributes to improve the recycling rates of CRMs from e-waste and batteries by producing and pilot testing requirements for collection, transport and treatment of products containing sufficiently high concentrations and amounts of critical raw materials.

The project first looked at the current situation of CRMs contained in products, at the feasibility of their recovery from waste and at requirements that already support such recycling in existing standards [1]. On this basis requirements were then developed for actors of the EEE and battery waste management industry [2].

The assurance and verification scheme were developed, to provide the framework for certification of the compliance of the waste management value chain with the CEWASTE requirements. The assurance system specifies the rules and procedures to be followed by various actors involved with the implementation of the scheme. The verification system was developed to support the processes addressed in the assurance scheme, i.e. the auditing of facilities against the CEWASTE requirements, and preparation of operators for these audits.

1 Introduction

The 2017 EU-list of critical raw materials (CRMs) includes 27 materials. Their recycling rates from waste products are, however, low. Since recycling is one approach to mitigate the criticality of CRMs, the CEWASTE project aspires setting up and establishing requirements for a standard and an assurance and verification system for the collection, transport and treatment of products containing CRMs to enable their recycling and to create a level-playing field for the operators along the end-of-life (EoL) chain. At the same time, the requirements shall – besides the recycling of materials listed as CRM – also improve the recycling of other valuable materials.

The assurance and verification scheme were developed, to provide the framework for certification of the compliance of various actors with the CEWASTE requirements and are presented in the next sections.

2 The CEWASTE assurance system

The CEWASTE scheme is a voluntary third-party certification scheme and has been designed with the objective to contribute to the recovery of critical raw materials from key types of waste. It can be placed in a broader perspective where regional policies and legislative frameworks aim at promoting a circular economy and addressing sustainability challenges with a focus on waste streams from electrical and electronic equipment (EEE) and batteries.

A framework for the assurance system has been devised, specifying the rules and procedures to be followed. The assurance system details how the CEWASTE scheme is organised (who makes what decisions) and specifies rules for certification bodies and

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auditors involved in the performance and assessment of audits and in the decisions as to when a facility is compliant and can be certified. It also specifies rules as to the eligibility of individuals and/or organisations acting under certain roles in the scheme. For example, individuals acting on behalf of the scheme as auditors, organisations assuming the ownership or part of the management board, etc.). How such rules are to be updated from time to time and maintained is also addressed.

2.1 Standards for assurance systems of product standards

The development of this system required determining what processes the assurance scheme shall address (auditing, audit assessment and the general scheme rules), how these processes are to be performed and how their implementation is to be supported through various templates and guidance.

As a first step, the various principles addressed in the ISO 17000 series and in the ISEAL Assurance Code of Good Practice were consulted to ensure the assurance scheme would be in line with such frameworks, as a minimum in regard to consistency; rigor, competence, impartiality, transparency and accessibility.

This CEWASTE assurance system and scheme rules were developed according to the guidelines of the standard ISO/IEC 17067:2013 (Conformity assessment — Fundamentals of product certification and guidelines for product certification schemes), taking into consideration clause 6.5.1 which specifies elements to be included in a scheme:

- The scope of the scheme;
- Requirements against which relevant waste operators are to be certified;
- Requirements for certification bodies;
- Methods and procedures to be used by the conformity assessment bodies and in the certification process;
- Aspects related to the certification of conformity such as its content and how it can be used;
- Resources required for operating the scheme;

The requirements for Certifications Bodies (CB) were developed considering the essential requirements of the standard ISO/IEC 17065:2012, which specifies requirements for certification bodies certifying products, processes and services to be operational. ISO/IEC 17000:2004 on Conformity assessment (Vocabulary and general principles) was consulted and where relevant, terms and definitions therefrom were adopted to the CEWASTE scheme rules.

The ISEAL Assurance Code (ISEAL, 2018) specifies normative requirements for implementing an assurance system. The code applies specifically to assurance systems for assessing conformity with sustainability standards and related chain of custody standards. The ISEAL Credibility Principles provide the foundation for the normative sections of the Standard-Setting Code. The following principles are given as guidance for making decisions in unanticipated situations and have been taken into consideration in the system development: sustainability, improvement, relevance, rigour, engagement, impartiality, transparency, accessibility, truthfulness and efficiency.

2.2 The CEWASTE scheme rules

The *assurance system structure* includes various elements (scope, requirements, rules for its management, rules for certification bodies, rules for auditing and conformity assessment, etc.). Methods and procedures to be used by the individuals and organisations involved in the certification process, have been developed to assure the integrity and consistency of the outcome of the conformity assessment process. To ensure the conformity of facilities with the CEWASTE requirements, the assurance system operates on three levels, or processes:

- The CEWASTE certification scheme rules - these provide the general framework for the functioning of the certification scheme, including rules for registered CEWASTE Certification Bodies.
- The auditing process - here rules, templates and guidance's have been established to support the auditing of facilities that have applied for or hold a valid CEWASTE certification.
- The review process - here too, rules, templates and guidance's have been established to support the review of audit results and the certification decisions.

The *objective* of the CEWASTE assurance system is to contribute to an improved recovery of valuable and critical raw materials (CRMs) from key types of waste through traceable and sustainable treatment processes in the entire supply chain of secondary raw materials. This is addressed through assuring the compliance with the CEWASTE standard requirements, which aim on the one side at increasing the amounts of CRMS recovered and on the other side at ensuring that processes which contribute to the recovery of CRMs shall have a minimum level of sustainability.

The CEWASTE Scheme is *applicable* to the processes of collection, transport and treatment of waste electrical and electronic equipment and waste batteries.

The general *scope* of the CEWASTE scheme is defined in the CEWASTE certification requirements (the requirements against which conformity of operators is assessed). The scope of a specific certification is based on two dimensions:

- the type of facility being certified; and
- the waste fraction being handled.

The *CEWASTE requirements* are referred in the CEWASTE rules as the requirements against which facilities seeking certification are to be certified. Further information on the requirements is available in a separate paper and presentation ["Sound recycling and transboundary movements of WEEE containing critical raw materials - CEWASTE Requirements" – [2]). The CEWASTE rules prescribe an *update* of the requirements and their annexes, as a minimum every eight and every four years respectively. Additional *revisions* are to be initiated in the case that new materials are added to the European Union "Communication on the list of critical raw materials" [3]. Progress and respective changes in legislation or in the technical performance of the processes addressed through the CEWASTE standard are also to be considered for initiating a revision at earlier intervals. The scheme rules also foresee annual meetings of auditors to discuss different views as to the interpretation of requirements and the need for revision of the requirements or of the verification system to ensure a homogenous implementation.

The CEWASTE project and the voluntary certification scheme focus on the End-of-Life waste management of products, consisting of the following value chain actors: collection and logistics facilities, pre-treatment and recycling facilities.

The scheme currently refers to a scheme owner a management board and its members, and a technical advisory board and its members. For each of these, the rules detail the roles and responsibilities. The scheme details how it is to be maintained and implemented, and how and by whom decisions are to be made.

Requirements are included as to the *registration of Certifications Bodies* and the maintenance of the registration. It is also described how the scope of registration of a CB is to be determined and revised and how to proceed in the case that that the conditions of registration are no longer fulfilled, and the CB is to be suspended and withdrawn.

The eligibility of *auditors* and what skills they must have in order to be accepted to the pool of auditors is detailed. This is given in general for auditing of the CEWASTE requirements whereas specific conditions may apply for the auditing of some waste fractions (e.g., batteries).

The CEWASTE rules describe the certification process in detail, referring to the application for certification, its performance (audit) and assessment and the decision as to conformity and certification. The process is presented in Figure 1. Details are also given as to the process of changing the scope of an existing certification (extension or reduction) and grounds for certification withdrawal.

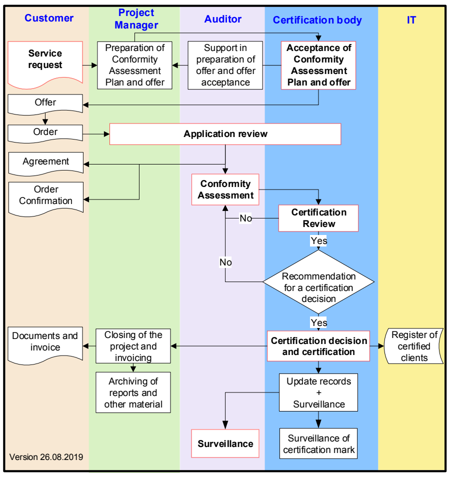

Figure 1: CEWASTE certification process flowchart

3 The CEWASTE verification system

In parallel to the assurance scheme, a verification system has been developed to support the processes addressed in the scheme rules. To support the auditing of facilities against the CEWASTE requirements, auditing templates and tools (check-list) have been developed to be used during audits. These are further accompanied by an Assurance manual for operators of the EEE and battery waste management sectors (providing guidance as to how to demonstrate compliance with the scheme requirements) and a Verification manual for auditors (providing additional background about the requirements to harmonize the assessment process).

To develop the verification system, existing verification systems of E-waste management facilities and raw material certification systems were analysed (e.g., WEEELABEX, SWICO, etc.). Such systems partly inspired the approaches adapted for verification of the CEWASTE requirements, particularly in relation to

CENELEC requirements included in the CEWASTE standard. Experience of auditors was also taken into consideration for deciding on specific aspects of the tools developed in this system.

The verification system includes templates and tools that have been designed to support the various procedures developed as part of the assurance system. Each of these is relevant at different phases of the certification process and addresses the various aspects of relevance at that stage. In general, certification includes a few stages as illustrated in Figure 2.

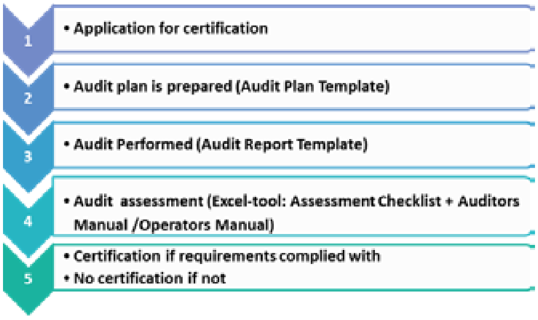

Figure 1: CEWASTE certification process flowchart

The CEWASTE *Audit Plan* template is to be used by auditors to plan the certification audit and makes clear for the operator which staff members are to be present in different stages of the audit and what facilities and activities are to be reviewed for conformity throughout the audit.

The CEWASTE *Audit Report* template is to be used by the auditor to document the audit and the assessment of conformity.

The *Audit Assessment tools* have been developed in excel format in relation to the "Assessment of Conformity" of facilities, i.e. their auditing. They integrate the CEWASTE requirements that are of relevance for the conformity assessment, namely, those on management and QHSE and those of relevance for collection and logistics and for treatment facilities. For each requirement, questions (for the auditor checklist) and explanatory texts (for the auditor and the operator manuals) have been included. The excel format allows both operators and auditors to "filter out" requirements that are not relevant for their facilities, for example based on waste stream fraction or based on value chain stage. This is possible through using the filtering option in the applicability columns (Operators; Type of Waste).

It is also possible to use the filter options to navigate to a specific requirement. The tool has been devised so that the requirement clause numbering and titles as well as the requirement text appear alongside the explanatory information that consists of the manual and thus it allows the user both to check the specifics of the requirement as well as to better understand its meaning or implementation and compliance aspects.

The tool has also been designed with different sheets so that requirements are allocated into two groups:

- Management – here requirements that deal with the management system of a facility and that address quality, health, safety and environmental aspects are located;
- Technical – here requirements are located that are related to the collection and transport of waste and that deal with pre-treatment, treatment and depollution.

The *tool for auditors* includes a checklist and a manual, which are merged to allow the auditor higher convenience in the use of the tool. The checklist has been developed to support the auditing and includes questions for each of the CEWASTE requirements. The auditor manual provides explanatory information and considerations of the assessment of conformity. Both can support the auditor during an audit through the provision of guidance information and clarification as to what level of performance is considered compliance and in what cases a major or minor non-conformity is to be identified. However, they are also useful for the preparation of audits and the final stage of assessing and deciding on the conformity of the requirements and the eligibility of the operator's facilities for certification.

The project team has consulted with the writers of the Handbook for Auditing the EN 50625 standard, which has been developed for the SWICO and the SENSerecycling Certification schemes [4]. The handbook has been used in the consideration of questions and explanatory information that is provided for some of the requirements in the checklist and the manuals.

The *assurance manual or operator tool* has been developed for operators that would like to certify their facilities (in whole or in part) against the CEWASTE requirements. It can also be used by operators that would like to gain a better understanding as to these requirements to consider certification in the future. Here, explanatory text and information are given for each requirement from the perspective of conformity of a facility. Aspects that the operator is to consider in preparing its facilities for certification and for the audit are detailed. This may refer to the type of documentation that is eligible as evidence of conformity in some cases, threshold levels in relation to measurable requirements, aspects that need to be addressed in management plans, etc.

The excel tools also contain general information as to the CEWASTE scheme and requirements, such as the structure of the requirements in focus of the audit, diagrams on the flow of CRM equipment, components and materials in relation to the CEWASTE requirements. A summary sheet provides the auditor with an overview of the non-conformities identified during the audit and thus assists in the final assessment and decision.

4 Outlook

The current version of the templates and tools is a work in progress. The CEWASTE requirements and the tools and templates are still to undergo a pilot stage, where their usability shall be tested in the course of performing pilot audits in several countries. Consultation with stakeholders is also planned, in line with the ISEAL Assurance Code of Good Practice. Thus a last revision is still planned for both the CEWASTE scheme rules and the templates and tools that have been developed with it.

For further information c.f. the papers and presentations of Otmar Deubzer, United Nations University SCYCLE, et al. ("Products, Technologies, and Normative Requirements for Recycling of Valuable and Critical Raw Materials") and of Sonia Valdivia, World Resources Forum, et al. ("Sound recycling and transboundary movements of WEEE containing critical raw materials - CEWASTE Requirements").

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Sound Recycling and Transboundary Movements of WEEE Containing Critical Raw Materials - CEWASTE Requirements

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Abstract

Recycling rates of most critical raw materials (CRMs) are close to zero. To close this gap, the Horizon 2020 CEWASTE project elaborates sustainability, managerial, technical and traceability requirements as part of a certification scheme for sound CRM recycling and transboundary movements of WEEE containing critical raw materials. The CEWASTE requirements were developed by taking the European Standards on Collection, Logistics and Treatment Requirements for WEEE (EN 50625-1 approved in 2017 by CENELEC (European Committee for Electrotechnical Standardization) as starting point as these provide most comprehensive guidance relevant for the purpose of the CEWASTE project [1]. Only where they were not sufficient to meet all CEWASTE objectives, new requirements were developed. These include technical requirements for final treatment of waste li-ion and lead-acid batteries, waste magnets and fluorescent powders; requirements for addressing health and environmental competences development, communication aspects as well as traceability requirements. Considering the international nature of the value chains and transboundary movements of wastes concerned, the Basel Convention was highlighted where required. CEWASTE requirements follow the principles of being technologically and economically feasible; focusing on optimal sorting and removal before treatment; promoting continuous improvement of CRM recycling practices supported by a management system; being auditable; and allowing traceability for WEEE with high environmental and social risks in value chains outside of Europe.
A strong stakeholder consultation resulted in about 300 comments received. A validation process through a pilot testing in about 20 companies from Europe, Turkey, Colombia and Rwanda supports the requirements development and their acceptance. A second online consultation will take place in early 2021 and the final version will serve the CEWASTE Certification and Verification Scheme [2].
The project's ambition is to provide a set of requirements that help improving the recycling of critical raw materials under sustainable conditions in international value chains.

1. Introduction

The 2017 EU-list of critical raw materials (CRMs) includes 27 materials [4]. Their recycling rates from waste products are, however, low. Since recycling is one approach to mitigate the criticality of CRMs, the CEWASTE project aspires setting up and establishing requirements for a standard and an assurance and verification system for the collection, transport and treatment of products containing CRMs to enable their recycling and to create a level-playing field for the operators along the end-of-life (EoL) chain. At the same time, the requirements shall – besides the recycling of materials listed as CRM – also improve the recycling of other valuable materials.

In order to increase the CRM and valuable materials recovery, relevant components (key CRM Components - KCC) from key equipment (key CRM equipment - KCE) are determined [5]. For the KCC, CEWASTE requirements were defined (or simply referred to) based on the European Standards on Collection, Logistics and Treatment Requirements for WEEE (EN 50625-1 approved in 2017 by CENELEC (European Committee for Electrotechnical Standardization), which is the most comprehensive set of standards available and relevant for the purpose of the CEWASTE project. Henceforth this set will be named CENELEC standards. The requirements development process followed a multi-stakeholder consultative based approach (see chapter 2). In the case of the following KCC no sufficient requirements were identified or there is none existing at all; hence, new

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guidance was developed: waste batteries, magnets, printed circuit boards and fluorescent powders.
Chapter 3 summarizes the sustainability, traceability, managerial and technical requirements.

2. The process and principles

2.1 Multi-stakeholder consultative process

The following events support the consultative process towards the CEWASTE requirements development in line with the ISEAL Code of Good Practice for sustainability standards development [3]:

- Two rounds of public online consultation. The first one from December 2019 to January 2020 and the second round in early 2021 for a duration of one month. 300 comments were received during the first consultation.
- A physical stakeholder meeting at the WRF 2019 Conference in Geneva (Oct, 2019).
- Pilot testing in about 20 companies from Europe, Turkey and Rwanda, Colombia between September and October 2020.

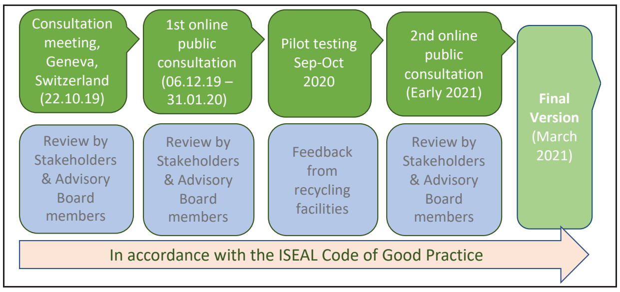

Figure 1: Stakeholder consultation process compliant with ISEAL

2.2 Principles

The CEWASTE requirements were developed based on the following principles:

- Technological and economic feasibility;
- Focus on optimal sorting and removal before pre- and final treatment
- Continuous improvement of CRM recycling practices through a management system
- Auditability
- Traceability for WEEE with high environmental and social risks in value chains outside of Europe such as waste batteries and printed circuit boards.

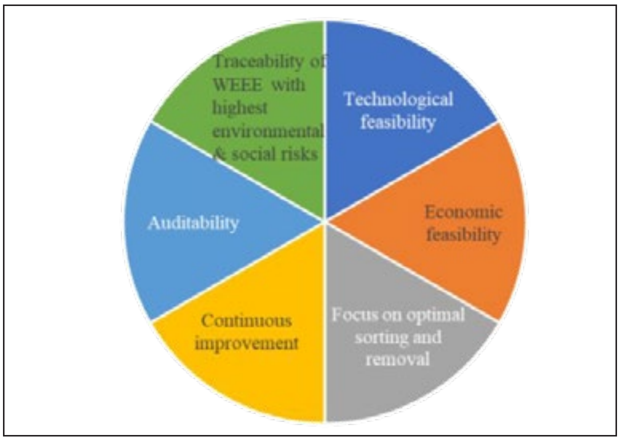

Figure 2: CEWASTE requirements principles

3. Managerial, sustainability and traceability requirements

The structure of the CEWASTE requirements document follows the structure of the CENELEC standards (see Figure 3).
The definitions clause makes reference to existing definitions and provides new ones in case needed (e.g. due diligence). The managerial, sustainability and traceability requirements are in clause 4 and technical requirements are presented in clause 5.
Complementary information is provided in the Annexes. In Annex I the list of KCE and CRM contained as well as main toxics in wastes is presented. Annex II introduces an example of a monitoring an evaluation plan in support of the management system. Annexes III to VI refer to technological options for treating waste batteries, magnets and fluorescent powders.

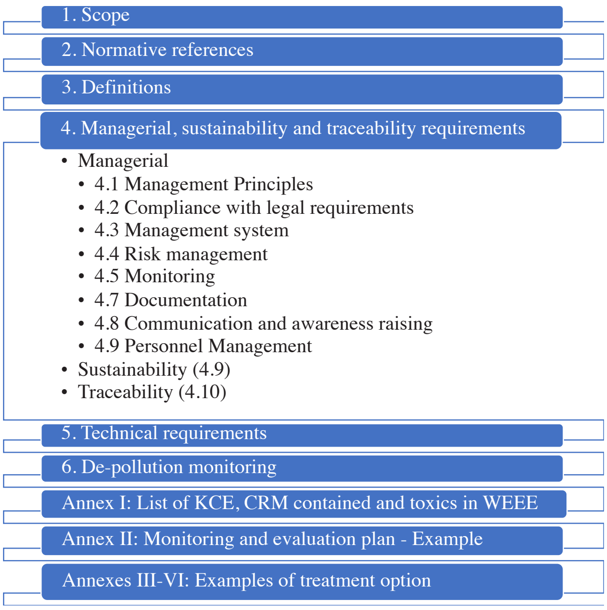

Figure 3: CEWASTE requirements – Structure

Main gaps identified include technical requirements for increasing the recovery of CRM from fluorescent

powders, printed circuit boards (PCBs), batteries and magnets.
It is worthwhile to note that the re-use phase is not part of the CEWASTE scope.

3.1 Managerial aspects

Aiming at developing and continuously improving the management system of operating facilities, collection and logistics facilities, treatment and final treatment operators shall comply with clauses 4.1 to 4.5 and 4.7 to 4.9 related to 'managerial requirements' (Figure 3). An example of a monitoring and evaluation plan is in Figure 4 (parts 1 and 2).

Key performance Indicator	Definition	Actions / Responsibilities
Objective 2.1 Increasing CRM recovery		
% of CRM streams monitored of the total	Portion of streams with CRM content monitored in accordance to the CEWASTE requirements	-Provision of training to workers concerned / H6S department manager - Provision of required measurements devices / H6S department manager
% of recyclable units collected of the total	Portion of key CRM equipment collected which fulfils the quality goal established	-Training about quality risks and the quality goals of the operator -establishment of a system for records management of quality of inputs and outputs of key CRM component or equipment produced

Figure 4: Monitoring & evaluation plan – An example – Part 1

Key performance Indicator	Resources needed	Base-line in year 0	Threshold or target for years 1 to 5	Results /date of measurement
Objective 2.1 Increasing CRM recovery				
% of CRM streams monitored of the total	-Measurement devices - Visuals for training	30 %	Year 1: 50 % Year 2: 80 % Year 3: 100 %	60% / 31 Dec year 1
% of recyclable units collected of the total	-Measurement devices - Visuals for training	20 %	Year 1: 50 % Year 2: 80 % Year 3: 100 %	60% / 31 Dec year 1

Figure 4: Monitoring & evaluation plan – An example – Part 2

3.2 Sustainability aspects

Sustainability requirements include:

- Environmental protection from emissions of (pre-)treatment processes (clause 4.10.1)
- Local communities well-being (clause 4.10.2)
- Society related aspects (4.10.3)

It is well understood that employees' concerns such as those about 'training', 'occupational health' and 'contractual aspects' are often considered sustainability issues. However, in order to facilitate the reading from the 'employee' perspective, these topics are placed in the personnel management part (clause 4.9) together with other general employee-related topics.

3.3 Due diligence for traceability

Traceability requirements are placed in clause 4.6 and apply to lead-acid waste batteries and PCBs.
The due diligence approach is elaborated for monitoring and demonstrating compliance upstream the value chain. Due diligence results are useful for external communication purposes e.g. to customers.
Under this approach, each party of the value chain is required to conduct a second-party verification process to trace and document compliance with the CEWASTE requirements of the processing of CRM-containing materials such as waste batteries and their streams.
Note: For printed circuit boards guidance on traceability is given in the CENELEC TS 50625-5 document by means of contractual obligations in the first tier of suppliers and by downstream monitoring requirements.

3.4 Technical requirements focusing on gaps identified

The requirements that operators and facilities shall follow to recycle key CRM equipment and key CRM component shall follow are presented in clause 5.
Technical requirements developed for the KCC base on the sufficient availability of evidences, experiences and national and European recommendations which contribute to advance in this area.
Overall, the sequence of activities follow the one applied by the CENELEC standards. Users of the CENELEC standards. will recognize main new developments in the following clauses:
Clause 5.6 Shipping. For movements within a country or for transboundary movements, considerations from the Basel Convention [6] and other international conventions related to shipping need to be taken into account.
Clause 5.7 Sorting. For optimal sorting, as starting point, the following received at collection points, collection facilities and logistics facilities shall be collected separately:

- Fluorescent lamps (containing fluorescent powders)

- CRT monitors and TVs (containing fluorescent powders)
- Temperature exchange equipment (TEE) (containing magnets)
- Household appliances other than TEE (motors/drives containing magnets)
- Laptops (hard disk drive - HDD), desktop Computers (HDD), mobile phones, tablets and similar devices containing printed circuit boards and magnets
- External CDDs, ODDs, devices with internal CDDs/ODDs
- Magnets from WEEE and electrical engines from all types of electrical vehicles
- Batteries from electric vehicle (BEV) and (plug-in) hybrid electric vehicle (P)HEV
- Li-ion batteries
- Lead-acid batteries

Clause 5.10 Removal of KCC. Specific requirements for the removal of components containing CRM are further elaborated in this clause and concern:

- Waste batteries
- Fluorescent powders
- Waste magnets
- Printed circuit boards

Clause 5.11 Final treatment. It is required that the separated fractions/components containing CRM are treated in facilities that are designed for the recycling of the concerned CRM and that self-declare having implemented

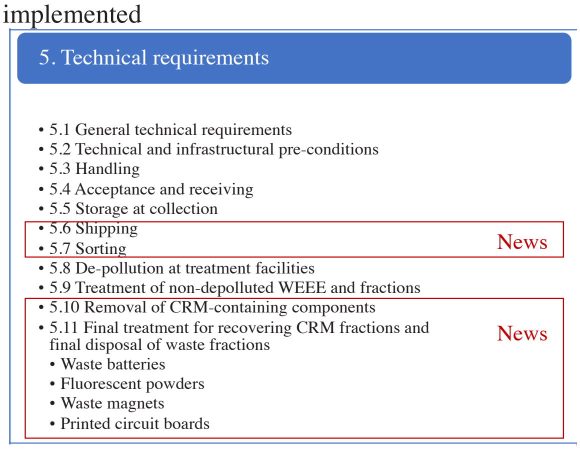

Figure 5: Technical requirements - Main new developments

CEWASTE requirements. Technological options for treatment are presented in the Annexes III to VI, except for the PCB.

An example with the steps followed for lead-acid and li-ion waste batteries is presented in Figure 6. In this diagram flow, concerned sub-clauses within the CEWASTE are given on the sides of the graphic and cover the removal, delivery, acceptance, sorting and final treatment. Recovered CRM would include antimonial lead and cobalt.

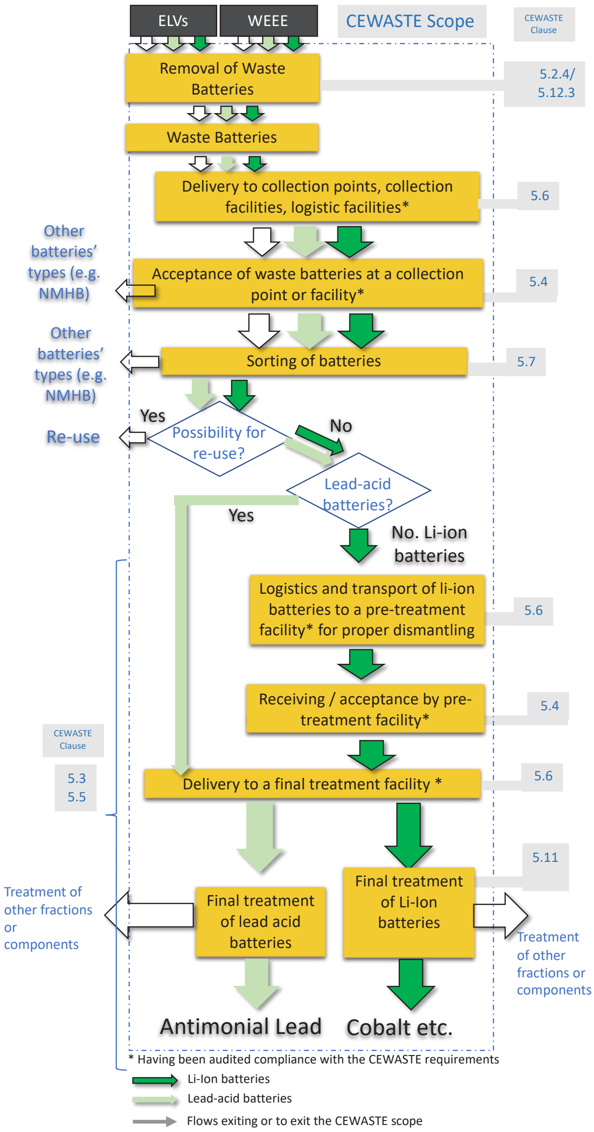

Figure 6: Flow process for implementing technical CEWASTE requirements in waste batteries

In the case of waste batteries, requirements and recommendations are provided for lead-acid and lithium-ion batteries and not NiMH batteries. Lead-acid batteries are key WEEE according to the Basel Convention and is subject to strict controls when part of transboundary movements. Lithium-ion batteries is a growing waste stream not yet under the Basel Convention list subject to control. NiMH batteries are decreasing their market relevance, hence, the project consortium decided not to consider this as critical WEEE for the purpose of the project.

4. Outlook

A framework for certification of the compliance of various actors with the CEWASTE requirements is developed under the CEWASTE project [2]. This includes an assurance and verification scheme.

The CEWASTE requirements fill the gap and fundamentally complement the CENELEC series of standards. This is applicable worldwide to any facility dealing with the recycling of WEEE focusing on waste batteries, printed circuit boards, magnets and fluorescent lamps. Through their use recovery of critical and valuable raw materials will be increased and recycling improved. Notably, compliance with CEWASTE requirements of waste batteries and PCBs management will be demonstrated via due diligence. The CEWASTE requirements are conceptualized as public good and the final version will be published in 2021.

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Supply Chain Risk Assessment: Predicted and Actual Non Compliance in N-Long Supply Chains

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Abstract

Over 1200 suppliers had been asked if their traded goods are compliant with

A) REACH Regulation 1907/2006 for controlling chemicals in discrete articles

B) RoHS Directive 2011/65/EU for banned substances in Electrical/Electronic Equipment (EEE)

It was partly anticipated, in our joint contribution with Frank MEHLICH for the Electronics Goes Green 2016, that the probability of non compliance

1) is often a coupled worst case aggregation of the answers for A, B — for each article

2) has a factor: The longer the supply chain is, the less probable is an article‘s compliance „in the shops“.

Can the outcome be predicted by a theory of probabilities? What are the actual results? The authors propose to apply the IEC 63000 for a risk reduction and to cluster materials into three risk categories under a factor method. The paper also discusses the limits of formats such as IPC 1752/A or 1754.

1. Introduction

There is a growing recognition that producers with rather complex Bills of Materials (BOM) can face supply risks under extended producer responsibility schemes. These place the sole responsibility for non compliant products on a producer of electrical or electronic equipment (EEE). A producer's risk is constituted by internal product design failures and by several external factors, for example that suppliers are not in compliance with the substance restrictions for materials [4]. This may affect the materials selection process as a base for a company's purchasing activities. It also points at initial sampling as the core process for suppliers' proof of compliance [1]. The technical regulations and acts referred to in this paper are all about potentially toxic substances in EEE.

In the largest economic areas of the world, the legal requirements for a "Restriction of Hazardous Substances in EEE" (RoHS) surpass the common electrical safety and electromagnetic compatibility or radio emission legislation, by placing a restriction of chemical substances in EEE in order to foster an improved recyclability, recoverability, or reusability of components for repair. The US State of California has a similar "Safe Drinking Water and Toxic Enforcement Act" of 1986, called "California Proposition 65" (CalProp 65), which can be considered the “mother” of all these legal acts and technical regulations. It defines the citizens' „right to know“. The EU's "Registration, Evaluation, Authorisation and Restriction of Chemicals" (REACH) Regulation 1907 of 2006 also aims at the same citizens' right to get to know substances defined by the United Nations Globally Harmonized System (UN GHS) in products. REACH is applicable in a post-BREXIT United Kingdom, in the EU plus the EFTA (Iceland, Liechtenstein, Norway, and Switzerland). The framed B2C answer period of 45 days on private consumers' requests (Pull) is coupled with other legal duties such as directly informing commercial customers (B2B) about „Substances of Very High Concern" (SVHC) at the time of delivery (Push). Starting on 2021-Jan-05, a database called SCiP is the legally defined B2B and B2C tool to fulfill such information duties [15] in the EU.
As any RoHS legislation directly sets a substance restriction if a concentration threshold of a certain toxic chemical substance is surpassed in a material, it is much stricter than both the REACH and the Californian Proposition 65's control of chemicals in a complex product plus its components. Which metrics are suitable for reducing the environmental [2], economic, and social risks under a sustainable EEE strategy? Are there economic benefits and risks for it?

If non-compliant products can be financially risky for a producer in all of the world's main economic areas, is the risk only related to the length of the supply chain? How can the risk be modelled if a product faces two different legal challenges such as RoHS and REACH in the EEU? What are the main risk factors? With which factor methods can they be predicted, for a risk reduction strategy? Is the major factor only the supply chain's length? For that purpose, N-long chain are defined by N as the number of chain links (suppliers). The suppliers can either be importers, producers, or traders (distributors). If the risk can be predicted by a theory of probabilities, what are the actual results of a campaign asking the suppliers if they trade compliant products? Are there other findings?
More research is needed on how the risk grows if there are alternative suppliers for components (multiple sourcing).

2. Modelling the Risk

The first assumption in a field study was that there are eight possible answers to the questions asked to over 1200 suppliers „Are your supplies in compliance with the following two pieces of legislation?".
The two questions could be described as the double rolling of a four-sided dice when the conformity scheme as in IEC 63000 [5] is added.
A commercial reply would be a declaration of conformity on company paper, duly signed and/or stamped. Backup data could be a full material declaration in an IEC 62474 [6], [7] or in alternative formats. In some cases, laboratory test reports are needed, for example a Type 3.1/3.2 certificates based on EN 10204, or a chemical analysis to exclude SVHC.

The second assumption is that for the probability of non-compliance the Risk Denominator as in Table 1 is

$$P(R) = \frac{1}{(4/8)} = 2$$

$$\text{whereas. } P(A) = \frac{\text{number of positive results}}{\text{number of results}} = 4/8$$

In Table 1, „Others" is defined as

a) electronics industry: Directive (EU) 2011/65/EU of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS) or national equivalences such as SJ/T 11363, GB/T 26572 & SJ/T 11364 Labelling Requirements (PR of China RoHS), or EAEU, Technical Reglément 037/2016 (5 member states including Russia) [1], [2], [16]
b) passenger cars and light commercial vehicles in the on-road vehicle industry: Directive 2000/53/EC of 18 September 2000 on end-of life vehicles (ELV) [3] and GB/T 30512 (PR of China ELV)

The RoHS Directive is not applicable for automotive mass-produced vehicles, or their components.

Possible Outcome	R=REACH	OTHERS = {RoHS,ELV}	RISK Denominator
RC	„compliant"		0
RN	"Not compliant"		2
RW	"No Commercial reply, without back-up data"		2
RE	"No Commercial reply – however, backup data exist"		1
OC		„compliant"	0
ON		"Not compliant"	2
OW		"No Commercial reply, without backup data"	2
OE		"No Commercial reply – however, backup data exist"	1

Table 1: Risk Denominators

Notes to Table 1:
The existence of backup data in various declaration formats, for example IEC 62474 [16], may lower the risk. Such data could still be risky if the declaration is deemed inaccurate or outdated (as in older JAMA/ JAPIA sheets with obsolete reportable substance lists), as we will explain later on,. Or they are based on the wrong industry's declaration criteria [1], for example „RoHS for cars". The factor methods will be discussed later on, before we aim at a risk reduction strategy. The weighted means is that the risk of „non compliant" equals the risk of „"No Commercial reply, without backup data" (see also Table 5).

It was a heated debate among the members of the survey team and among external experts if such evaluation would be justified that no commercial reply, without backup data, is risky. Having compared the source texts [9], [10], [11], [13], [14], [1], [2], and [4], we decided that it is justified. A high impact factor is occupational health.
If we conclude that getting the supplier answers as in Table 1 equals the throwing of 4-sided dice two times, then the following coding is possible:
S = {RC;RN;RW;RE;OC;ON;OW;OE}
If we further attribute probabilities to the results "RISK" = 1, "LOW RISK" = 0, then the two risk categories S = {1;0} are added, so we can conclude:
P(1)=4/8, P(0)=4/8
According to common industry interpretations of the IEC 63000 as in [1] , [5], [9], and [16], the acceptable backup data may change the risk categorisation in a weighted pattern for R as follows:
"HIGH RISK" = 2, "MEDIUM RISK" = 1, "LOW RISK" = 0 can be described as shown above.

Explanation: A risk denominator of 1 or even 2 (for very outdated data) might be attributed, for example, if the declaration is not given in an IEC database format but in a Excel Sheet or even in an obsolete reporting format such as JIG 101 [16]. Outdated data sets are often not being recognised by actors in the supply chain as a thread to product compliance [12].
So for the theory of probabilities, S = {2;1;0} for rolling one dice results in:

P(2)=0.50 for high risks
P(1)=0.25 for medium risks
P(0)=0.25 for low risks

If either the result for REACH or for RoHS/ELV is "Non compliant", the overall result for the whole product is "Non Compliant" (possible market failure):
Again, S = {RC;RN;RW;RE;OC;ON;OW;OE} can be grouped as follows:

Probability or Results	Worst Case Risk Denominator	Probability or Results	Worst Case Risk Denominator
P(RC;OC) =1/16	0	P(RW;OC) =1/16	2
P(RC;ON) =1/16	2	P(RW;ON) =1/16	2
P(RC;OW) =1/16	2	P(RW;OW) =1/16	2
P(RC;OE) =1/16	1	P(RW;OE) =1/16	2
P(RN;OC) = 1/16	2	P(RE;OC) = 1/16	1
P(RN;ON) = 1/16	2	P(RE;ON) = 1/16	2
P(RN;OW) = 1/16	2	P(RE;OW) = 1/16	2
P(RN;OE) = 1/16	*1*	P(RE;OE) = 1/16	1

Table 2: Aggregated worst cases, with risk denominators

In case of P(RN;OE) = 1/16, the Risk Denominator was set to 1, overriding the aggregated worst case result of 2. Here, we argue that the existence of backup data for the result OE with a Risk Denominator of 1 can be explained as the decisive factor. With the help of backup data for RoHS, showing the materials chemical breakdown, a supplier response that a shipped article was not REACH compliant could be verified or falsified.

By looking at the backup data, you could decide whether there is a REACH non compliance risk or not. Often, companies are able to verify their suppliers' responses with the suppliers' materials data. This is the reason why the Risk Denominator for P(RN;OE) = 1/16 was set to 1, not to 2 -- as there is in fact a set of backup data at hand in this scenario.

Otherwise, if there was no such materials breakdown available, the aggregated worst cases would be P(2)= 12/16=0,75, and P(1)=3/16= 0,1875, P(0)=1/16= 0.0625. As we weigh the risk for a non compliant, supplied article to be lower if there are backup material datasheets at hand, we argue that the risk for P(RN;OE) = 1/16 has a Risk Denominator of 1.

So the combined, weighted risk results in P(2)=11/16 = 0.6825, P(1)=4/16=0.25, P(0)=1/16=0.0625.

To graphically display results on a Wheel of Fortune,

$$P(A) = \frac{\text{a field's inner angle in } ^\circ}{360\ ^\circ}$$ shows:

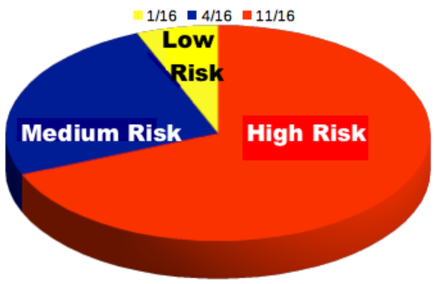

Figure 1: Pie Chart of Probability

However, are these typical Laplace experiments?
No — because Pierre-Simon Laplace (1749-Mar-28 – 1827-Mar-05) would have used two perfect four-side dice where any number from one to four is likely to fall. This would be true if all experiments had a finite number of results with the same probability. For Laplace, the result of one dice would not influence the other's result. As explained in the beginning, REACH is different from RoHS so the dice

are different in their probabilities, and the impact of the RoHS dice may be stronger depending on the market. Furthermore, one dice's result is coupled with the other one's as a worst case aggregation: If either the results for REACH or RoHS/ELV is "Non-compliant", the overall result for the whole experiment is "Non compliant" (possible market failure) [1]. Therefore, our assumption is that it is a "Non-Laplace Experiment" to predict the probabilities of non compliant supply chains.
The results for "High Risk" (P = 0.6875) displayed in red are higher than the "Low risk" category (P = 0.0625) as shown in yellow and the P=1 "Medium Risk" category depicted in blue (P = 0.25). See Fig. 1.

To summarize the findings for n-long supply chains: We admit the limitation that we had only considered linear supply chains, not diverted ones as in complex products with a long Bill of Materials (BOM).
The higher the value is for n, the higher the risk for non-compliant results is. So n may also give the number of times the two "compliance" dice are rolled (or the numbers are drawn via a "Wheel of Fortune" as in Figure 1) for REACH and RoHS/ELV. There would be 4 x 4 = 16 results. To graphically display this assumption, the following Figure 2 shows the risk categories, their probabilities, and the results depending on the supply chain's length: The supply chain risks of legal non-compliance depend on the supply chain's length. Compare Figures 1 and 2. The results of the modelling in the table above show that the theoretical risk of non-compliance with both REACH and RoHS/ELV is considerably high, at 0.6875 < 1. The longer the supply chains are, the more often two „compliance" dice are rolled, all the higher the risk can be seen for many articles' non-compliance, as Figure 2 shows. This has an international significance.

Recent surveys of customer contracts show that RoHS and RoHS-similar requirements now affect markets in roughly 2/3 of the world: India, China, Turkey, the Eurasian Economic Union (Armenia, Belarus, Kazakhstan, Kyrgyzstan, Russia), Japan, South Korea, the EU, the EFTA, and the USA.

3. Relevance of the IEC 63000 on a global scale

REACH or REACH-similar legislation for the registration, evaluation, and authorization of chemicals including those in solid materials now cover roughly more than 1/3 of the world's area: PR of China, Japan, South Korea, Turkey, EU + EFTA, and USA. A further impact can be expected through the recent United Nations Globally Harmonized System for the classification and the labelling of chemicals (UN GHS) for dangerous/hazardous chemicals (cf. [16], pp. 28-30). Recent studies refer to aspects about ways and means of exchanging information in comparable supply chains for textiles [10], [11]. Whereas REACH or similar pieces of legislation such as the CalProp 65, require a supplier statement only if a supplied article contains certain substances, RoHS and ELV [3] require a stricter management of substances at a materials level. The IMO Hong Kong Convention for shipbuilding and ship recycling, as implemented by using the ISO 30005 for an inventory of hazardous materials, has a similar approach.
Here a (full) materials declaration is a way to track which materials are non compliant. One of the conclusions is that any development in one industry sector often has a delay or a range of diverging approaches in other industries. Also, there are different software tools available, for example in Asia such as Japan's ChemSherpa or CAMDS, Chinese Automotive Materials Data System, due to different national and sectoral approaches.

As a result of the findings, a choice of the reporting formats is suggested, and arguments are given for the preference. In the final chapters certain reporting formats connected to the factor methods for risk assessment will be recommended.

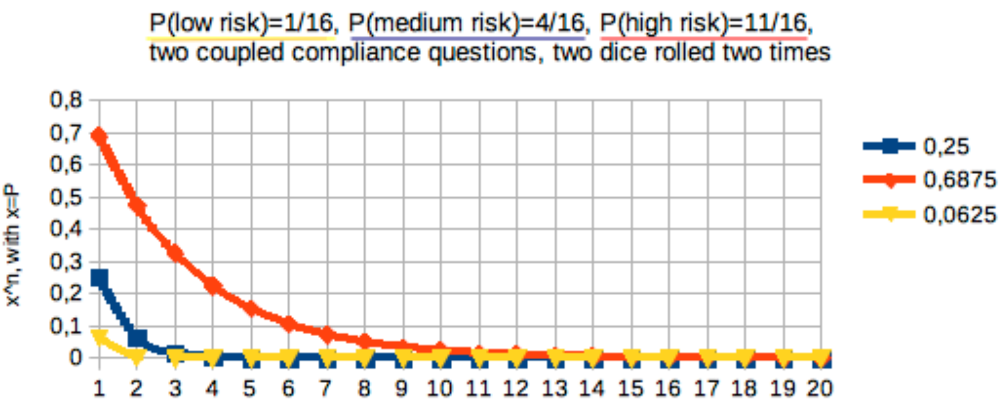

Figure 2: Display of probability P, depending on the length of supply chains n

In practice, it is common to receive outdated versions of supplier declarations. That might be acceptable for the slowly changing RoHS 2 legislation but could be rather detrimental for the rapidly increasing REACH requirements. What is needed is a list of substances in homogeneous materials (like the *Global Automotive Declarable Substance List, GADSL*) and the reporting thresholds for substances that are either declarable (reportable) or prohibited. See the sources [7], [5].
The GADSL is updated twice a year, to amendments of the REACH Candidate List. However, many companies are at odds with the change management in complex articles, especially in mass-produced common parts. Alternative screws, for example, may affect many Bills of Materials. The contents of the diverse alloying elements' tables need to be checked against a pre-defined table of substances that are either "prohibited" due to their "hazardous/dangerous" properties, or just plain "declarable" to the customers. An international company needs to ensure that the underlying list is up to date reflecting the legal requirements in different countries, see Table 3.
Why does the IEC 63000 [5] refer to the IEC 62474 [6] standard for a full material declaration? As it is an international electrotechnical standard with a reportable substance list [7], the IEC 62474 has an advantage. It is updated along with the REACH, RoHS and China RoHS changes in its online version. Therefore, the IPC formats might be sufficient for sector-specific RoHS 2 and REACH compliance purposes, with a limited compliance promise due to their infrequent updating. Ideally, they have to be conveyed along all actors of a given supply chain in a central database, not as Excel sheets. If an older set of information in an Excel format such as JAMA/JAPIA or obsolete JIG 101, for example, is used, the underlying "reportable substance list" or the information itself might be outdated. If these standards including IPC 1752 or 1754 [16] are not updated and transmitted via online databases, with some exceptions as transmitted via .xml, they remain static „as declared on a certain day", and do not have an automatic update trigger.
Another issue is the data sets' interchangeability and compatibility. Neither the electronics industry (IPC 1752) nor the aerospace & defense industry (IPC 1754) endorse the GADSL for substance thresholds that should commonly be observed when creating an automotive full material declaration. All kinds of industries have their own industry-specific substance lists. Therefore, the data cannot easily be exchanged between industries. In brief, IPC 1752, JIG 101 and JAMA /JAPIA Sheets not frequently updated can often be described as „not sufficient" for an up to date automotive REACH or ELV materials reporting.
According to common industry interpretations [1], [9], and [16] of the IEC 63000 [5], the acceptable backup data examples may include the following:

Materials	Examples: Backup Data Sources
Any above basic material levels: EEE components, EEE	"SCiP" database for information on "Substances of Concern in articles as such or in complex objects (Products)" [15], provided by the European Chemicals Agency (ECHA) in Helsinki, Finland
Any material	Laboratory test report such as Micro X-Ray Fluorescence Analysis, Atomic spectroscopy, 3D Atom Probe (3DAP), and others
Metals	EN 10204 Laboratory Test Report 3.1/3.2 from a steel mill, CDX/ IMDS Material Data Sheet, Granta MI Data, DataCross/mds.web, etc.
Automotive Products - incl. metals, plastics, EEE, polymeric compounds, laminated compounds, allow where-used analysis of strategic raw materials, or conflict minerals	**Full Materias Declaration (FMD) Formats:** Material Data Sheets MDS [3],[4], JAMA/JAPIA Sheet (Excel based), frequently observed in Japan and China; EN 10204 laboratory test report [1], [2] **Database entries: International Material Data System (IMDS)** may include JAMA/JAPIA upload and former MACSI user data, Chinese Automotive Material Data System (CAMDS), JAMA/JAPIA uploads, MACSI (Peugeot-Citroen Materials Database) prior to 2017
Electronic Products (also for Railroad, Shipbuilding, or others) - incl. metals, plastics, electronics, polymeric compounds, laminated compounds, allow where-used analysis of strategic critical raw materials [8], or conflict minerals in components	**Full Material Declaration (FMD:** Material Data Sheets (MDS), IPC 1752A materials declarations in the electronics industry, IPC 1754 materials declaration [16] in the aerospace & defense industry, IEC 62474 materials declarations in the electronics industry [6], [7]; JIG 101 [16] (still infrequently found but obsolete) in the EEE industry; many company-specific formats [1], [16] **Database entries:** around 10 to 20 different approaches exist, for example databases such as Granta MI, Compliance Data Exchange (CDX, ship building, also for aerospace), iPoint, BOMcheck, Octopus (railroad), Data Cross, IDIS 2 (automotive dismantling data), ChemSherpa, Recycling Passport [9] according to PAS 1049 (EEE)

Table 3: Examples of materials declaration backing up the answers to compliance questions

For automotive declarations of conformity, data sets should not surpass a certain "age" being defined by the period of time that had elapsed since the last GADSL update.
So most probably, the recent addition of the SCiP database, as an entry in the following Table 3, requests data from all sorts of industries. So the issue of reaching an agreement of interchangeable data formats to be used in all kinds of databases that are no industry-specific isolated "islands" remains a challenge [16]. So how can suppliers be asked about their product compliance?

4. Methodology: Whom to ask for compliance in practice?

The supplier survey as a study had not used a randomised set of participants. Rather, the suppliers were carefully chosen because of their importance for the articles as sold to the customers. The suppliers providing technical services such as business photographers, hotels, business fair organizers, and auditing companies did not show up on the supplier list after its cross-checking with other departments. The acceptance criteria as in Table 4 were defined then.
Additionally, suppliers for certain services and pre-defined articles used in the building infrastructure of for production tooling and not for mass produced products were excluded after receiving no or a negative answer. The control group were those suppliers having participated in the forerunner study (historic evidence), and other suppliers with answers handed in during a trade fair. Others were explicitly included after internal discussions. One of the selection filters that needed to be defined is that of external services for surface treatment. For example, if a company outsources the Chromium plating of metals, it can hardly control the used substances and mixtures directly. Therefore, it was important to identify such external services by means of cross-checking the technical documents, and to explain the importance of the study to suppliers in view of the final article's compliance. As part of the supplier survey, the Purchasing Department generated a list of suppliers and part numbers that formally meet the selection criteria:

Criterion	**Method of Proof**	**Reason for inclusion**	**What to do in case of not meeting the criteria?**
Declaration for parts A is based on the receiver's list of known part/article numbers B: If the number A is part of B, then the delaration is acceptable	Check the part number structure	IEC 63000: status of conformity must be addressed at part/ article number's level [5] conformity cannot be declared on terms too broad such as „for all we sell" [5]	If no part number is given at all: reject and ask for new reply. If based on supplier's part number system, re-send receiver's list and ask for an equivalence declaration and/or conversion list. If no such equivalence is recognised, reject it.
Declaration for parts A is based on the actual legal requirement	1. Identify the latest legal requirements 2. Check if they are cited correctly	For example, the former versions of RoHS or China RoHS may deviate in their requirements and implementations from the actual versions	If an obsolete version of the legal requirement is cited, reject the declaration. — Ask for a new declaration.
Declaration for parts A is not older than a year.	Check the date of issue. If there is none, reject the reply.	1) The REACH Candidate List is being enlarged with new substances every half a year. [4] 2) The RoHS List of Banned Substances is updated roughly every two years, with different market scopes [7].	If the declaration has no date of issue, reject it and ask for a new one. If the date of issue is outdated, ask for a new declaration.
Declaration has a market relevant legal format, for example: The Person C that issued the declaration is a member of group D who are allowed to issue such papers.	Check if the declaration is duly signed and/or stamped with company letter head	Example: an e-mail is often not seen as a legally relevant format under commercial law In Asia, personal name stamps may have more legal relevance than a mere ball-pen signature. In Europe, it might be the opposite.	If the declaration is not duly signed/stamped ans issued with a company letter head, reject it and ask for a new one. Issued by a staff member not part of the management: Ask the company if this person is allowed to issue the document.

Table 4 : Acceptance Criteria for a Supplier Feedback based on the IEC 63000

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A set of rough criteria referenced to in the REACH and RoHS texts and internal criteria criterial had defined – beforehand – the acceptability of the supplier answers, by some of the acceptance criteria as shown in Table 4.

5. Study Implementation

The supplier campaign was started in autumn 2016. After working on the theoretical assumptions, two part-time teams (five participants each) with changing membership depending on the tasks and one full-time leader managing both teams had set up the following: A supplier portal was set up on behalf of the Production Department that listed the roughly 1,200 suppliers' about 42,000 articles as delivered during the last three years [11]. There was a substantial support from the Sales Department. The Lead Department under the IEC 63000 was the Purchasing Department with its core purchasing processes, including Customer Supplied/Directed Parts. The Joint Supplier Window was set up jointly in the REACH/RoHS Office and the Materials Lab. Due to practical reasons such as limited resources for the survey, this time- and stock-relevant framework was decided. The deliveries were listed up by their part numbers known at the receiving end of the supply chain (OEM point of view) [12].
The survey letter had two attachments, a RoHS letter explaining what to do under the legal requirements for that market, and a similar REACH letter. These described not only the calculation method for the different threshold levels (Prohibited vs. Declarable) but also other duties such as the reporting of certain substances in materials to authorities and business partners, for example for a proper REACH registration.
The gross bulk of replies arrived during the next six months, often after sending many reminders.
In around 25 % of all cases, the responding party answered that they do not know the full chemical composition of the articles they sell.
Also, even if the composition was known, the supplier replied that they could not check if their materials meet the requirements. This was narrowed down to a 5% rest where the surveyors had to declare the materials' compliance by themselves, either by analytical tests (< 1 %) or by comparing the articles under consideration with similar articles of the same supply chain (under multiple sourcing) or from comparable other suppliers [2].

6. Results

What needs to be adressed is the *Drop Out Rate* as shown in Figure 3. Under a sustainable development, the exit option constitutes a considerable economic and social risk. The total number of suppliers shrank by about 9 %. Roughly three percent of the suppliers opted out of business as a result of the first survey letter. The rest was removed from the supplier roster after the Purchasing Department decided to do so under its own business responsibility. As [11] does not want to publish further details, these are withheld. The main conclusion that many companies have drawn is to amend their Terms and Conditions, especially for suppliers with the respective REACH and RoHS requirements including the SCiP requirements.
Figure 3 shows that after one year, the response rate was 100 %. This has only been reached in cooperation with most cooperative suppliers who handed in the materials in use to allow one of the project teams to evaluate the compliance by themselves, without the suppliers' own judgement.

6.1. Discussion of Actual Results and Further consequences

The main assumption that the probability of non-compliant articles increases with the supply chains' length is proven. The group of suppliers surveyed with the most complex articles included three to four companies that took the longest time and the biggest efforts to obtain information from their supply chain with negative results. Consequently, REACH and RoHS can have an enormous impact on international businesses. A Purchasing Department, in order to

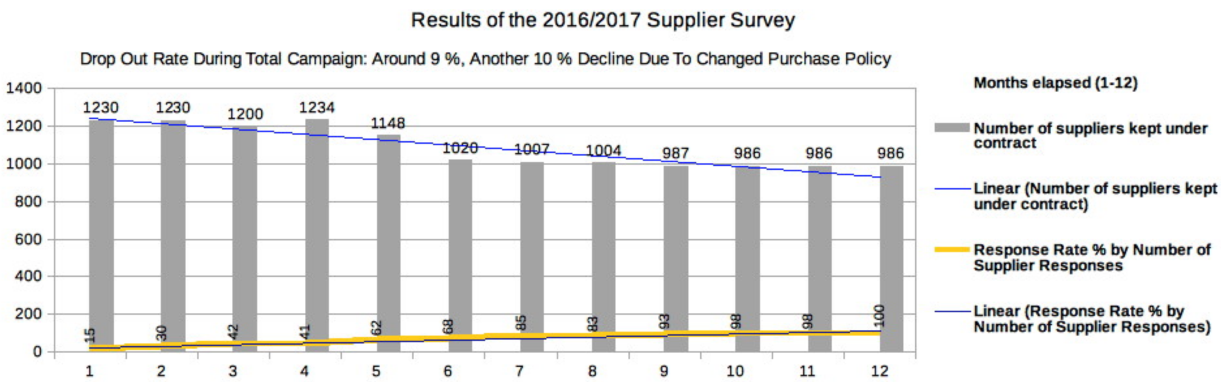

Figure 3: Results of the 2016/2017 Supplier Survey

evaluate the risk, would need to closely and carefully cooperate with other departments to define if a supplier can be substituted if it is a low-risk supplier. Some of the risk mitigation measures are considered under the LIFE Ask REACH Project [11] which had spurred further fruitful discussions. This has led to a Risk Evaluation Matrix modelled after the one written by the Automotive Industry's Guidance on REACH (AIG) Task Force [4], [2]. www.acea.be.
The following Table 5 summarises the Factor approach.

For a practical point of view, companies can more or less easily evaluate standard metals and other common materials, for example: Whenever the chemical composition of common materials is being made public by their alloying elements, e.g. via the CDX database, www.cdxsystem.com and through similar sources as cited [16], the impact on RoHS or REACH compliance can be verified. Special materials rely on the information the manu-facturer would provide, for example for plastics or for adhesives.

Copyright © 2019 by Carsten Dietsche. All rights reserved.			**Degree of damage - trustworthiness of the supplier with regard to REACH conformity**		
		Factor	**1**	**2**	**3**
Supply Risk Analysis *or* Supply Chain Risk Analysis **According to CoSo Approach or based on ISO 31000 Risk Management**			**Low:** Fully trustworthy supplier - Minor impairment of health or damage to the environment is possible	**Medium:** Less trustworthy supplier - Health impairments (including absence from work) or damage to the environment are possible.	**High:** Supplier is not trustworthy - Severe impairment of health (possibly with death) or damage to the environment possible
Factor Indicating the probability that the material, component, assembly or product may contain REACH-relevant substances	**1**	**Unlikely Occurence:** An unexpected combination of factors would have to coincide in order for the product not to be conformal and also to pose a risk.	**1**	**2**	**3**
	2	**Possible:** A risk or a hazard due to non-conformity could occur. In principle, however, this case is unlikely.	**2**	**4**	**6**
	3	**Likely:** If certain factors were to occur, the non-compliance would become dangerous/hazardous and lead to negative effects.	**3**	**6**	**9**
	4	**Very likely:** The occurrence of non-conformity and the resulting danger is almost unavoidable.	**4**	**8**	**12**

Type A	A written assurance (Supplier Declaration, Ship Building: Supplier Declaration of Conformity, SDoC according to the Hong Kong Convention on environmentally sound ship building and recycling) and a declaration of the contents (MD, Material Declaration – if applicable a Full Materials Declaration according to IEC 62474/IPC 1752A/ IPC1754, CDX or IMDS "Material Data Sheets", or similar formats) of the supplier are required.
Type B	A Declaration of Contents (Material Declaration, if possible a Full Materials Declaration according to IEC 62474/ IPC 1752A/ IPC1754, CDX or IMDS "Material Data Sheets", or similar formats) of the supplier's shipped articles is necessary, including the relevant data out of the supply chain for the sub-suppliers *(subject to discussion in many industries, as there are often no standard procedures at hand outside Automotive, Aerospace & Defence, Ships).*
Type C	Supplier's Material Declaration (Full Materials Declaration, if applicable according to IEC 62474/ IPC 1752A/ IPC1754, CDX or IMDS "Material Data Sheets", or similar formats) and Laboratory Test Report (e.g. Analytical Test Report according to EN 10204) are necessary. The laboratory has to be qualified and/or accredited for that purpose, for example under EN ISO/IEC 17025.

Table 5: The Factor Method for Risk Reduction

If there is no information at all, with a higher risk of non-compliance, the IEC 63000 [5] foresees a laboratory analysis. All in all, a global materials selection has to take into account the legal and customer requirements in each area or industry [2], the chemical and physical properties, the price, and the number of alternative suppliers [10] for a broadened multi-source procurement.

6.2. High Risk Impact

If there are not so many alternative suppliers available on the market, this can easily produce a high-risk impact whenever a business partner is not responding to the survey or is sending negative compliance declarations. The impact for a joint customer project can be very harmful for both business partners, especially if a supplier is in Category Type C with a high risk as shown in Table 5. If in Type B the supply chain including all sub-suppliers is relatively long, it takes up to half a year to retrieve the sub-supply data, which was one of the outcomes of the supplier survey. Many suppliers outside the Automotive or Aerospace industries are often not very familiar with material data sheets and the use of such databases, cf. [1], [2], [16]. Therefore, it is a vital business interest for a risk-conscious company to identify and to mitigate supply (chain) risks by a prudent supplier management that has a long-term benefit both for Sellers and Buyers.

7. Discussion of the Risk Assessment Method

The risk assessment "on paper" has one flaw: It is a factor method only. As an immediate follow up, a manufacturer or importer should apply purchase centered risk reduction methods that may be company- or industry-specific. Prof. Ab Stevels (formerly with Delft University of Technology) as one of the "founding fathers" of the European RoHS Directive called it a "prioritized action agenda" how to proceed best. Risk reduction as one item on the global agenda may depend on the market area, as e.g. the risk in mainland China might be considerably higher than in other areas. For example, in one country the environmental agencies might be politically weakened on purpose. In Europe, a Directive has to be transfered into national laws that may differ in each county [1], [16]. However, legal requirements such as REACH (an EU-wide regulation with the same requirements in all affected countries), China RoHS or the CalProp 65 force the manufacturer of products to show why these are sold as being compliant (reverse burden of proof). In California and the PR of China, there is a product labelling for compliant or non-compliant products. The risk for RoHS is that if a public body or competitors find out that a product is not compliant, this might either result in a legal fine or a loss of reputation once the non-compliance is published. Under most legal regimes, the party claiming that a product is not compliant has to prove it (burden of proof).

8. Summary: Challenges Ahead

Risk mitigation measures by requesting both commercial compliance statements and (full) material declarations from suppliers will be discussed after further research. The method had been co-developed with a vehicle manufacturer in the UK in 2019. The underlying supplier study, however, had been conducted in a non-automotive environment, and then been cross-read against common challenges that can be found in both industries, such as updating the information drawn from the Bills of Materials.

The action agenda, in Ab Stevels' words, can be used to allow a considerable cost reduction, too. By applying some effort, a company can drop rather complex, expensive materials — that contain heavy metals and also cause high costs in occupational health and safety's terms — with simpler materials that are less costly. If a company approaches its suppliers with a cooperation strategy, suppliers may also point out where to reduce the number of alternative components, or where to introduce compliant alternatives. Additionally, the factor method needs to be applied throughout the entire supply chain, starting with placing basic materials on the market. For this purpose, many companies still have to implement initial sampling methods both with their suppliers and their customers that categorically include material declarations, either via the SCiP database (EU) or via a full material declaration. If the information about traces of heavy metals, for example is not traded with the components in a bundle, product manufacturers fail to prove compliance which might result in legal fines and/or a loss of reputation.

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Accelerating the Circular Economy with Rare Earths Minerals

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Abstract

Dell Technologies is a global leader in transforming circular design thinking into full-scale commercial practice. At Dell, we are finding ways to implement a circular approach for our own products and to help our customers take advantage of technology's ability to deliver new value in new ways, to examine the bigger systems, to identify efficiencies, and to uncover new opportunities. Electronic devices that use magnets built from rare-earth metals continue to end up in landfills. E-waste poses an excellent opportunity: mining end-of-life IT storage equipment and hard disk drives for rare-earth oxides, using them to augment supply, buffer market volatility and avoid the impacts of additional mining. To expand our circular economy, Dell has partnered with Seagate and Teleplan to use reclaimed rare-earth elements from old hard disk drives into new products. By using closed-loop recycled rare-earth material, Dell is able to help eliminate portions of environmental and social impacts of mining, mitigate business risks associated with virgin material, and overall emphasize Dell's position as an environmental leader.

1 Introduction

Humanity is at a crossroads. Every year, we use more resources than the earth can regenerate. What's more, the pressure on natural resources can only intensify. By 2030, global population is projected to grow by 1 billion while poverty rates decline and per capita consumption of all kinds of goods increases. And yet there's a solution in clear sight. The way we consume resources in the traditional economy has waste as its ultimate end result, but the stuff we throw away contains many immensely valuable materials.

It is predicted by the Solving the E-Waste Problem (StEP) Initiative that 72 million tons of e-waste were produced in 2017. Technological advances, decreasing manufacturing costs, decreasing consumer price, and increasing consumer sales have led to electronics having shorter life cycles, and therefore increasing the rate of electronics products reaching end of life. Most of this e-waste is exported to developing countries, finding its resting place in small towns where the technology and resources can be insufficient to deal with the quantities and compositions of this e-waste, causing health and environmental risks for that community.

This challenge presents an opportunity to re-imagine how our economy works, designing out waste, using materials more efficiently, and delivering value without creating more "stuff." Dell is leading the industry toward a circular economy, one which considers the entirety of a product's lifecycle, from considering recyclability in the early design stages to incorporating recycled content back into new products. Development of closed loop and other circular economy programs require these aspects to be considered to allow products to be easily disassembled and components to be reused or recycled. Creating a closed-loop supply chain in which plastics from end-of-life (EOL) electronics are used in parts for new products was the first step in entering the realm of the circular economy.

In 2014, Dell partnered with Goodwill through the Dell Reconnect Partnership and our ODM (original design manufacturer), Wistron, to take the plastics from old computers recovered through our recycling programs and turn that back into new plastic parts for new products. Dell became the first company in the industry to produce a computer made with closed-loop recycled plastics and we've used more than 35 million pounds of closed-loop plastics in over 125 models of our products since FY15. The process Dell developed for closed-loop plastics became the model for UL Environment's closed-loop standard, and Dell was the first to achieve certification. We expanded our closed-loop programs to include gold in 2017, creating new motherboards with recycled gold from e-waste. This process caused 99% less environmental damage while avoiding $1.6 million per kilo in natural capital costs and 41 times the social impacts of gold mining.

In addition to plastic and gold, the content of other unused materials, such as rare earth metals, within end-of-life electronics poses an opportunity for businesses.

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When businesses become able to reuse the precious materials from the old electronics, as well as dispose of wastes from reprocessing properly, they can generate significant economic, social, and environmental benefits. Businesses that have begun participating in this recycling method rather than relying on traditional mines not only reduce the environmental impact that e-waste creates but also decrease the mining impacts that occur when using solely virgin metals – all the while branding their company as environmentally friendly.

An increasing number of electronic devices are being scrapped in landfills that use magnets built from rare-earth metals – including hard disk drives, MRI machines, and most motors from electric/hybrid vehicles. Many of these could be recycled, but as of 2011, less than 1% of rare-earth metals world-wide were being recycled. At the same time, rare-earth metal mining creates toxic environmental by-products and the sector has had problems with poor safety standards. Businesses seeking to build a transparent supply chain try to hold their suppliers to a high standard when purchasing these metals and can face a complicated process of checking and trusting suppliers. Further, the vast majority of mines are concentrated in just a few countries, representing potential continuity risks for supply chains. For these businesses, such as Dell, finding sources other than these mines to source the needed metals used within so many of their products is a priority.

Dell is unique in that it already has access to a large volume of hard disk drives to recycle. A lot of the hard disk drives that are returned through the Dell return stream are given a second life where they are tested, refurbished if needed, and sold again. If during the testing the hard disk drives are determined to be EOL, they are scrapped. In one year, about 1.4 million hard disk drives are scrapped from the Dell return stream worldwide. Each of these is an opportunity to replace the total hard disk drives that Dell purchases in the same time frame. With this huge untapped resource of rare earth metals at Dell's fingertips, this recycled material could be used in a multitude of ways.

In 2018, we piloted a Trade-in Swap and Incentive Program between Dell EMC and Teleplan (a storage device recycling/recovery specialist) to give new life to non-functioning hard drives collected from used storage products. Using an industry-leading data wiping and refurbishment process, Teleplan uses proprietary software to wipe data from collected hard disk drives and evaluates if the drives can be refurbished and resold as a white label, rather than being shredded and recycled. This has generated $13 million to date and has kept 303 tons of material out of the waste stream. Drives that cannot be refurbished are disassembled and recycled to be used in the closed loop recycling process (Figure 1). Through this takeback program with Teleplan, we now had access to a large amount of recycled hard drive materials, prime to enter a new closed-loop process.

Between continuity risks in the rare earth market, Dell's access to a viable HDD return stream, and available magnet recycling technologies, we knew that rare earth magnet recycling was the right opportunity to pursue to continue Dell's closed-loop legacy. In 2018, Dell developed a successful partnership with Teleplan and Seagate which created a new process for closed-loop recycling of rare earth magnets.

Figure 1: Recycled material

2 Developing the Supply Chain

Dell has been a leader in the circular economy, and we knew from our previous closed-loop programs that building a strong coalition across the complete value chain is critical for success. Dell partnered with Goodwill and Wistron in 2014 to tackle closed loop plastic, and we expanded the program in 2017 to include gold. This built on a strategic partnership and expanded our closed-loop materials into a new computer component: motherboards. In 2018, Dell worked with suppliers again to further expand our recovery and reuse programs by identifying a new closed-loop process to recover the rare earth magnets from recovered enterprise equipment.

A recycler in the Dell network, Teleplan, was located in Malaysia and also served as a recycler for Seagate, from whom Dell buys a substantial portion of their hard disk drives. Located onsite at Teleplan's facility was Shan Poornam (SPM), their partner who handles the breakdown and recycling of components. Teleplan and SPM disassembled the EOL hard disk drives to the sub-component level, then used a heat process to remove the steel casing from the hard disk drive magnet assembly. Teleplan could then ship the recovered magnets as a whole, or SPM could process them further into a rare earth oxide powder.

Dell had identified a potential recycling partner, but a hard disk drive manufacturer also needed to be selected. We consulted with Dell's Hard Drive General Commodity Manager and determined that three potential suppliers could support the program. After reviewing each supplier's knowledge and interest in a pilot program, Seagate was selected as the best supplier to start this initiative. They were one of Dell's largest suppliers, aligned with our corporate sustainability goals, and excited to build on the existing relationship. Upon further discussion with Seagate and downstream mapping of their supply chain, we learned that one of their magnet manufacturers had in-house recycling capabilities. They had developed this process in response to the high fluctuations of rare earth prices, and periodically incorporated recycled material into their magnets.

Through partnerships with these suppliers, Dell was able to develop a new process for closed-loop recycling of rare earth magnets in which magnets are recovered from recycled enterprise equipment collected through Dell Technologies' takeback programs and reformed into new magnets for new hard drives.

3 Implementing the process

While Dell had documented many lessons learned throughout our previous closed loop programs, a new set of partners and materials also brought a new set of opportunities and challenges for the team to work through. We had to overcome multiple challenges, including internal alignment, external stakeholder buy-in, and accelerated timelines to meet product launch dates.

Logistical challenges arose during early program development phases while assessing potential recycling partners. Seagate's magnet manufacturer had the production capacity to handle the large amounts of magnet material collected through the Dell return stream; however, they would only accept incoming recycled material in a magnet form, not as a rare earth oxide powder. Since Teleplan had the ability to disassemble hard drive disks into a magnet form to meet these requirements, they were selected as the initial recycler to accompany Dell and Seagate in the pilot.

However, we understood that to have the greatest impact and create true industry change, all of Dell's major hard disk drive suppliers and recyclers would eventually need to be involved. We kept this point in mind when constructing the program to ensure scalability to include other partners in the future. The magnet manufacturers incoming material requirement was shared with Teleplan, and Seagate also agreed to work with their supplier to develop the capabilities to accept a rare-earth oxide powder.

Once Teleplan and Seagate were selected as the key partners, the next step was to develop a core team and project plan to execute a closed loop magnet pilot. We initially pitched the idea to the Dell quality and development hard disk drive teams, who were very skeptical and concerned with the project. Since the magnet is a critical component of a functioning drive, any impurities or defects in the magnet would cause severe issues. Throughout all of Dell's previous closed loop programs, we never compromised component or product performance to include recycled content. The goal was to create a closed-loop product that meets the same quality and performance standards as a traditional product. This vision was shared with the Dell engineering teams, and due to the fact that Seagate's magnet manufacturer had the recycling capabilities in-house, they were on board to continue with us on the journey. This challenge also turned into a positive opportunity, as one of the initial skeptics to the program, the Engineering Hard Drive Project Manager, helped share the circular economy vision throughout his organization.

The Dell Latitude 5400 and 5500 notebooks were selected as the products to launch the pilot magnets. This was an exciting opportunity for all parties to be included in one of Dell's largest products, but it also meant we had a few short months to execute the program. Weekly meetings were held with Dell, Seagate, and Teleplan team members to collaborate. Being transparent with all parties aided productive brainstorming sessions needed to find creative solutions to meet the quickly approaching deadline. For example, the magnets needed to be disassembled and sent to the magnet manufacturer quickly, as the recycling, manufacturing, and qualification process took multiple months to complete. The teams worked to pull together an expedited shipping plan to keep the project on schedule.

Once the operational aspects of the program were in place, a cost model for the initial shipment and sustaining program needed to be developed. Since Teleplan's hard disk drive recovery and Seagate's magnet manufacturer were both located in the Asia region, the additional material movement did not pose a financial or logistical concern. In addition, since Seagate's magnet manufacturer had the recycling capabilities in house, there were no additional processing costs incurred, so the price of the closed-loop hard disk drive was equivalent to a traditional hard disk drive. A financial challenge did exist during the exchange of recycled magnets from Teleplan to the magnet recycler, since there was no marketplace to define a baseline market price for recovered magnets in "whole magnet" form. In order to make this program sustainable long term, an internal Dell model was developed based on the market prices for the elements in a rare-earth magnet (Neodymium, Iron, Boron, Aluminium, Niobium, and Dysprosium) to ensure fair market prices for this exchange.

The result of the program was a partnership with Dell, Seagate, and Teleplan to create the industry's first closed-loop hard disk drive magnet. Magnets from EOL Dell EMC hard drives were sent to Teleplan in Malaysia where they were disassembled to a magnet form, then sent to a magnet recycler and manufacturer in Japan. They then formed new magnets with closed-loop recycled content to be used in new Seagate drives that shipped in Dell Latitude 5400 and 5500 notebooks. The pilot produced 25,000 closed-loop hard drives but has since continued with the opportunity to scale in volume and to other materials.

Our process differs from others exploring magnet recycling since we can reform magnets into many different shapes to allow for use in numerous drives models. The program was also set up in a way where our recycled magnets may be used in competitor's drives or even other magnet industries, creating the potential to expand the closed-loop initiative to other components in addition to hard disk drives, truly driving the industry towards a circular economy.

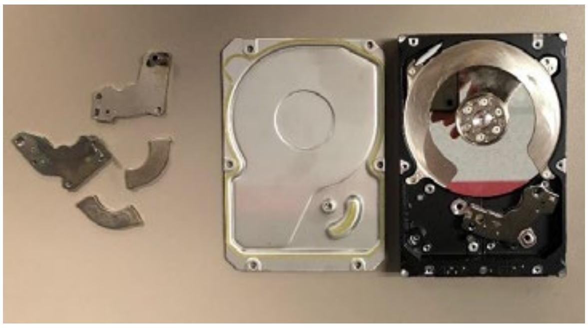

Figure 2: Disassembly

4 Environmental and economic benefits

The greatest benefits of closed-loop rare earth magnets come from with the environmental impacts that are reduced when using reclaimed rare earth metal over virgin rare earth metals. Rare earth mining and refinement create various environmental hazards. In the areas around mines, people are suffering from cancer, plants are unable grow, livestock are mutated, and those in the surrounding area are breathing dangerous sulphuric acid. Every ton of isolated rare-earth elements creates one ton of solid waste containing radioactive elements, 20,000 gallons of acidic wastewater, and airborne contaminants – including 10,000 cubic meters of acid gas fumes with dust containing radionuclides.

Since many rare earth metals are mined together, a demand for one increases the costs for all. Closing the loop on rare earth elements creates an alternative material source that can help to stabilize cost fluctuations of material prices.

Dell's closed loop rare earth initiative offers an alternative source to help address these environmental and social impacts, while also contributing to the corporation's greater drive to help the planet and global communities. Dell's closed-loop rare earth magnet pilot alone displaced roughly 100kg of mined rare earth oxides to make 25,000 hard disk drives for use in Dell Latitude 5000 series notebooks. This is the first time Dell Technologies has recycled materials from enterprise equipment into client computing equipment.

While this may be a small fraction of recycled content in each hard disk drive, we see this as the first step in a much larger solution. There are opportunities for this program to scale in size by increasing the recycled content in each hard disk drive magnet and growing closed loop hard disk drive usage to other Dell client and enterprise products, with the goal of becoming an industry wide effort. The program is also scalable, with the ability to divert an estimated 8,000 pounds of magnets material from landfills annually to create over 300,000 closed-loop drives annually. We have already scoped this beyond the pilot and additional recycled magnets have since shipped.

Even though many benefits were achieved with the launch of this closed-loop rare earth magnets initiative, there is still much opportunity to expand the project and create even greater outcomes. The amount of rare earth metal that our electronics and magnet recyclers can process is scalable and can be increased to match demand. Recyclers' production demand also depends on their total input volume and the quality of their input materials. This capacity leaves room for a greater input volume and thus would result in a greater output of rare earth oxide that could be used to produce more hard disk drives.

Greater input into recyclers can be achieved from Dell and other companies routing their downstream e-waste into a closed loop process. Since the 1.4 million hard disk drives in the annual Dell Return Stream make up only 4% of the hard disk drives purchased over the same time frame, it is very clear that there is potential for a greater volume to be diverted from e-waste and recycled. If all of the rare earth oxide had been harvested from those 1.4 million drives, an estimated 268 tons of rare earth oxide would have been recovered. Based on 2018 market prices, purchasing 268 tons of virgin rare earth oxide would cost around $29 million USD, depending on the composition of elements.

There is also the opportunity for the hard disk drives magnet material to be used in speakers, microphones, or fan motors within a Dell product. This could provide great opportunities to use both recycled plastics and rare earth magnets in the same product. The potential for using recycled rare earth magnets in other computer components shows how large this initiative can grow and potentially increase the percent of recycled material used in manufacturing electronics. This program could also scale by purchasing other rare earth metal products to recycle into hard disk drives, such as magnets from MRI machines or motors from electric cars.

The expansion of new green technologies for rare-earth metal recycling has a lot of potential impact. It can shift the industry to use these recent technologies and lessen their environmental impact while also promoting suppliers to look for alternatives, such as recycling, rather than buying precious metals from mines that have low safety standards and cause numerous damages to the environmental and society. With the success of Dell's continuation of their circular economy, Dell continues to be a leader as one of the first to successfully achieve a closed loop supply chain for rare earth magnets. It is up to companies like Dell to pave the way, to exemplify how the electronic industry can provide the great benefit of technology while minimizing the environmental and social costs it takes to manufacture and produce these products.

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D.4

REGULATION: ECODESIGN, LABELLING AND FUTURE REGULATORY AREAS

How to improve the circularity of smartphones? A case study in the context of the Ecodesign Directive

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Abstract

Smartphones are products with a huge global market (almost 1.7 billion of smartphones are shipped every year in the world), a relatively short replacement cycle (2 years on average), and a residual value that decreases rapidly over the time of use. In the legal framework of the EU Ecodesign Directive (2009/125/EC), this paper presents a case study about the feasibility of requirements on material efficiency for smartphones, with which to improve their "circularity".

1 Introduction

1.1 Circular Economy and Ecodesign Directive

In the European Union (EU), the implementation of policies related to the Circular Economy (CE) is currently taking place with great emphasis. Already in 2015, the (first) Circular Economy Action Plan [1] pushed for surpassing the traditionally linear "take-make-discard" economic model and replacing it with a virtuous circle where the added value in products and materials is kept for as long as possible, waste is minimised, and resources are reused when a product has reached the end of its life to create further value.

In 2020, a new Circular Economy Action Plan [2] has been adopted at EU level, announcing initiatives along the entire life cycle of products, targeting for example their design, promoting circular economy processes, fostering sustainable consumption, and aiming to ensure that the resources used are kept in the EU economy for as long as possible. Among the various strands of activity, a legislative action is explicitly foreseen on mobile phones and tablets, to ensure that devices are designed for energy efficiency and durability, repairability, upgradability, maintenance, reuse and recycling. Within this policy framework, a pivotal role in order to foster resource efficiency is attributed to the Ecodesign Directive (European Union, 2009), in particular by promoting durability, repairability and recyclability of products. The Ecodesign Directive [3] requires manufacturers placing products on the EU market to improve their environmental performance by meeting mandatory minimum energy efficiency requirements, as well as other obligatory environmental requirements such as water consumption, emission levels or material efficiency aspects. The legislative framework based on the synergy between the Ecodesign Directive and the Energy Labelling Regulation [4] has been up to now of paramount importance, as it improves the energy efficiency of products and removes the worst-performing ones from the market, with positive effects on consumer expenditures over the life cycle of products and on extra revenues for industry, wholesale and retail sectors.

1.2 Material efficiency of smartphones

A recent report [5] from the Joint Research Centre of the European Commission investigated several material efficiency aspects of smartphones, identifying a list of possible actions for improving their performance with respect to aspects such as durability, repairability, upgradability, use of materials and recyclability. In line with these findings, material efficiency can be defined as the ratio between the performance of a system and the input of materials required, and can be improved through strategies aimed at minimising material consumption and waste production [6].

The relevance of material efficiency for mitigating environmental impacts depends on the relative impacts associated to the life cycle stages of a product [7]. Material efficiency is very important for smartphones. In fact, the direct impacts associated to the life cycle of such devices are mainly shaped by raw material extraction and manufacturing processes [5]. Compared to other ICTs such as computers or TVs, smartphones have a relatively lower use of electricity in the use phase [8]. However, the use phase becomes relevant when considering indirect energy consumption relating to data traffic (telecommunication network and data centres).

With an estimated market share of 1.7 bn units in 2020 [9], smartphones are very popular devices whose

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global contribution to greenhouse gas emissions is growing globally and is becoming greater than for other Information and Communication Technologies (ICT) devices [10].

1.3 Aim and structure of the paper

The aim of the paper is to discuss the feasibility of Ecodesign requirements on material efficiency in the case of a specific product group, i.e. the smartphones. This paper is organised in five sections. Section 2 describes the factors hindering the material efficiency of smartphones, both from the end-user and the product side. Section 3 presents the material efficiency hotspots following an analysis of the environmental impacts of smartphones. Section 4 devises a potential policy approach, and finally section 5 summarises the main findings of the paper.

2 User- and product-related factors hindering material efficiency of smartphones

The replacement cycle of smartphones was about 21 months in 2016, as global average [11]. This is close to the service contract length typically signed by consumers in Germany [12], as well as in other countries. The shorter the replacement cycle the higher the amount of e-waste generated, as well as the higher the consumption of materials.

The replacement of smartphones is often influenced by a perception of functional obsolescence driven by new models on the market [12]. However, other important causes of replacement include loss of performance, failures, misuse (e.g. drop on a hard surface and contact with water), and the lack of software support [13].

Results of a consumer survey [14] suggest that frequency of failures in smartphones can be relatively high. 47% of failures were reported to occur in the first two years of use, with the highest number of problems relating to battery (42%) and operating system (OS) (14%). In terms of repair frequencies, displays are the most critical parts [15].

Batteries degrade over time and with use. A sufficiently long battery lifetime can avoid the replacement of batteries and prolong the use of devices [16]. The lifetime of batteries is measured as calendar life and cycle life, which are desirable characteristics for batteries. Apart from design characteristics and ambient conditions, the battery lifetime depends also on operative conditions and user behaviour [17].

With respect to displays, almost 75% of damages are due to drops on corners or edges [18]. In case of damage, the entire display unit must be typically changed. Smartphones can be designed to withstand display stresses due to drops and contact with water [13]: product testing already covers durability tests against mechanical shocks, scratch resistance tests, water- and dust-proof tests [5]. Furthermore, screen protectors and protective cases can provide an additional level of resistance to mechanical stress [5].

In case a failure or damage occurs, a number of technical aspects and conditions can hinder or facilitate the repair of smartphones [19].

First of all, a lack of spare parts availability and software/firmware updates, as well as their price to the end-user, can be important barriers to repair. However, there is huge variation in the cost of repair, partly due to the difficulties associated to the replacement of batteries and displays. Repair of the display can cost up to 15-40% of the purchase price of new devices, while repair costs can be above 10% of the product price for other repair operations [5].

Repair could be facilitated when modular design concepts are implemented, when reversible fasteners are used, and when the repair can be carried out with simple and broadly available tools. However, design of smartphones has been shifting towards an increased use of adhesives and glues, which can in general make disassembly more difficult although reversible adhesives are now emerging [5].

Other important aspects to increase the durability of smartphones are the use of standardised interfaces (e.g. for connectors and external power supplies), and the availability maintenance and repair information. Currently, access to some information may be restricted because of safety, confidentiality and liability issues.

3 Enviromental analysis of material efficiency hotspots

The environmental impacts of the device and its parts are mainly due to raw materials extraction and processing, and parts manufacturing and assembling [20]. With a narrow focus on Global Warming Potential (GWP), the impact associated to the extraction and sourcing of gold and other metals (e.g. palladium) might be relevant for smartphones [21]. Cobalt, copper, gold and silver are also important materials for impact categories relating to resource scarcity, eutrophication and human toxicity [22]. In particular, contribution to life cycle impacts appeared significant for integrated circuit (IC), printed wiring board, display and camera. A smaller contribution could be instead associated to the battery [5].
Material efficiency strategies can effectively reduce environmental impacts [5], especially when oriented to extend the lifetime of the device and its parts (e.g. through design for reliability of repairability concepts),

and recovering value through reuse and remanufacturing (see Table 1).
Extending the average replacement cycle of devices from 2 years to 3 years was calculated to reduce the climate change impact by -30% (as an order of magnitude). Savings would be more moderate but still significant when the extension of lifetime is associated to battery change or display repair. The decrease of impact is still higher when remanufactured or second-hand devices are purchased (about -50% and -80%, respectively).
Furthermore, as a complementary strategy, the recycling of smartphone at the end of life (EOL) could reduce the climate change impact by 5%. Benefits of recycling would be better depicted through indicators relating to the scarcity of materials (e.g. Abiotic Depletion Potential). According to Proske et al. [23], recycling at the EOL could reduce impacts associated to materials and manufacturing stage by: 3% for GWP, 6% for ecotoxicity, 9% for abiotic depletion of fossil fuels, 10% for human toxicity, and 59% for abiotic depletion of elements. Moreover, recycling of materials is important because the composition of smartphones cover many critical raw materials (e.g. cobalt, rare earths) and minerals from conflict-affected and high-risk areas (e.g. gold) [24].

Material efficiency improvements through lean designs were instead considered more uncertain and difficult to quantify.
Furthermore, an important aspect to consider is that the inclusion of the energy used to operate communication networks would increase the climate change impact dramatically (by 250%). An energy demand of 55.7 kWh/year was estimated for operating the communication network, compared to 4 kWh/year for battery recharging and 4.7 kWh consumed for the assembly of a device (Cordella et al. 2020).

Table 1: Estimated impacts on GWP as an effect of material efficiency scenarios for smartphones

MATERIAL EFFICIENCY SCENARIO*	EFFECT ON THE GWP IMPACT
Replacement cycle increased to 3 years	-30%
Replacement cycle increased to 3 years with display/battery change	-23%/-29%
Purchase of remanufactured device (1:1 displacement)	-48%
Purchase of second-hand device (1:1 displacement)	-79%
Recycling at the EOL	-5%
Consideration of telecommunication network	+250%
*In the reference scenario smartphones are replaced every 2 years. At the end of life devices are kept unused at home and impacts relating to the usage of communication networks are not considered	

4 Policy approach

4.1 Process for the preparation of Ecodesign measures

The preparatory work for an Ecodesign measure (i.e. and Ecodesign Regulation) entails technical, procedural and legal steps. A specific product group is firstly analysed in a preparatory study, where the feasibility of proposing Ecodesign (and/or energy labelling) measures is investigated, following a techno-economic-environmental assessment in line with the Methodology for Ecodesign of Energy-related Products (MEErP) [25]. The MEErP provides policymakers with a comprehensive amount of findings, among which an analysis on the product functionality, on market figures and trends, on user behaviours, on the environmental impacts over the product life cycle and on the identification of the 'design option[1]' with the least life cycle cost (LLCC). The subsequent step is an 'impact assessment' [26], in which different policy options are analysed, across different impact dimensions (such as cost competitiveness, technological development and innovation, end-user affordability). If the analyses give favourable results, i.e. a potential Ecodesign (and/or energy labelling) Regulation is judged as feasible and effective to the extent that it sustainably decreases the environmental impacts of a certain product group, further procedural and legal steps take place. The process comes at its conclusion with the adoption of the Ecodesign Regulation and its publication on the Official Journal of the European Union.

4.2 Policy approach for the environmental impacts of smartphones

Following the findings of the recent report from the Joint Research Centre [5], an Ecodesign preparatory

[1] A specific product architecture, with technical features which make it more advanced and/or more efficient when compared to the 'base case', which is the average EU product defined for analysis.

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study[2] has been launched in early 2020, with the aim to investigate viable regulatory solutions to increase the reuse, repair and recycling rates of smartphones (and tablets, as long as it will emerge that, independently from typical usages, they share the same/similar physical and software architecture as smartphones, mainly with a difference in size). These requirements would affect smartphones at the moment of their placing on the market. Aspects related to durability, repairability, upgradability and recyclability are being analysed, by examining inter alia a) resistance to accidental drops, b) protection from water and dust, c) battery accessibility and longevity, d) availability of software/firmware/operating system updates, e) product durability, f) ability of the product to be disassembled, g) availability of priority spare parts, h) data deletion and transfer functionalities, i) ability of the product to be disassembled, and j) provision of appropriate information for users, repairers and recyclers.

If the relevance of the aforementioned aspects will be confirmed, the most suitable formulations at policy level will be analysed and proposed, with particular regard to the inclusion of such requirements within an Ecodesign Regulation. From this point of view, and as an effect of the policy commitment of the 2015 Circular Economy Action Plan [1], there is already a quite extensive set of Regulations (most of which have been published in 2019 [27]) whereby certain categories of requirements have been systematically addressed, notably:

- *Requirements on repairability*
  - Compulsory availability of critical spare parts for a given period, both for professional repairers and end-users
  - Ability of the product to be disassembled with the use of commonly available tools
  - Access to repair and maintenance information
  - Delivery of the spare parts within a maximum time
- *Requirements on recyclability*
  - Information on material content/typology
  - Information on dismantling steps, tools or technologies needed to access the targeted components.

It is also noteworthy to report the specific material efficiency requirements for servers and data storage products [28], related to ICT aspects:

- Compulsory availability of a functionality for secure data deletion
- Provision of latest available version of firmware.

Finally, requirements on durability have been proposed less frequently within the Ecodesign legal framework.

Developing Ecodesign requirements for smartphones will also imply facing a number of horizontal issues and challenges, which are described in the following subsections.

4.2.1 Fast technological evolution versus procedural timing

Smartphones, like all ICT products, undergo very fast technological changes [5], and this obviously implies a regulatory challenge. Criteria for providing a methodological framework to tackle this challenge can be found in literature, e.g. the concept of the "policy action window" [29], which is the maximum allowable timeframe to develop Ecodesign requirements. Exceeding this timeframe would mean being exposed to the risk of developing requirements that would be outdated at the time of their publication. A recent report [30] highlighted how, while a standard (Ecodesign) regulatory process for a product group takes around three and a half/four years, there have been cases where this process has taken significantly longer. From the above it is clear that, when preparing Ecodesign measures for a fast evolving product group such as the smartphones, the timeliness of the regulatory process will be a key factor in the policy success (bearing in mind that the needs and obligations of the standard procedural workflow have to be respected).

4.2.2 Applicability of the MEErP to the modelling of material efficiency requirements

As foreseen in the MEErP [25], smartphones on the EU market will be analysed in their technical features, and the LLCC should be identified. Ecodesign requirements are usually set on the basis of the identified LLCC, to gradually push the market towards increased energy efficiency levels. Given the importance of material efficiency aspects in this specific case study, an additional challenge [31] consists in the fact that the presence of environmental externalities makes it difficult to achieve high material efficiency, when only considering an end-user perspective (whereas in the case

[2] https://www.ecosmartphones.info/

of energy efficiency the interest of the owner of the appliance, who also pays the electricity bill, is well aligned with the societal interest of decreasing energy consumption). The MEErP will be revised (inter alia, to analyse if material efficiency aspects can be modelled more effectively) during 2020-21. As the findings of the MEErP review study will not be available in due time for the analysis on smartphones, dedicated approaches (on top of the existing ones already enshrined in the MEErP) for the modelling of economic and environmental impacts of material efficiency requirements should be adopted, in particular for the factoring in of product expected lifetimes, related trade-offs with other energy or material efficiency aspects, and environmental externalities. This should be accompanied by the systematic introduction of repair costs in the life cycle costs, when feasible, i.e. ensuring minimum data quality requirements on costs/prices (to prevent the modelling of design options with too scattered/uncertain information). Finally, the accounting of societal life cycle costs could certainly help in giving a robust rationale for establishing material efficiency requirements, in particular on recyclability. In fact, not integrating externalities in the consumer life cycle cost analysis would most likely result in not being able to highlight the differences in technological options in terms of recyclability [31] as, in general terms, there are no economic benefits, from the consumer viewpoint, in choosing more recyclable products.

4.2.3 Development of quantitative metrics

Adequate metrics and standards for assessing material efficiency aspects are a key factor in ensuring the uptake of material efficiency requirements [32]. To this extent, a standardisation mandate [33] was issued by the European Commission in 2015, asking the European standardisation organisations to develop ‘horizontal’ standards related to material efficiency in the framework of the Ecodesign policy (such as on durability, repairability, recyclability, recoverability and reusability). These ‘horizontal’ standards, now available, lay down the general principles, leaving the assessment at product-specific level to (subsequent) dedicated ‘vertical’ standards, if needed. Therefore, when Ecodesign requirements for smartphones would be proposed, it could be necessary to have the support of suitable quantitative methods for the assessment of material efficiency aspects, such as specific metrics to quantify the ability of a smartphone to be disassembled or dismantled. This will quite likely require further standardisation efforts, and the involvement of relevant stakeholders will be instrumental to ensure a successful delivery of the required methods.

5 Conclusions

A recent report from the JRC assessed the relevance of material efficiency aspects for smartphones, with the aim of compiling a list of possible actions for improving their performance with respect to aspects such as durability, repairability, upgradability, use of materials and recyclability.

Starting from this base, this paper elaborated on potential regulatory approaches aimed to increase the circularity of smartphones. It was shown how the Ecodesign Directive can provide the legal framework for improving the circularity of smartphones through the implementation of design measures addressing the above-mentioned material efficiency aspects. Various challenges from the regulatory point of view, such as timeliness of the process, fast technological evolution, applicability of the MEErP for the modelling of material efficiency requirements, and development of quantitative metrics and standards, were also discussed.

6 Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission. Neither the European Union institutions and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained therein.

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Regulating ICT products through EU ecodesign and energy labelling measures – a new approach

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Abstract

Product efficiency policies, such as minimum efficiency requirements (MEPS) and energy labelling, have been a great success. They result in large energy savings, a lower cost of ownership for end-users and drive innovation. Continuation and further development of these policies is part of a portfolio to improve energy and resource efficiency in view of the necessary reduction of CO_2-emissions. However, apart from displays, computers and servers, ICT products are not regulated for energy and resource efficiency in the EU. ICT products are seen as a special case, being "hard" to regulate because of different technical and market characteristics compared to other products. The challenge is to find those regulatory characteristics (instruments and policy process) that can properly deal with the technical and market characteristics of ICT products and achieve the desired policy aims.
This paper firstly looks into the background of the problems before taking up the challenge by proposing a strategy to regulate ICT products. Such a strategy can be summarized as follows: use a broad product group definition with a broad performance metric in combination with not too stringent targets (e.g. eliminating 30% of the least efficient products) that come into force taking into account the price development of the product in the market. If after applying the limits sufficient spread in energy efficiency is left, energy labelling classes can be defined. On top of this, built in a procedure that can quickly revise and update the regulation. Regarding resource efficiency, the paper shows that regulating these aspects for ICT products does not seem to differ from the (challenges of) regulating resource efficiency for other products. A reparability scoring index could be included on the energy label.

1 Introduction

Product efficiency policies, such as minimum efficiency requirements (MEPS), energy labelling and voluntary agreements, have been a great success [1], [2]. They result in large energy savings, a lower cost of ownership for end-users and drive innovation. Continuation and further development of these policies is part of a portfolio to improve energy efficiency in view of the necessary reduction of CO_2-emissions.

ICT (information and communication technology) products are seen as a special case, being "hard" to regulate because of different technical and market characteristics compared to other products. The fact that ICT products are by definition connected to other products, introduces system aspects, e.g. the use of ICT products can result in energy savings in other products, installations or buildings. The Circular Economy Action Plan [3] also highlights the circular economy potential (resource efficiency) of ICT products. Figure 1 provides an overview of these aspects, acknowledging that they are connected.

The challenge is to find those regulatory characteristics (instruments and policy process) that can properly deal with the technical and market characteristics of ICT products and achieve the desired policy aims.

To do so, the paper will first look into several general issues and the background of the problems to be able to more specifically define the challenges for regulating energy efficiency of ICT products. Then, it will present proposals to meet these challenges.

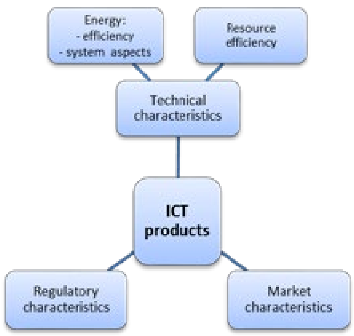

Figure 1: Overview

2 ICT products: technical, market and regulatory characteristics

2.1 Introduction: general developments in products

The development of electronics and software has dramatically changed (energy-using) products in general. This includes products being "programmable" meaning that the functionality is not changed by replacing hardware but by providing different "instructions" (programmes) to the product, and products being connected to a network and becoming depended on that connection. A typical example of a product that in the last years has changed from a hardware only into a programmable and connected product is the lamp. The classic lamp will emit light in one color and can be switched on and off. LED lamps can be connected to the home network or internet to be controlled remotely and can change the color and brightness of the light output. The combination of software playing a major role in the function of the product and dependence on connectivity for the functionality of the product creates 'virtual' products ([4], p. 174). Virtual means that the function the product provides is produced outside the product that is operated by the end-user; the internet-connected thermostat is an example of a virtual product.

The consequences of the two general trends (software and connectivity) are the following. Software (co)determines functionality, therefore functions can easily be modified and added, resulting in products with multiple functions or a large variety of options to tune the main functions. Software, in combination with sensors, also allows for better control of the performance of the product, e.g. to react on changes in load: dishwashers adapting performance to the degree of dirt on the dishes or washing machines adapting the number of rinsing cycles to remaining particles in the rinse water.

Furthermore, with functions realized in software these functions can easily be updated; not only in new products but – because of the network connection – also "on the go" as the product stays at the place where it is used. So, the product the consumer bought can change functionality by means of a software update or upgrade. This is nothing new for personal computers, set-top boxes or tablets but is now also done for washing machines.

2.2 Technical characteristics

2.2.1 Introduction: what are ICT products?

Given the trends indicated in the foregoing section, it can be concluded that almost all products have "ICT characteristics": ever more products are connected to a network and almost all products have a processor in some form and include software. However, the term 'ICT products' is reserved for products that have information (data) processing and connectivity as their main function, e.g. computers, routers, base stations, network attached storage, servers, home gateways, telephones. Also consumer electronic (CE) products, e.g. televisions, audio systems and set-top boxes, can be considered as a subgroup of ICT products.

A distinction can be made between network equipment and edge devices, where network equipment can be subdivided into ICT infrastructure (data centres, networks and other infrastructure) and user premises network equipment (small network equipment: SNE).

Note that the category edge devices also contains other products than ICT products that are connected to a network: e.g. connected washing machines, smoke alarms and boilers. Moreover, the boundary between edge devices and SNE is blurred because several edge devices have network functions, e.g. a set-top box or a beamer can have a network access point. In line with the observations in the foregoing section this means that differentiation probably needs to be done on a functional level.

2.2.2 Technical characteristics: energy aspects

This section briefly lists the energy aspects related to ICT products and connectivity. First, connectivity needs power: products that are connected to a network will less likely be switched off. They "listen" to the network, also when not performing their main function, in order to be able to react to signals on the network (network standby).

Many devices that connect to a network, especially smaller, operate on a battery or are energy wise autarkic through energy harvesting. These products have an intrinsic motivation to use as little energy as possible and therefore are mostly disregarded by efficiency measures. However, they might be relevant for resource efficiency measures (see section 2.2.3).

The power and energy consumption of externally powered products (230 V mains, Power over Ethernet (PoE), USB powered) can easily be measured. However, measuring efficiency also requires measuring performance which is often more difficult. Furthermore, the concept of efficiency suggests that power consumption varies with varying performance; however, many network products do not (yet) vary power consumption with performance.

Connected products can influence the performance or energy consumption of other products, and e.g. in the scope of building automation this is the specific purpose of products like thermostats and sensors. More general, evaluation of the energy consumption of individual ICT products needs to take into account system impacts, including the use of (renewable) energy in data centres. This is difficult from both a methodological and practical perspective.

2.2.3 Technical characteristics: resource efficiency

The Circular Economy Action Plan [3] specifically pays attention to the contribution of eco-design measures to the circular economy (resource efficiency). Non-energy impacts like resource efficiency become (relatively) more important when energy consumption is decreasing; e.g. for laptops non-energy impacts are more important than energy impacts.

Resource efficiency aspects of ICT products are dominated by electronics. This means that, contrary to energy efficiency aspects, they are less influenced by software developments and changes in functionality. With increasing integration of electronics, the importance of the production phase further increases and per unit there is less material to be recovered.

Resource efficiency impacts are dominated by the life time of the product. This in turn depends on durability, repairability, upgradability and performance obsolescence (newer products on the market have a better performance). Especially products with regular software updates, e.g. computers but also smart phones, can become obsolete by a vicious hardware-software cycle.

2.3 Market characteristics

The market of ICT products is characterized, driven or sometimes dominated by the technology development of the main component, the chip (processor, storage). New chip generations offer increased integration, new functionalities and increased performance, often with increased efficiency.

Or stated the other way around, product development of ICT products depends on the generation of chip technology that is used. Products with the newest generation in general offer newer/more functions and increased performance and are sold at a premium price. However, when production continues learning effects and marketing (the more units are sold the less exclusive they are and the lower the price premium can be) result in quickly decreasing prices until the generation is superseded by the next with better performance and/or new features.

ICT products show a relation between performance and efficiency: products with higher performance are in general more efficient. The reason is that new chip generations that deliver the higher performance are more efficient; they even need to be more efficient to deliver the higher performance within the acceptable thermal limits. However, for these products the relation between efficiency and price is a spurious one: a product is more expensive because it has a better performance and thereby also more efficient. Apart from this, if efficiency is to a large extent determined by software and not by (more expensive) hardware, the relation between efficiency and cost becomes weaker because software costs are largely fixed and therefore the cost per unit depends on the number of units sold.

2.4 Regulatory characteristics: challenges to regulate ICT products

Why is it so hard to regulate the energy efficiency of ICT products, according to the EU framework? First, the Ecodesign Directive stipulates that requirements shall be aiming at the least life cycle cost point. This assumes that there is a relation between the efficiency and the price of a product: more efficient products cost more, but use less energy and therefore have lower running costs. If the design options to make a product more efficient are implemented starting with the option with the shortest payback period, then the total life cycle costs will first decrease until they reach a minimum, the least life cycle cost point. After this point, the total life cycle costs will increase because the increase of the product price is no longer compensated for by saved energy costs. At some point the life cycle costs will be equal to the starting point where no design options were implemented, and the most efficient products even may have higher life cycle costs.

However, for ICT products the assumption of a positive relation between efficiency and price is flawed (see section 2.3; [4]), so the least life cycle cost methodology cannot be used to set requirements.

Second, the methodology requires insight into (future) design options to make products more efficient, and – indirectly – insight into development of the performance and functionality of the product. However, manufacturers are not willing to disclose information, including costs, on these developments, and certainly not on new features and functionalities. Moreover, certainly on the longer run, also manufacturers probably have little idea about new developments and specifically which developments will become mainstream.

A third point is that the process for setting requirements takes time, which increases the uncertainty about the actual performance and functionality of the products to which the requirements would apply. Is the product that is analyzed during the preparatory phase still on the market when the requirements come into force? Therefore, it also seems less suitable to set multi-tier requirements, because these require a longer time horizon.

Finally, it is difficult to assess savings potentials of ICT products that can be realized by applying regulatory measures. Partly this is because of the point made above that it is difficult to estimate future product and market developments, certainly when focusing on specific products. Another issue is that apparently large efficiency improvements happen without any regulatory intervention. Especially for mobile products, increasing efficiency is a must because of limited battery capacity and thermal management. The latter aspect also plays a role for mains powered ICT products like set-top boxes and routers. And in general, each successive chip generation is more efficient. However, on the other hand, when designing ICT products priority is given to functionality and time-to-market because a premium price can be asked for products with new or improved functionalities that are new on the market.

Thus, the challenges are first to make a case for regulating ICT products and – if this case can be made – second to develop a suitable methodology/process for regulating ICT products. The rest of this section will provide a general argument for regulating ICT products, whereas the next section will develop a new approach for regulating energy efficiency of ICT products.

The case for regulating ICT products is made by a combination of the following:

- The large and increasing volume of ICT products.
- For most ICT products, the (maximum) power consumption is limited.
- Improving energy efficiency comes at no or very little material cost; it mainly requires attention in the design phase.
- Looking at individual products on the market, variation in energy efficiency exists although it may be limited.

The large and increasing volume of ICT products means that the total energy consumption on ICT products is significant and will increase [5], [6]. The limited power consumption per product means that the energy consumption of a product is of little relevance for the individual end-user and will not be a motivation to buy a more efficient product. Also, performance and features are more relevant than energy efficiency, and in some cases like set-top boxes and routers that are supplied by a service provider, the end-user does not even have a choice.

So, the combination of the significant and increasing total energy consumption and the limited consumption per product would in principle justify regulatory action.

The two other points indicate that improving energy efficiency is possible and is not an excessive burden for manufacturers. The last point refers to variation in energy efficiency for individual products at a certain point in time. However, paying attention to energy efficiency as a long-term strategy will also influence the development of future chip generations, as developments in mobile products show.

3 A new approach for regulating energy efficiency of ICT products

3.1 Introduction

From the foregoing section the following challenges can be identified when regulating energy efficiency of ICT products:

- Defining the product group to be regulated, taking into account that functionality can easily be changed through software.
- Setting minimum efficiency targets, including the date of entry into force, taking into account that the least life cycle cost methodology may not provide any guidance.
- Estimation of savings and relation with other instruments.

These challenges are related as the following illustrates. Using a "broad" product definition will leave less loopholes to exploit for avoiding a specific model to be covered. However, setting minimum targets might become challenging because a broad spectrum of (secondary) functions need to be taken into account. A solution could be to set relatively relaxed minimum targets to accommodate for a variety of (secondary) functions and apply an energy label to identify the most efficient products.

3.2 Defining the product category

Currently a broad definition of ICT products ('information technology equipment') is given in article 2(7) of regulation EC/1275/2008:

'information technology equipment' means any equipment which has a primary function of either entry, storage, display, retrieval, transmission, processing, switching, or control, of data and of telecommunication messages or a combination of these functions and may be equipped with one or more terminal ports typically operated for information transfer;

This definition can be seen as including consumer electronics, although not all CE products use telecommunications. Annex I, point 3 of regulation EC/1275/2008 provides the following definition of consumer electronics:

equipment for the purpose of recording or reproducing sound or images, including signals or other technologies for the distribution of sound and image other than by telecommunications.

The definition of ICT products above in principle covers all functions of ICT products: entry (input), storage and retrieval, transmission, processing, switching (routing) or control. It is not the intention of this paper to provide specific definitions of product groups, but the suggestion is to use the functions of ICT products; the main functionality can then be used to specify the (main) performance of the product: display area for the display function, storage capacity for the storage function, etc.

Unless further specified this will lead to relatively broad product definitions, which in turn point in the direction of a combination of not too stringent minimum efficiency targets and an energy label. Such an approach has the following advantages. It avoids discussing how to deal, e.g. by allowances, with specific variants or features of products, and leaves room for product development (new features). Second, it leaves room for an energy label approach that can be less sensitive to (new) features: an energy label does not ban products from the market. Third, it makes the target setting less sensitive to the quality of data, which specifically for the first time can be low.

A major issue to work on is the performance metric for the processing function. Further issues to look at are:

- Testing conditions for verification and enforcement.
- Software downloads and upgrades.

The testing protocol must prevent the use of "optimized modes" for testing that are not or less used in practice, e.g. specific "eco" modes or conditions that change whenever the end-user changes any setting; see e.g. experiences with televisions [7]. More difficult is the role of software downloads or upgrades after the product has been bought and installed; the revised energy label regulation contains a provision on this.

3.3 Setting minimum efficiency targets and energy labelling classes

The first step is to assess for a product group whether the relation between efficiency and price is positive, taking into account time and performance. For this assessment, historical data on these variables is needed; this data is also necessary for setting the targets. If the product has never/nowhere been regulated, collecting performance and power consumption data might be a challenge. Since ICT products are often worldwide traded products, also data from other parts in the world is useful. Regarding prices, not the absolute level but the relative price level is important, so consistency of sources is more important than coverage of different markets.

In case no or a positive relation between price and efficiency is assessed and therefore the least life cycle cost methodology cannot guide setting of requirements, three approaches can be distinguished based on the variation in efficiency in products on the market:

- A minimum efficiency approach where the level is set to cut off around 20% of the market.
- An average efficiency approach where the level is set to cut off around 50% of the market.
- A maximum efficiency or top runner approach where the level is set to cut off around 80% of the market.

The choice for a certain approach depends, amongst others, on the ambition of the policy. Other factors that play a role are the expected future developments in efficiency of the product combined with the need to ensure sufficient competition. As argued above, it may be useful to set not too stringent targets (around a 30 % cut off level) because this reduces flexibility regarding secondary and future functionalities. Also, the first time a requirement is set for a product group, manufacturers might need a bit more leeway.

If minimum requirements are set, energy label classes can be defined as follows. A reference power or energy consumption is defined, based on the metric used for the minimum requirement. Then an energy efficiency index is defined as $EEI = E_{measured} / E_{reference}$. With the data, the (spread in) EEI of existing products is calculated and the energy class boundaries can then be set evenly across the range of EEI. The energy label can also be used to provide information on resource efficiency aspects, notably on repairability ("repairability score").

Selecting the appropriate entry into force date is the second parameter of a product efficiency measure. Although the procedure in this section is to be applied when there is no direct relation between price and efficiency, it is known that for some products a higher efficiency can be more easily achieved by higher performing products which cost more, certainly when recently introduced on the market. Also the date of entry into force needs to take into account the impact of the measure on manufacturers. Therefore, it is proposed that the average price decrease of the product guides the setting of the entry into force date, as follows. Calculate the average price p_{MEPS} of the products that remain on the market when applying the target level (at the time of analysis T_0). This price should decrease to the average price of products p_0 on the market before applying the target level. The reasoning is – as with the least life cycle cost methodology – that consumers do not need, on average, to pay more. Assuming that the price of the product decreases exponentially over time with time constant c , the entry into force date T_1 can be calculated by $T_1 - T_0 = -\ln(p_{MEPS}/p_0)/c$.

This date of entry into force is a first indication and can be subject to other considerations. The entry in to force date of product information requirements, including labelling, can in general be one year from publication of the regulation and is independent of the entry into force date for the requirements.

It has been argued that consistency and a long-term approach are important to secure persistent savings from any product efficiency policy. This means that the procedure described above should be repeated regularly. The procedural challenge is to keep such revisions as short as possible; below follow some suggestions. It might be useful to specify the procedure in the regulation, including a clear deadline.

The procedure described in this section assumes that sufficient variation in efficiency in products on the market exists. So, the first step in the revision process is to assess the variation in efficiency on the market. The data for this exercise should be available due to the provisions in the regulation. Second step is a check of the product definition and the efficiency metric: are these still capturing the large majority of products on the market? If one of these two checks is negative (not enough variation, definition and/or metric not up to date) then a more elaborate process might be needed. If both checks are positive, then the procedure as indicated above can be repeated, and the new targets and date of entry into force can be published.

3.4 Combination with other instruments; estimation of savings

Regarding combinations with other instruments, it has been already suggested above to combine minimum requirements with an energy label. This assumes that the efficiency metric captures the largest part of the energy consumption of the product and that differences in energy consumption between classes are relevant.

Outside the EU, several ICT products are covered by the voluntary US-EPA Energy Star programme. This raises the question whether a voluntary label that rewards the most efficient products could be combined with minimum requirements. This approach has as main drawbacks that a voluntary label would need to build-up brand awareness comparable to the EU energy label, and that it would "compete" with the Energy Star label. Regarding the latter, manufacturers are not keen on having different (voluntary) labels for products they ship worldwide. Using the Energy Star itself as such a voluntary label introduces issues of coordination, both procedural and content wise, with the minimum requirements set in the ecodesign framework.

Another point is estimation of savings. Savings are estimated as the difference between the BAU (business as usual) situation, without measures, and the situation with measures. In the case of the methodology suggested in this section, it is the difference between the energy consumption of products according to the original market distribution and the energy consumption according to a distribution where the 30 % least efficient products are improved to the minimum requirement, calculated over the life time of the products. The impact of the energy label could be simulated by an extra increase in the minimum efficiency, equivalent to e.g. removing another 20 % of the least efficient products, so that the impact of both minimum requirements and energy label would be the removal of the 50% least efficient products.

4 Conclusions and recommendations

This paper shows that it is possible to regulate energy efficiency of ICT products where the least life cycle cost methodology is not applicable.

Challenges for regulating ICT products are first defining the scope (product group) of a regulation and an efficiency metric. It seems desirable to use a relatively broad scope, e.g. home network equipment as suggested in the Ecodesign Working Plan 2016-2019.

A second challenge is defining a performance or efficiency metric for the product group to be regulated. In this case too, it can be desirable to choose a more broad, general metric in order to prevent fine tuning by means of allowances.

These and other considerations resulted in the suggestion for the following strategy for regulating ICT products: use a broad product group definition with a broad performance metric in combination with not too stringent targets (e.g. eliminating 30% of the least efficient products) and an energy label if there is sufficient spread in efficiency left. Moreover, built in a procedure that can quickly revise and update the regulation.

Furthermore, testing conditions and software downloads have been identified as issues to look at, but these also play a role when regulating other products.

Apart from the definition of the product group, regulating resource efficiency aspects for ICT products does not seem to differ from the (challenges of) regulating these aspects for other products. Information on some resource efficiency aspects can be provided on the energy label and/or the product information sheet.

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Avoiding losses of energy savings caused by possible circumvention of EU Ecodesign and Energy labelling regulation and standards

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Abstract

Whereas reasons for and remedy against non-compliance under EU Ecodesign and Energy labelling legislation have already been well analysed, the topic of suspect test results or ‘circumvention’ received a lot of policy and media attention only recently, not only for car emissions, but also regarding potential negative effects for other legislation. The European Union’s Horizon 2020 research and innovation programme is funding the project “ANTICSS – Anti-Circumvention of Standards for better market Surveillance”. This paper provides initial results: a clear definition and examples of ‘circumvention’ in the context of EU Ecodesign and Energy labelling legislation and relevant harmonised standards, a rough estimation of the magnitude of possible energy saving losses due to ‘circumvention’ based on collected cases and tested products, and alternative test procedures to unmask ‘circumvention’ under testing conditions. Finally, initial recommendations for policy makers and standardisation bodies to prevent future ’circumvention’ under EU Ecodesign and Energy labelling are given.

1 Introduction

The European Commission estimates that 10-25% of products on the market do not fully comply with energy efficiency labelling regulations and around 10% of potential energy savings are lost due to non-compliance [1]. According to a Special Report ‘EU action on Ecodesign and Energy Labelling: important contribution to greater energy efficiency reduced by significant delays and non-compliance’ of the European Court of Auditors this would roughly correspond to the final electricity consumption of Sweden and Hungary combined [2]. Reasons for non-compliance include a missing or incorrect energy label, the non-compliance with information requirements, as well as incorrect classification of the energy class.

While the reasons for non-conformity, i.e. ‘non-compliance’ with requirements, and possible remedial measures have already been well analysed, the issue of suspect or manipulated test results, i.e. ‘circumvention’ of measurement standards and minimum requirements in the context of EU Ecodesign and Energy labelling, has only recently started to receive political attention.

Triggered by the diesel scandal, in which vehicles contained a certain defeat device that guaranteed compliance with emission limits only on the test bench, the aim is to investigate whether such manipulations are also possible under other EU legislation.

Against this background, the European Union’s Horizon 2020 research and innovation programme is funding (2018-2021) the project ‘ANTICSS – Anti-Circumvention of Standards for better market Surveillance’ conducted by 19 partners of independent researchers, Market Surveillance Authorities, test laboratories, standardisation and consumer organisations of eight countries. Overall objective is to assess and clearly define ‘circumvention’ in relation to EU Ecodesign and Energy labelling legislation and relevant harmonised standards, assess the potential impacts of circumvention and facilitate preventing future circumvention acts under EU Ecodesign and Energy labelling.

2 Circumvention and delimitation to other effects

2.1 Circumvention is different to non-compliance

One of the most important findings of the research project is that ‘circumvention’ goes far beyond ‘non-compliance’ and is at the same time much more difficult to detect: Market Surveillance Authorities can detect non-compliance relatively easily by inspecting product documentation and/or by laboratory tests. The information and results are compared with the requirements laid down in legislation and standards. If they do not conform with the Ecodesign and Energy labelling requirements, the Market Surveillance Authorities can claim the product as non-compliant.

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In contrast, in case of circumvention the product does not directly appear to be non-compliant during testing. At first glance, the products appear to meet all requirements and conditions in the standardized laboratory test. However, the test results are influenced in such a way that they are more positive specifically under test conditions: by circumventing minimum requirements or measurement standards or by exploiting (potential) weaknesses or gaps in standards and legislation.

2.2 Definition of circumvention

2.2.1 Article on circumvention in recently adopted Ecodesign regulations

Most of the recently adopted Ecodesign regulations include an article on circumvention (see Figure 1):

Article in recently adopted Ecodesign regulations

Circumvention

The manufacturer, importer or authorised representative shall not place on the market products designed to be able to detect they are being tested (e.g. by recognising the test conditions or test cycle), and to react specifically by automatically altering their performance during the test with the aim of reaching a more favourable level for any of the parameters declared by the manufacturer, importer or authorised representative in the technical documentation or included in any of the documentation provided.

Figure 1: Article on circumvention in recently adopted ecodesign regulations

The focus is on situations where the product is programmed in a way to *'recognize' the test situation* and *automatically* optimize the product performance and/or resource consumption specifically *during* the test.

2.2.2 More comprehensive ANTICSS definition of circumvention

The ANTICSS project has extensively investigated the possibilities of circumventing the system. Through literature research and analysis of existing legislation and measurement standards on ecodesign and energy labelling, possible gaps and loopholes were identified.

Further, in a survey of 278 experts from manufacturers, Market Surveillance Authorities, test laboratories, as well as consumer and environmental organisations, 39 suspicious cases were collected and analysed.

These reported cases clearly show that circumvention under EU Ecodesign and Energy labelling not only applies by automatic detection of the test situation and alteration of the product performance during testing as already included in some Ecodesign and Energy label regulations (see Figure 1) and prohibited accordingly.

In addition, a better test result can also be achieved by making certain pre-settings or *manual* alterations to the product – exclusively for the purpose of performing the test. Such 'manufacturer's instructions' are sometimes necessary for the implementation of the standard procedures, e.g. for safety reasons, and therefore officially included in some test standards. However, if instructions are solely provided for test laboratories and at the same time (mis-)used in a way that the result is specifically optimized under testing, this also counts as circumvention in the opinion of the ANTICSS project.

A third way of circumvention could be by programming products to achieve very good energy efficiency or resource consumption values specifically for the period in which the conformity test is usually performed or for a predefined number of test cycles. At the time of delivery, the product is already programmed in a way to automatically change its performance *some time after the product is put into service*, to make it more attractive to users but at the expense of the officially labelled energy or resource consumption which is usually measured directly after the product is put into service. The automatic alteration does not take place *during* the test but only afterwards, and the algorithm is already installed in the delivered product, i.e. not provided via external software update as this would be prohibited according to the most recent Ecodesign regulations.

Against this background, the ANTICSS project developed a more comprehensive definition of circumvention including all three possible routes (see Figure 2):

ANTICSS definition of circumvention

"Circumvention is the act of designing a product or prescribing test instructions, leading to an alteration of the behaviour or the properties of the product, specifically in the test situation, in order to reach more favourable results for any of the parameters specified in the relevant delegated or implemented act, or included in any of the documentations provided for the product."

The act of circumvention is relevant only under test conditions and can be executed e.g.

a) by automatic detection of the test situation and alteration of the product performance and/or resource consumption during test, or

b) by pre-set or manual alteration of the product, affecting performance and/or resource consumption during test or

c) by pre-set alteration of the performance within a short period after putting the product into service

Figure 2: ANTICSS definition of circumvention

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2.3 ‘Jeopardy effects’

Besides rather clear acts of circumvention, i.e. designing a product or prescribing test instructions, leading to an alteration of the product in order to reach more favourable results *specifically in the test situation*, several cases not being that clear were collected in the ANTICSS project, nevertheless being suspicious.

The main point is the clause of the ANTICSS definition that “the act of circumvention is relevant *only* under test conditions”. In some cases, however, the manufacturer’s instructions as basis for product set-up during standard testing are not exclusively included in the ‘instructions for test laboratories’ but also in the user instructions. Partly, even the harmonized standards refer to instructions in the user manual. For example, EN 60350-1 for measuring the performance of household electric cooking appliances under EU Ecodesign states that “Removable items specified in the user instructions to be not essential for the operation of the appliance in the manner for which it is intended shall be removed before measurement is carried out.”

Formally, this provides the possibility of such product setting also in users’ everyday life. Nevertheless, in some cases the operation of a product according to the manufacturer’s instructions seems to be a rather exceptional use and not the usually intended or main operation of the appliance. So, it remains suspected that the inclusion of certain instructions, even if officially admitted according to the standards, is intended for reaching more favourable results mainly under testing. In most of the product’s usual operations, the measurement results obtained in this way will rather be worse than the declared performance parameters.

Against this background, the ANTICSS project developed an additional category called ‘jeopardy effects’ which may not be classified as circumvention per se but become possible due to loopholes or other weaknesses in standards or regulations (see Figure 3).

ANTICSS definition of jeopardy effects

Jeopardy effects encompass all aspects of products or test instructions, or interpretation of test results which do not follow the goal of the EU Ecodesign and/or Energy labelling legislation of setting ecodesign requirements and providing reliable information about the resource consumption and/or performance of a product. These effects may not be classified as circumvention but become possible due to loopholes or other weaknesses in standards or regulations.

Figure 3: ANTICSS definition of jeopardy effects

2.4 Delimitation to ‘missing representativeness’ of harmonized standards

Circumvention acts and jeopardy effects as defined by the ANTICSS project are not to be confused with the fact that test standards might not always reflect typical consumer usage and latest technological developments and for these reasons measurements in real life might deviate from the declared performance parameters.

Resulting differences in energy consumption between standard tests and measurement approaches that better reflect real world usage can lead to consumers having a false impression of running costs in the home; and test standards that do not keep pace with technological progress can prevent the measurement of energy used by these new features, and fail to incentivise manufacturers to make those features energy-efficient. [3] Further, the underlying average European usage patterns in harmonized standards might deviate from typical appliance operations due to country-specific differences in usage behaviour; e.g. in some southern countries washing is usually done at lower temperatures than applied in the standard tests.

Although this ‘missing representativeness’ of some test standards is unsatisfactory, it cannot be classified as circumvention if manufacturers strictly follow the harmonized standard tests for determining the product performance values to be declared e.g. on the Energy label, but the realistic consumer use deviates from these measurement conditions and results.

Nevertheless, according to the Energy labelling Regulation (EU) 2017/1369, harmonized standards shall aim to simulate real-life usage as far as possible while maintaining a standard test method with measurement and calculation methods included being reliable, accurate and reproducible. [4]

On the other hand, the more harmonized standards deviate from typical user behaviour, entail very specific conditions or include ambiguities and loopholes, the higher is the likelihood that products are designed to be able to detect these test conditions or test cycles or that manufacturers exploit the loopholes in a way to achieve more favourable results for their products, i.e. the risk of circumvention or jeopardy effects is increasing.

3 Alternative test procedures to detect circumvention or jeopardy effects

Within the ANTICSS project, alternative test methods to detect the circumvention behaviour or jeopardy effects were developed for 18 different suspected cases and tested for their applicability and effectiveness by the test laboratories in the project. It has to be noted that the ANTICSS alternative test methods differ from those test methods that have been alternatively developed by other organisations to better reflect real life usage conditions for products, i.e. addressing the missing representativeness of test standards (see previous section), for the following reason:

As described above, when products or respective test settings have been manipulated with the aim of circumvention or exploiting loopholes, products apparently appear to conform the legal requirements when tested with the standardised test methods. Therefore, only those aspects of the test conditions which are under suspect of manipulation are varied very slightly. At the same time, the alternative procedures are still designed as close as possible to the standard procedures with the aim to ensure comparability with the original measurement results (although, it was not proven within the ANTICSS project that those alternative methods deliver repeatable and reproducible results comparable to the original standardised methods).

If, however, the alternative approach leads to inexplicably relevant changes in the measurement results, this may indicate that the appliance might have been specifically optimised for the standard test.

4 Circumvention or jeopardy effects: Test results of ANTICSS

4.1 Example 1: Dishwashers – specific loading instructions

Standard EN 50242:2016 for measuring the performance of electric household dishwashers, states: '*The dishwasher manufacturer's instructions regarding installation and use shall be followed*.'

In the tested dishwasher model, it is necessary for the standard testing to remove or alter the position of many of the "accessories" that are fitted to the appliance as supplied. Instructions on removal of all the relevant parts are solely given in the 'Instructions for Test Laboratories', not in the user instructions.

For the ANTICSS alternative testing procedure, tests are conducted according to the standard conditions (EN 50242:2016) and manufacturer's instructions but *without* removing or altering the accessories. An alternative loading scheme is designed, fitting the maximum number of place settings and corresponding serving pieces when the machine is loaded "as supplied".

With the alternative loading scheme and all accessories kept included in the machine, only 12 instead of 16 place settings can be fitted into the dishwasher, see Table 1. By this, the capacity, i.e. loadable number of place settings, is decreasing by 25%. The specific energy and water consumption per place setting increase by 29% and 34% compared to the standard test results. The energy efficiency class, however, is not affected.

	Standard test results	ANTICSS alternative test results	Deviation
Standard place settings (ps)	16	12	-25%
Specific energy consumption (Wh/ps)	47.2	60.9	+29%
Specific water consumption (L/ps)	0.68	0.91	+34%
Energy efficiency class	A+++	A+++	No difference

Table 1: ANTICSS test results, dishwasher model

By these manufacturer's instructions regarding a loading scheme exclusively provided for test institutes, the product is manually altered, and the resource consumption is affected only during the test situation.

The loading capacity is one of the declared parameters on the Energy Label and thus a purchase criterion for consumers. Since the loading capacity is also used to calculate the Energy Efficiency Index (EEI), a higher loading capacity might help reaching a better energy efficiency class, although this is not the case for the specific model tested within the ANTICSS project.

4.2 Example 2: Ovens – volume measurement without shelf guides

Standard EN 60350-1:2016 for measuring the performance of household electric cooking appliances states the following for measuring the volume:
'*Removable items specified in the user instructions to be not essential for the operation of the appliance in the manner for which it is intended shall be removed before measurement is carried out*.'

In the tested oven model, the user instructions contain one specific recipe for making yogurt which indicates it is necessary to remove the accessories and shelves and the cooking compartment must be empty.

Due to this specific recipe in the user instructions, the standard measurement of the volume has to be done removing all shelf guides. For the ANTICSS alternative testing procedure, tests are conducted according to standard conditions (EN 60350-1:2016), however, the volume of the oven is measured *with* the shelf guides in their position.

In the alternative procedure, the volume with shelf guides included is significantly lower (9 litres or around 13%) than in the standard procedure without the shelf guides, see Table 2. The energy consumption is the same for the standard and the alternative testing. However, the difference in the volume has an impact on the calculated Energy Efficiency Index (EEI) which is 5% higher than under standard test conditions. For the tested model, however, the higher EEI does not result in a change of the energy efficiency class.

	Standard test results	ANTICSS alternative test results	Deviation
Volume (L)	71	62	-13%
Energy consumption (kWh/cycle)	0.71	0.71	0%
Energy Efficiency Index	83.5	87.7	+5%
Energy efficiency class	A	A	No difference

Table 2: ANTICSS test results, oven model

The inclusion of a recipe where the shelf guides are not needed (which is then basis for the standard testing) was not exclusively provided in the instructions for test laboratories only but included in the user instructions.

At least theoretically, this provides the possibility of such a setting also in real life. Nevertheless, the use of an oven without shelf guides seems to be an exceptional use and not the operation of the appliance in the manner for which it is usually intended, so it remains suspected that the inclusion of such a recipe is intended for reaching more favourable results under testing.

The volume of an oven is one of the declared parameters on the Energy Label and thus a purchase criterion for consumers. Since the volume is also used to calculate the Energy Efficiency Index (EEI), a higher volume might help reaching a better Energy Efficiency Class, although this is not the case for this specific model tested within the ANTICSS project.

4.3 Example 3: Refrigerating appliances – screen switch-off function

Standard EN IEC 62552:2013 for measuring the performance of household refrigerating appliances states: '*The refrigerating appliance shall be set up as in service in accordance with the manufacturer's instructions*.' For the tested refrigerating model, a display of a controller is activated each time the door is opened. The appliance does not have a functionality to turn off the display permanently.

It only has a parameter which controls whether the display remains always on or is turned off after 24 hours without door detection; it is not possible to increase or shorten this time in the settings. The user instructions state to leave the 'screen switch-off function' in the preset value (i.e. turn-off after 24 hours without door openings) in order to save energy and that in case the preset switch-off function is disabled the energy consumption will slightly increase.

Therefore, also the standard test has to be done with the screen switch-off function enabled, i.e. automatic turn-off after 24 hours without door openings. However, as the standard test does not foresee any door openings this means that the display will be permanently turned off under testing, whereas in everyday life, the display will most of the time be activated due to the normal use of the refrigerator with daily door openings.

For the ANTICSS alternative test procedure, the input power of the display is measured separately during an off cycle of the cooling system, while switching the display on and off. The difference of the measured input power is accounted to the display. The annual energy consumption of the appliance is then calculated by adding the energy consumption of the activated display (estimating the number of days per year the display is activated) to the annual energy consumption under standard conditions.

	Standard test results	ANTICSS alternative test results	Deviation
Energy consumption (kWh/year)	169	186	+10.3%
Energy Efficiency Index	20.3	22.4	+10.3%
Energy efficiency class	A+++	A++	1 class

Table 3: ANTICSS test results, refrigerating model

The results show an additional energy consumption of around 17 kWh/year due to the display that cannot be switched-off manually, see Table 3. This is an increase of 10.3% compared to the standard testing. Considering the values of the alternative method, the energy efficiency class would change into A++ instead of A+++.

The incentive for having the display activated is to have a digital clock on the refrigerator. In case the consumer is away for a longer period, the cabinet can save energy by disabling the display after 24 hours. However, during the harmonized tests, the doors are not opened for a period far exceeding the 24 hours period.

As result of the controller algorithm, the display is automatically switching off during the standard testing. The appliance operates as if the consumer is not at home and deactivates the display to save energy. In respect to this, the measured and declared energy consumption of the standard test represents only the most efficient mode of the appliance which is not providing a reliable value about the actual energy consumption during real use.

4.4 Example 4: Ovens – automatic temperature reduction function

The test cycle according to EN 60350-1:2016 for measuring the performance of household electric cooking appliances consists in a first step of an energy consumption measurement, done with a brick (soaked up with water to simulate a piece of beef) loaded in the centre of the oven. In a second step, a consecutive temperature measurement of the empty oven is done. Between the two steps, the door necessarily has to be opened to remove the brick. To measure the energy consumption of the oven in the first step, a certain temperature-rise as defined in the standard has to be reached in the centre of the brick.

The results of the ANTICSS testing revealed the following for one tested model (see Figure 4). During the first step (energy consumption measurement) in the ECO mode, the temperature in the oven was considerably lower than the targeted temperature setting: The total length of the first step was 54 minutes, but only during approx. 20 minutes the temperature of the centre of the oven was around the set temperature of 190°C. After this, the temperature decreased down to 89°C whereas the expected and 'normal' behaviour of an oven would be to maintain the temperature of around 190ºC for most of the time of step 1. The temperature was only increased again *after* the door was opened for removing the brick. In the second step, the temperature remained stable during the test period.

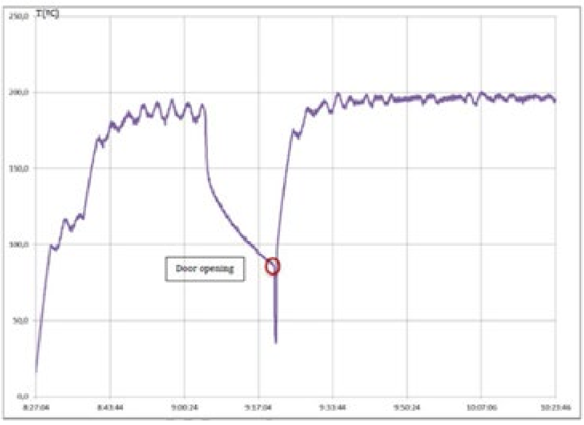

Figure 4: ANTICSS results of an oven model in ECO mode: energy consumption measurement (step 1) and temperature measurement (step 2)

Whereas in a tested non-ECO mode ("fan assisted" mode) of this model the temperature in the centre of the oven remains stable for both the energy consumption measurement and the temperature measurement.

Further, another model tested in ANTICSS did not show this behaviour: both in ECO and in "Conventional with fan" mode of that model, the temperature in the centre of the oven remained stable for both steps.

It seems that the ECO mode of the first model has been specifically designed to reach lower, i.e. more favourable values for the energy consumption by reducing the temperature while still maintaining the target to reach the required temperature raise in the centre of the brick. Only after the first hour, i.e. usually when the testing duration of the energy measurement is finished, the temperature remained stable at the required temperature setting. Probably the opening (and re-closing) of the oven door necessary in the standard testing might have caused the significant increase of the temperature, or, alternatively, after a certain pre-set period of time, so that the required temperature value could be reached for the subsequent temperature measurement.

4.5 Example 5: Televisions – automatic backlight reduction function

It is well known that the test video to be used for the standard measurement according to IEC 62087-2:2015 for the determination of the power consumption of audio, video, and related equipment such as televisions includes hard cuts every few seconds, i.e. fast moving images being far away from the characteristics of average broadcast content. Further, prior to the start of the standardised test movie, a countdown clip is shown. This countdown lasts for 10 seconds and does not contain any fast-moving images. After the 10 seconds, the movie content is played. This might facilitate recognizing this sequence as a test video and implementing special functions to reduce for example the luminance (backlight or OLED) during this loop to decrease the power consumption specifically in the test situation.

Assuming that the trigger for a possible brightness adjustment function might be the specific start sequence of the test video, for the ANTICSS alternative test procedure, the 10 minutes video of the IEC 62087-2 was divided in two parts with the order of the test video sequences changed for the measurement of power consumption: the last 5 minutes were running first and afterwards the first 5 minutes of the video.

The ANTICSS tests show that one of the models has a special function to detect fast changing content. The backlight (finally the input power) is reduced step by step starting at about 95 W at the start of the test video and settling down at about 85 W after 100 seconds for the rest of the 10 minutes test sequence (see Figure 5).

The ANTICSS alternative test did not lead to relevant deviations to the standard measurement. This means, that the detection of fast-moving pictures was independent from the initial sequence of the standard video.

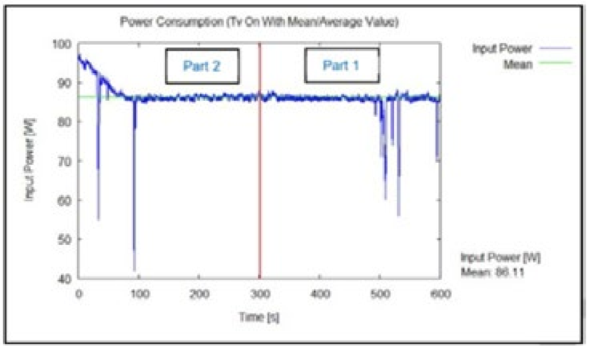

Figure 5: ANTICSS results of alternative testing of a television model using an automatic backlight reduction function

In the ANTICSS project, it could not be analysed if the backlight reduction function only detects the specific fast-moving images of the standard test video under IEC 62087-2 or if the technology also applies to any content in real life that entails rapid scene changes and/or depicting a large amount of motion such as sports programmes. Two further models tested did not have such a backlight reduction function.

In principle, this technology can be used to gain more favourable results of the declared parameters. However, for the specific tested model this was not exploited – on the contrary: the *declared* values for the on-mode and annual power consumption were significantly higher, i.e. 23% *worse* than the results of the standard measurement, even resulting in a lower energy efficiency class A instead of A+ as measured, see Table 4. According to the manufacturer, this over-declaration is a safety margin due to variations between units resulting of the construction process, i.e. to ensure all units being compliant when tested by Market Surveillance Authorities.

	Standard test results	Declared	Deviation
On-mode power consumption (W)	85	110	-23%
Annual power consumption (kWh/year)	118	153	-23%
Energy efficiency class	A+	A	1 class

Table 4: ANTICSS test results, television model

5 Possible impacts of circumvention and jeopardy effects

Possible impacts shall be illustrated for the dishwasher case (see section 4.1).
The alternative test resulted in a decrease in place settings (ps) from 16 to 12 that can be loaded into the machine. This leads to an increase of 33 % of cycles necessary to clean the same amount of dishes per year:

$$\frac{280\ cycles/year\ *\ 16\ ps/cycle}{280\ cycles/year\ *\ 12\ ps/cycle} = 1.3\vec{3}$$

Thus, 373.33 cycles instead of the 280 standard annual wash cycles would have to be run per year. The measured electricity consumption per cycle under standard conditions was 0.76 kWh, resulting in 211.4 kWh/year (without consumption in low power modes). The result of the alternative test was 0.73 kWh/cycle. Multiplied by the number of 373.33 cycles/year, the annual electricity consumption sums up to 272.9 kWh/year.

Table 5 presents the input parameters used for the calculation of the possible losses of energy savings of an A+++ dishwasher model with a rated capacity of 16 ps when only 12 ps per cycle can be loaded.

Input parameters	Calculation values
Annual electricity consumption declared, 16 ps	211.4 kWh/year
Annual electricity consumption calculated, 12 ps	272.9 kWh/year
Resulting annual additional electricity consumption	61.5 kWh/year
Annual dishwasher sales 2020 [5]	9’280’000 units
Market share of devices with a rated capacity of ≥16 ps [APPLiA]	4%
Primary energy factor [6]	2.1

Table 5: Input parameters for calculation (DW 4.1)

The potential losses of electricity, respectively primary energy, are shown in Table 6, assuming in one scenario that 50% or in another scenario even 100% of the dishwashers with a rated capacity of ≥16 ps can realise these high capacities only by applying such dedicated loading instructions specifically in the standard test.

Potential annual losses	Assumed circumvention rate 50%	100%
Electricity (GWh/year)	11.4	22.8
Primary energy (GWh/year)	24.0	47.9

Table 6: Potential annual energy losses

The ANTICSS test results show that not only the electricity consumption, but also other performance parameters might be optimised for the standard test. E.g., in the dishwasher case also the water consumption was affected by the special test instructions. In another case of dishwashers, the results suggested a slightly improved cleaning performance under standard testing. In the case of ovens (see section 4.2), the manufacturer's instructions lead to a higher volume under standard test and thus a more favourable value of the EEI which might result in a better energy label class.

A lower performance of appliances under real life conditions will probably be noticed by consumers and might provoke them not using the ECO modes anymore but switching to other, probably even more resource-intensive programme settings. The resulting effects – should circumvention take place on a larger scale – would be fatal in several respects: in addition to the lost savings and climate protection potential, the trust of society and business in these key EU policy instruments might be massively damaged.

6 Conclusions and initial recommendations

Initial results of the ANTICSS project show that circumvention of EU Ecodesign and Energy labelling legislation is in principle possible, might have severe impacts and goes far beyond non-compliance: When products or respective test settings have been manipulated with the aim of circumvention or exploiting loopholes, products apparently appear to conform the legal requirements when tested with the standardised test methods. Therefore, alternative test methods are necessary that have been developed and proven to work in the ANTICSS project. It is recommended that Market Surveillance Authorities should apply them in case of suspicious products to detect and prove the acts.

The analyses also revealed that circumvention might not only apply by *automatic* detection of the test situation and alteration of the product performance *during* testing as already included and prohibited in some Ecodesign and Energy label regulations. Better test results can also be achieved by making certain pre-settings or manual alterations to the product or test situation exclusively for the purpose of performing the test, or, by programming products to achieve very good energy efficiency values specifically for the period of conformity testing or a predefined number of test cycles with automatic change of the performance shortly *after* the product is put into service. Therefore, it is recommended to extend the current definition in the regulation to also cover these circumvention approaches.

Further, it is recommended to develop harmonized standards as close as possible to average real life usage of products. The more standards deviate from typical user behaviour, entail very specific conditions or include ambiguities and loopholes, the higher is the likelihood that products are designed to be able to detect these specific test conditions or that manufacturers exploit the loopholes in a way to achieve more favourable results for their products, i.e. the risk of circumvention or jeopardy effects is increasing.

Finally, several harmonized standards explicitly refer to manufacturer's instructions regarding installation and use that shall be followed during standard testing, mainly for safety reasons. The ANTICSS project revealed that in some cases the operation of a product according to the manufacturer's instructions seems to be a rather exceptional use, not the usually intended or main operation of the appliance. So, it remains suspected that the inclusion of such instructions, even if officially admitted according to the standards, is intended to reach more favourable performance results under testing. These acts may not be classified as circumvention but become possible due to loopholes and should be avoided in future standards or legislation.

Final recommendations for policy makers and standardisation bodies as well as capacity building measures for key actors of market surveillance and test laboratories to prevent future circumvention under EU Ecodesign and Energy labelling will be provided on the project website www.anti-circumvention.eu.

7 Literature

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New energy label: how to promote the uptake of more efficient energy- related products

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Abstract

Regulation (EU) 2017/1369 introduced a new energy labelling system repealing Directive 2010/30/EU and the first Directive 92/75/EEC. Therefore, energy label has been recently *rescaled*. The use of the rescaled labels can be seen as a tool to push innovation and investments in designing energy efficiency products. In addition, the new energy label will serve as a boost for savings in environmental impacts and in the economics of EU families. This paper focused on the activities driven by and European project (BELT) for facilitating the communication of the rescaling of the label. A coordinated approach between the interested actors, from manufacturers to consumers will facilitate the transition and the understanding of the possible impacts. The project is developing a tool for estimating the environmental benefits and is showing that the introduction of the new energy labels and the expected corresponding increase in sales in more energy efficient products will result in savings worth over 36 thousand of kilotons of CO_2 and billions of euros saved by consumers.

1 Introduction

Aiming to promote the uptake of more efficient energy-related products, providing consumers with accurate and comparable information regarding energy consumption, performance and other essential characteristics of domestic household products, Regulation (EU) 2017/1369 [1] introduced a new energy labelling system repealing Directive 2010/30/EU and the first Directive 92/75/EEC. Therefore, energy label has been recently *rescaled*. New regulation applies to dishwashers, washing machines and washer-driers, refrigerators, lamps, electronic displays (and commercial refrigerators with direct selling function). The new regulations, that will fully enter into force in 2021, consist of: a return to the well-known and effective energy labelling scale 'A to G' for energy efficient products; the use of a digital database for all new products placed on the EU market; the exhibition of supplementary information (i.e. water consumption per cycle, noise emission…); the introduction of eco-design measures. This paper shows the opportunities arising from the entering into force of the new European Regulation on Labelling of domestic household products (energy label rescaling). The rescaling brings up also a series of important issues for manufacturers in relation to eco-design requirement. Namely, according to the Eco-Design Framework Directive, manufacturers need to be compliant to new energy efficiency requirement, functional requirements, resource efficiency requirements (e.g. availability of spare parts, after sales services to be provided to the costumers, provision of repair and maintenance information), new test methods (i.e. it will prohibited to install software that can recognize testing phases). This study covers specifically the use of the rescaled labels as a tool to push innovation and investments in designing energy efficiency products. After understanding the environmental, social and techno-economic impacts driven by the new regulation, the innovation opportunities that manufacturers identify in the rescaled energy label will be analysed.

2 State of the art

This section gives an overview of the current trend in terms of household appliances sales, preferred sales channels (in shops and online), consumers' choices and behavioral trend. These aspects are important to understand the impact of the new energy label in terms of volume of appliances affected by the chance and to properly assess the from consumers' acceptance risks.

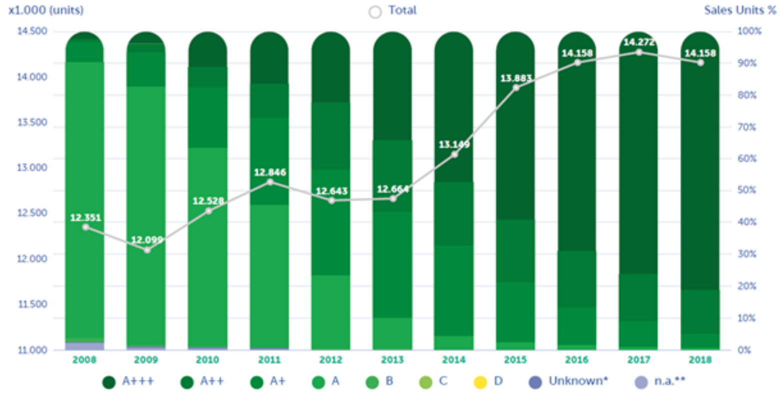

Figure 1. Share of sales per energy label class – Washing machines. Source: [2]

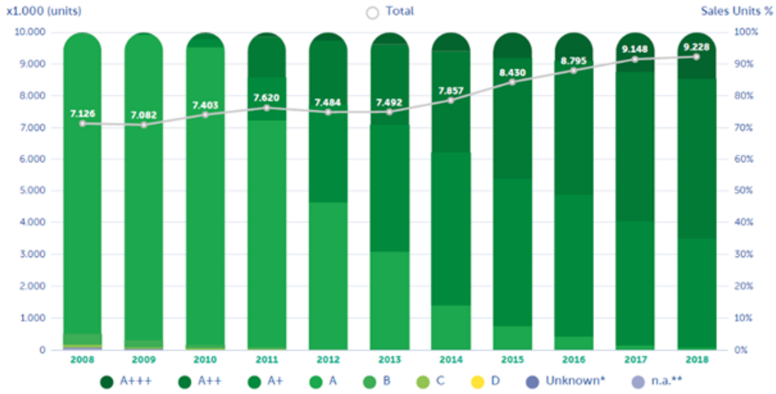

Figure 2. Share of sales per energy label class – Dishwashers. Source: [2]

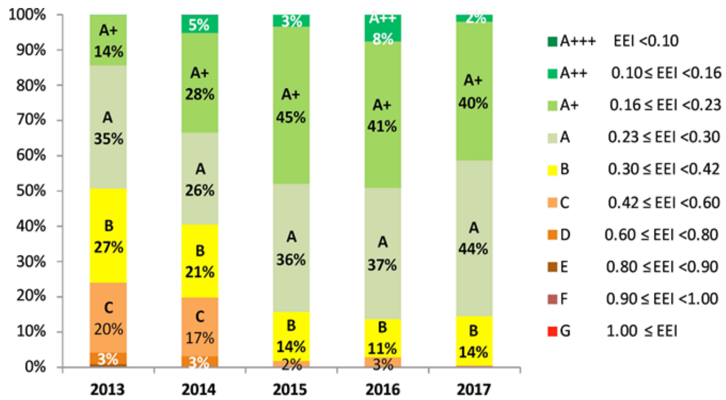

Figure 3. Share of sales per energy label class – TVs

2.1 Current market composition

The data regarding the current market composition are summarized in the following subsections. Sales data for home appliances (washing machine, fridges, dishwasher) and breakdown per energy class were obtained from APPLIA at EU level [2, 13, 14]. Literature and market data obtained from industry experts were used for TVs [3]. For lamps, breakdown per energy label category was not available from the literature.

2.1.2 Washing machines

Figure 1 shows how during the period 2008 – 2018 the energy efficiency of washing machines increased, and that by the year 2018 almost all products placed on market were of the top three energy efficiency categories. At the same time, this suggests that the energy label is not effectively using the entire range of categories to differentiate products according to their efficiency and a rescaling would be needed.

2.1.2 Fridges

Similarly to other appliances examined here, during the period 2008 to 2018 the energy efficiency of products placed on the market increased, meaning that by 2018 all products were of categories A+++ and A++, and also suggesting that a rescaling of the labels was needed in order to effectively differentiate products on their efficiency.

2.1.3 Dishwashers

Figure 2 shows how in the last few years almost all sales corresponded to products in the categories A+++, A++, and A+, indicating that the energy efficiency categories were not separating the products placed on market effectively.

2.1.4 TVs

Analysing Figure 3 it emerges that in 2017 almost no televisions in classes below B were sold in the EU, with 86% of the TV in the A categories. The annual sales of televisions in the EU-27 are expected to grow at a steady rate between 2020 and 2030. This sector has seen technological changes such as the gradual switch across Europe from analogue to digital broadcast and the introduction of flat-screen, smaller-footprint and better performing televisions. Additionally, the proportion in sales of smart TVs is increasing rapidly in the coming decade.

2.2 Market, consumers' and behavioural trends

Low interest and inflation rates in many European regions were driving historically high levels of consumer spending in recent years, with an obvious impact also in the sales of major domestic appliances (MDAs) [4]. Two key trends are emerging: a) sales are progressively shifting to an omnichannel context and b) consumers are increasingly concerned about the environmental impact of their product choices. The customer journey for consumer electronics and MDAs is gradually shifting to a multi-channel and "phygital" (physical + digital) experience: consumers browse alternatives online, including at retailers' ecommerce sites, and complete their purchases in a physical store, or the other way around; they can choose home delivery or prefer a click-and-collect model (purchasing online but collecting the product at a physical store of their convenience), as suits them best at a particular moment in time. This means that retailers need to ensure a consistent and smooth experience for consumers in this omnichannel context, which poses some challenges when it comes to addressing the questions that consumers might have regarding the more technical and larger appliances, especially in an online scenario. When it comes to sustainability/environmental concerns, especially present in MDAs such as washing machines and refrigerators but also impacting other product categories such as lamps, the percentage of consumers concerned about the environment grew from 37% in 2015 to 45% in 2018 [5]. According to GfK studies [6], for the top 5 MDAs (washing machines, tumble dryers, dishwashers, coolers/refrigerators and freezers) A++ appliances accounted for 25,6% of all appliances sold across 25 European countries, whereas A+++ appliances represented 21,7%. There are, nonetheless, differences between countries with Germany significantly ahead of other regions (71,1% of sales of the mentioned appliances in 2015 were A-rated). With consumers seeking the potential to save energy and water, the energy label in Europe will continue to be a key tool when it comes to helping them in their product consideration and purchase. Confirming this trend are consumer surveys, as cited by the European Commission, stating that around 85% of European citizens always look at the energy label before buying a product [7].

2.3 Need for a rescaling

Starting from 1995, European Union adopted the Energy Label as the instrument to support consumers as well as professional buyers in an informed purchase process of Electric and Electronic Equipment; guiding them in the selection of the most energy efficient products. The energy label is considered a successful tool that increased the supply and demand of the most performing products. Currently, products are labelled on a scale of A+++ (most efficient) to G (least efficient). Although initially most of the models were in the lowest classes (i.e. E, F, G), new models deserved higher until the situation where today most are now in the top classes (A+++, A++, A+), as also shown in section 2.1. This makes difficult for consumers to distinguish the best performing products. The label lost its effectiveness. The higher classes, with many "+", are too densely populated and almost no product belongs to lower classes. This causes confusion in customers: it is more difficult for them to identify the most efficient product and, as consequence, manufacturers are less pushed to improve their technologies. This is the reason why, the European Union has revised and optimized the energy label. The revision occurred through an Energy Label framework Regulation and different Delegated Acts [8,9,10,11,12], one for each family of products involved in the energy label change

3 BELT strategy to boost the energy efficiency

The label rescaling is going to cause market uncertainty. The rescaling brings up a series of logistical issues for manufacturers, distributors and for retailers, as well as confusing messages for all end users and buyers (consumer, public and business procurement). As an example, due to the energy label change, the same product might exist in the retailer's warehouse with the same IAN code but with two different energy label etiquettes (due to the coexistence, for a certain period of time, of the old and the new labelling scheme); new better performing models will be in the shops with an apparently lower label score than the previous or older model, thus generating confusion and uncertainty amongst end users while complicating the task of retailers and manufacturers when managing stocks and providing advice to consumers. Therefore, all customers and market actors have different issues with the new labels. Stakeholders (consumers, public and business procurement personnel) will be mostly confused and they might choose products against their best interests. Market actors (manufacturers, retailers and distributors) will face logistical and implementation issues as well as the possibility to fall into errors. Here it is presented the BELT strategy designed to minimize stakeholders' errors in the implementation of the new energy label.

3.1 Manufacturers outreach

One to the key objective of the project BELT is to raise the capacity of manufacturers to fulfil their obligations providing the correct label at the point of sale through distributors.

3.1.1 Training

BELT will assist manufacturers and retailers with specific training sessions, guidelines, workshops and materials to easily comply with the Regulation and to reduce all possible issues and bottlenecks in the implementation and roll out of the new labels. BELT consortium will ensure the direct involvement of retailers. A tailored set of training sessions are developed to meet the needs of the different stakeholders among manufacturers (e.g. management, design teams, etc). Manufacturers' suggestions and feedback will contribute to the development of guidelines concerning, for example, how to reduce compliance costs, maximise legal certainty and minimise errors to boost innovation.

3.1.1.1 CircuLab

The introduction of the new energy labelling system as well as new eco-design regulation, determines pivotal changes in manufacturers current procedures.

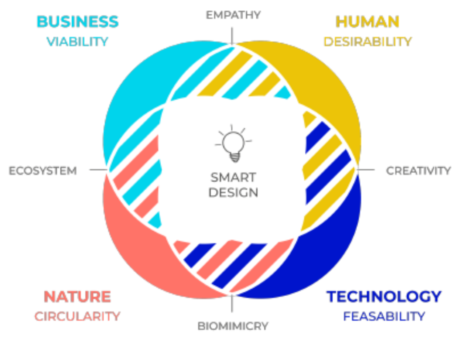

Figure 4. Circulab smart design approach

Dedicated training workshops will be organized to raise awareness and capacity building around new energy label topic and, more in general, sustainability issues, and how this can be a driver for innovation and building resilience. The potential that can be unlocked due to the adoption of the new energy labelling will be emphasised thanks to a specific tool/methodology: the Circulab. This methodology relies on a smart design process that encourages particpants to take a holistic view to to redesign their business and create positive impacts. One of the principles behind smart design requires moving beyond the simple ideas of viability and feasibility, to also consider human desirability and resilience (see Figure 4). At the same time, the game approach increases engagement and encourages innovative approaches.

Specific scenarios and examples specifically addressing the new energy label issues will be developed and used to help manufacturers to:

- design or re-design a new product, service or business models according to tailor made scenarios; these scenarios will reflect new energy labels acting as a driver for increased efficiency;
- take a holistic approach of their product system and value chain, including economic, technical, social, and environmental considerations

Actual challenges faced by market actors in the new energy label implementation identified include: deciding in which area to invest for increasing the energy class taking into account also eco-design regulation or how to communicate the environmental benefits other than the electricity consumption savings.

3.2 Implementation plan for retailers

Another pivotal objective of the project BELT is to raise the capacity of to fulfil their displaying respectively the correct label at the point of sale and providing proper information to consumers. Actions are foreseen for training employees, through the retailers' usual channels or developing new interactive (and digital, thanks to COVID) trainings. Communication plan dedicated to informing consumers at the point of sale, physical or for online sales, will be studied and put into practice. For example, A4 format flyers to be positioned in physical stores informing the start of the transition period (with the possibility to find 2 labels in the appliances) and future posters, totem for communicating the new label scheme starting from 01/03/2021 are foreseen.

3.2.1 Challenges for retailers

Key challenges for retailers include both internal/operational issues and consumer facing concerns. At an operational level, stocks' management during this period will be particularly demanding for retailers, given the different nature of requirements imposed by the EU regulations which are dependent on the type of product (light sources vs other products) and market introduction timings (existing models vs news models vs phase-out models). Checking suppliers' compliance and managing the logistics flows of appliances stocked at the retail side during the transition periods will be a demanding task. Moreover, many retailers now have their own brands of appliances, meaning they have a double responsibility as entities that not only do retail sales but also act as "suppliers". Especially challenging are also the longer cycles of shipment and customs procedures for extra-European imported appliances, which will force many overseas manufacturers to conduct testing and issue the new labels at much earlier stages of the innovation and market introduction cycle. Moreover, retailers will need to train a wide range of staff (commercial teams, store staff, ecommerce teams, customer support and many others) to ensure an adequate level of understanding about the new label, with the end goal of helping inform and advise consumers.

Given the fact that the two labels (existing and new) will start travelling inside the boxes of the impacted appliances still in 2020, consumers will actually be faced with the new label much sooner that in March 2021 (date for the swapping of the label at retail stores, both physical and online). Hence, the time gap between implementation on the manufacturers' and retail side is perceived as a negative factor that should cause some confusion and concerns amongst end consumers that might feel cheated. Thus, retailers are especially concerned with how consumers will perceive the new label and its transition periods and are developing communication strategies, namely inside the BELT project, to address these concerns.

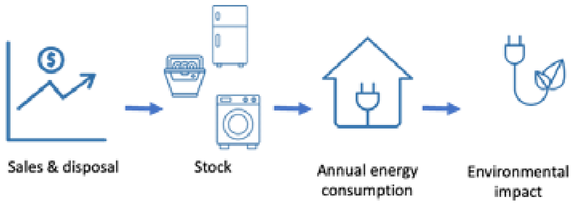

Figure 5. Methodology adopted to evaluate environmental benefits of the new energy label.

4 Understanding the environmental benefits of the introduction of new labels.

Understanding the environmental performances of the new energy label is an important driver for the successful implementation of the new labels. For this purpose, an excel based tool has been developed to assess the environmental impact of this policy under different sales scenarios future sales of scenarios and it will be updated with real market data once this becomes available.

4.1 Methodology

The scope of the study includes washing machines, dishwashers, refrigerators, TVs, and lighting appliances; while the countries considered are Spain, Portugal, Italy, Belgium, Slovenia Ireland, Greece, Croatia, and Lithuania, and Europe as a whole.

The impacts triggered by the project in terms of energy savings and CO_2 emissions reductions are calculated applying the following methodology (see Figure 5):

- sales data, for the past and the estimation for the future [2,3,13,14,15,16,17,18] are used to calculate the waste generated based on the disposal pattern derived from the common methodology adopted by the European Commission for the estimation of WEEE generated methodology [19]. Stock is then calculated as the difference between cumulative sales per product label category and the cumulative disposal of products. When sales data was available per energy class, stock could also be estimated per energy class;
- the product of the average energy consumption per energy label category and stock per year provides an estimation of the annual energy consumption, per country, per appliance. Energy consumption averages per appliance per energy label is determined considering market data and

industry experts' opinion. Energy consumption of the appliances has been calculated applying the formulas reported in the previous and new legislation concerning the energy labelling rules [20,21,22,23,24];

- annual energy consumption is then translated into environmental impacts using LCA methodology designed to capture the impacts due to changes in energy consumption, providing results in terms of the following impact categories: energy demand (MJ primary energy); GHG emissions (CO_2, methane, etc.); and other air pollutants (particulate matters, VOCs, etc.) [25,26].

Estimation of energy saving potential is made by considering the current and future stock of appliances in the target countries and the breakdown by energy class. Breakdown per energy class was not available for each country so the breakdown obtained at EU level was assumed for each of the individual target countries. Data was obtained from industry and industry associations when possible. Electricity costs and emission factors has been taken into account for each studied country [27,28].

To estimate the savings generated by the introduction of the new label scheme the reference scenario for each of the appliances, except for lamps for which data wasn't available, was defined as the situation without the introduction of new label, and by extrapolating the share per energy label compared to the trends that were available from APPLIA for dishwasher, fridges and washing machines, and the literature for TVs. For the introduction of the new label scheme, the developed tool allows the user to define the percentage of sales per energy label category. Preliminary results based on our own scenarios are presented here.

4.2 Results

Initial results show the potential benefits of the introduction of the new energy labels in terms of both environmental and economic benefits, suggesting that thousands of tonnes of CO_2 emissions and billions of euros could be saved due to reductions in electricity consumption. It is important to note that these results do not assume that all consumers reached by the project are replacing their appliances, but instead, that when consumers change their products they choose more energy efficient appliances.

As shown in Table 1, the introduction of the new energy labels and expected corresponding increase in sales in more energy efficient products is expected to result in savings worth over 17 thousand of kilotons of CO_2 and billions of euros saved by consumers. Putting these results in context, a benefit of *17,300 kt* of CO_2 emissions saved amount to approximately 3% of 2017 residential and commercial GHG emissions [30].

	2021	2026	2031
GWh Primary Energy	608	17,400	54,200
ktonnes CO_2	199	5,600	17,300
Tonnes air pollutants	17.6	515	1,660
Tonnes particulate matter	23.9	696	1,590
Million euros for consumers	100	2,970	9,750

Table 1 Environmental and economic benefits results at EU level for 4 appliances

These preliminary results will be updated once real market data of sales under the new labels become available.

5 Conclusion

The new energy label will serve as a boost reductions in environmental impact and economic savings for families in the EU. A coordinated approach between the interested stakeholders, from manufacturers to consumers will facilitate the transition and the understanding of the possible impacts. Retailers are working to ensure a smoother transition to the new label by providing adequate training to staff, and other value chain actors such as installers or services providers, and also by developing integrated communication strategies, in close collaboration with consumers' associations, to guarantee that consumers are properly aware and informed of the new label. The tool described in this paper represents a first attempt at estimating the environmental benefits of the new energy label implementation and by the end of the project the impact on the adoption of the new labels will be reviewed and will be quantified using the latest available data. The current results are based scenarios of sales per energy label category that will be validated and improved when the data on products under the new labelling scheme is added to the European Product Database for Energy Labelling (EPREL) database, and when actual sales data becomes available. At the same time, the results of this study contribute energy consumption and environmental data used in a Web tool, which is designed to help consumers understand the benefits of more energy efficient products on their environmental impact and running costs. It is highlighted that the additional value of the tool approach selected for this study is that the results can be updated, improved and refined by feeding the tool with real sales data broken down by energy according to the latest market developments. The flexibility of this approach is particularly important in the current Covid-19 pandemic, which is creating unprecedented economic instability and could impact appliance sales.

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On-Mode Test Method for Computers: Enabling the Development of an Energy Label

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Abstract

The energy efficiency of computers has been an important topic for policy-makers since the United States started the Energy Star labelling programme for computers in the mid 1990's. At European Union level, the Commission endorsed the Energy Star for Computers in 2003, and then in 2013 it established mandatory energy-efficiency requirements under Ecodesign which were in line with the Energy Star requirements. Until now, the assessment of computer energy-efficiency has focused on measuring energy use in an idle state, i.e. when the computer is not executing useful tasks. Moreover, a number of allowances are included, based on the detailed configuration of the computer. This paper presents a new test methodology that is designed to (1) allow a more accurate and targeted assessment of the energy and of the performance when executing tasks, (2) be virtually agnostic of architecture and configuration and (3) work with the most common operating systems. This new approach may open up the possibility of establishing energy performance classes under the well-known EU Energy Label, as well as streamlining compliance reporting and market surveillance.

1 Introduction

Two legislative instruments constitute the European framework for energy efficiency of products that complement each other, obtaining what is defined as a push-pull effect. Ecodesign [1] sets minimal requirements for products to be placed on the European Union (EU) single market: once requirements are set, it "pushes out" the worst products from the market from the moment they come into application. It is addressed to manufacturers, as it sets requirements that the "design" of new products must meet. The Energy Labelling [2] complements the Ecodesign policy and provides consumers with a simple instrument for a better informed purchase choice, by grading products according to a well-known A-G/green-to-red seven classes label: the improvement in products efficiency of new products coming to market, year after year, is reflected in an increasing number of models classified in the top classes and in fewer and fewer models populating the lowest ones [3].

This policy framework works to 'protect' consumers from the worst products, by pushing them out of the EU market, and fosters competition and stimulates technology progress among manufacturers, that improve product design in order to be rated in the top label classes. Moreover, the label guides purchase choice towards the more cost-efficient solutions, further increasing the average energy efficiency of products sold on the EU market. It enables informed choices and ensures savings on the energy bills of consumers and businesses.

At the EU level, the current regulatory measures affecting the environmental impacts of computers only consist of the requirements set out by Ecodesign Regulation No. 613/2013 [4]. The energy efficiency requirements are based on the standard IEC 62623, and a large number of allowances are granted according to the computer architecture and internal components and technologies (number of expansion slots, graphic cards, storage media distinguishing even the disk diameter, etc.). These allowances raise the bar of minimal requirements for products that incorporate those hardware components and specifications. Computers still do not have an energy label, thus consumers have no consistent way to make an informed purchase decision, and instead rely on sources such as the personal advice of an expert in the store or a simple assessment of running costs which doesn't capture the difference that may exist in computational performance.

The energy-efficiency of computers according to IEC 62623 assesses the energy use when the computer is in

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an "idle state" waiting for input. Until recently, this test method was considered an acceptable proxy of computer energy use, and this same approach is used in the Energy Star computers specification [5]. However, recent hardware and software improvements driven by the need to improve battery lifetime in mobile platforms progressively reduced energy use in the idle state, to the point where it is no longer a good proxy of the overall energy efficiency. Essentially now it is not possible to differentiate computer efficiency based solely on idle state energy use. Furthermore, existing benchmarks that test the 'performance' of computers are not suitable, as they are not designed to directly assess computer energy performance.

This paper describes a novel solution, based on software 'worklets' which simulate a collection of tasks reproducing energy use patterns that mimic real-world use, while being technology neutral, scalable, and providing consumer-relevant indicators for better informed choices depending on the intended use of the computer. This test method provides repeatable test results that are easily developed and reviewed, both for manufacturers and market surveillance authorities.

1.1 The review process

The preparatory work conducted when developing an Ecodesign regulation involves technical, procedural and legal steps. A specific product group is first analysed in a Preparatory Study, where the feasibility of setting Ecodesign (and/or energy labelling) measures is investigated, following an assessment involving technical, economic and environmental aspects in line with the Methodology for Ecodesign of Energy-related Products (MEErP) [6]. The subsequent step is an 'impact assessment' [7] in which the impact of different policy options are analysed across a variety of topics including cost competitiveness, technological development and innovation, end-user affordability, etc.). If the analyses performed to this stage yield a favourable result, further procedural and legal steps take place. The process reaches its conclusion when the draft regulation is published in the Official Journal of the European Union. When a product is already regulated under Ecodesign and those requirements are being reviewed, the aforementioned procedural steps are repeated and changes and improvements are introduced in the text of the Regulation, with the view to improve its effectiveness and level of ambition, and also to include new requirements, such as resource efficiency or new product categories.

For computers, the supporting study for the review [8] covered a number of aspects related to the energy used over the entire life-cycle and opened the possibility of introducing requirements aimed at not only reducing energy consumption in the use phase, but also to some extent, the embodied energy, i.e. the energy used in manufacturing and shipping. The embodied energy in electronic equipment is a relatively large proportion of the energy used over the product life cycle. And the decrease of embodied energy can be achieved not necessarily through efficiency gains at the manufacturing facilities, but rather by extending the product lifetime. In this way, the product amortizes its embodied energy and environmental impacts over a larger number of years, reducing the damage to the environment overall.

One of the ways to encourage design engineers to incorporate resource efficiency and other principles of the circular economy into electronics is through the energy label. This aspect then becomes additional motivation for establishing a computer energy label which guides purchase decisions and minimises embodied energy.

2 Methodology for deriving a metric for the energy efficiency of computers

The Energy Star specification [5] and European Ecodesign Regulation No. 613/2013 [4] are both complex documents. They use power allowances based on the computer architecture and internal components and technologies (number of expansion slots, graphic cards, storage media, distinguishing even the disk diameter, etc.). These allowances require accurate definitions for the components and increases the complexity and makes the work more challenging when considering different configurations of the same product [9]. Moreover, from the end-user perspective, some of the parameters really do not matter such as the diameter of internal hard disks or the presence of expansion slots which aren't needed, however their computer gets allowances to use more energy because of them.

A more suitable and transparent methodology for assessing the efficiency of computers is needed, and it should possess the following characteristics:

- **configuration agnostic**: able to test any configuration and assess additional memory or the presence of a graphics card in respect to its intended use;
- **technology agnostic**: compatible with all major operating systems and ideally not requiring review/revision more often than once every five years;
- **easy to use**: able to conduct tests without extensive specific ancillary equipment, apart from a regulated power supply and a meter for measuring power consumed during the test;

- **offer 'easy' assessment**: able to test without the need to disassemble the computer to verify internal physical configuration, memory, slots, etc.;
- **based on open source code**: the software is based on an open source code that can be inspected, corrected and improved / updated when needed.

In formal terms, the energy-efficiency of a computer can be defined as the ratio between the performance of a computer conducting a certain task (provided that it is possible to quantify performance) and the energy consumed by the computer conducting that task. Examples of energy-efficiency metrics in an active state for ICT products can be found in literature, such as:

- Computer servers - a test method was recently developed [10] to support the ecodesign regulation on computer servers [11]. This test method is representative of the user pattern of servers, is scalable, technology neutral and does not entail excessive costs. This metric is also incorporated in the ETSI EN 303 470 standard; and
- Televisions - a test method is set out in IEC 62087. It is considered an indicator of energy use of televisions in real conditions by energy regulators of different countries [12]. The metric determines the average power consumption after playing a 10 minute video clip weighted by the display area.

Along these lines, and based on the criteria laid down in the beginning of this section, a metric for the energy efficiency of computers, together with the related testing methodology (described in the next section), was developed.

The specific approach followed for computers uses a set of worklets which simulate the tasks they must perform when being used. The worklets are meant to represent common end-use functions such as word processing, graphics, gaming, numerical calculations and so-on. Due to the fact that the operating system has an influence on the performance of the computer, the worklets are run natively on the OS that is installed on the computer at the time it is placed on the market. In this way it is intended to correctly reflect the performance of the bundle (i.e., computer and OS) that will be experienced by the end-user.

3 Test procedure under development

A computer efficiency testing software suite was developed that is based on the Phoronix Test Suite, a benchmarking software tool that has been under development since 2004 [13]. This particular test suite package was chosen over other available options because it met several of our requirements including being open source, available at no cost, able to test multiple operating systems, and has a variety of worklets which test different aspects of a computer. The Phoronix test suite also calculates a quantitative metric which combines the computer's performance conducting the tests and its energy consumption. Our software development Team adapted the Phoronix test suite, creating the tool that is currently being pilot tested.

Whilst there is a working version of the test software, it is still considered a first draft of a testing tool that is under development. The draft has been adapted to run natively in three operating system environments: Microsoft Windows 10, MacOSX Catalina and Linux (Debian 10 Buster or Ubuntu 20.04 Linux 64-bit). A future update will adapt the tool to run in Google Chrome OS. There are 47 worklets which have been selected for analysis in this development stage, to enable the Team to ascertain how the performance of the computers varies when running this wide variety of worklets across the different specifications of the machines being tested.

The step-by-step procedure for the test set-up, the procedure to create the test USB stick, the step-by-step procedure for conducting the test and then analysing the results is all set out in a software reference manual which was prepared and posted on the project website. [14] A very brief overview of that document is provided here in this paper, and interested readers are encouraged to review the full, detailed procedure set out in the reference manual.

3.1 The test setup

Figure 1 depicts the standard set-up for conducting a test. It requires a laboratory grade regulated power supply (specification in EN 62623) to provide a clean power supply to the computer being tested (the UUT, or Unit Under Test). There is a measurement adapter, a power meter and a controller computer which records the power data as it is generated by the meter. A USB key is also needed for software installation purposes and for data transfer after the test.

The measurement adapter is simply a mains power socket which has separate voltage and current leads positioned between the power supply and the UUT for taking voltage and current measurements. The voltage is measured across the power supply and the current is measured immediately after the voltage, so it doesn't interfere in the accuracy of that measurement.

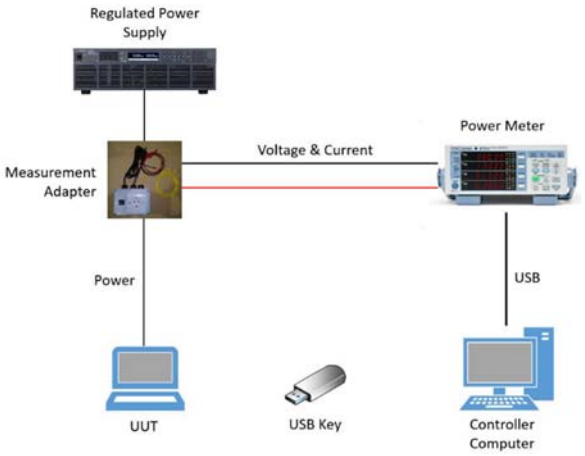

Figure 1. Test Hardware Setup [14]

Figure 2 depicts the circuit diagram for this configuration where V represents the measurement points for the voltage meter and A represents the measurement points for the ampere meter.

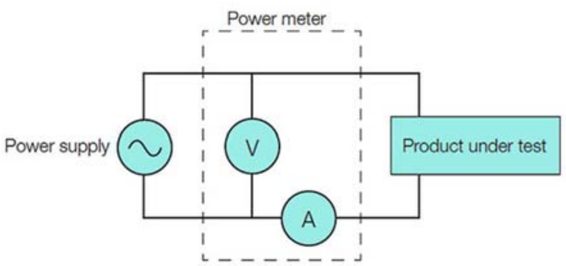

Figure 2. Measurement Adapter Configuration [14]

The power meter being used at this development stage is a Yokogawa WT310E, however the team fully intends to make the software testing suite compatible with several other power meter models which are commonly found in laboratories around the world.

The USB stick used for testing should be at least 16 GB and USB 3.0 or higher. A procedure to create the USB key with the appropriate software is then outlined in the different operating systems. Once created, this key is used to install the software on the controller computer (this only needs to be done once) and on the UUT (this is done for each computer tested).

The software installed on the controller computer allows the user to do the following: (a) synchronise the clock on the controller computer and the UUT, (b) check the connection between the power meter and the controller computer, (c) start/stop the acquisition of power measurements and (d) examine the results via a web browser application. Note too that an internet connection is required to allow for synchronisation of the clock on the controller computer and the UUT.

The software installed on the UUT includes the graphical user interface (GUI) and test suite management software which runs the test, all of the worklets and any additional package management applications that are needed like homebrew for MacOSX.

3.2 The test procedure

Once the software has been installed and the test hardware is set-up as in Figure 1, the UUT is ready to be tested. At the time of writing this paper, the package runs all 47 worklets in order to gather data on the performance of a range of different computer configurations.

The computer should have screen saver, screen blanking and automatic standby mode switched off. All operating system updates should be added and firewall software must be disabled on the UUT. If the UUT has a rechargeable battery (i.e., laptop), then the battery should be removed for the test. If the battery can't be removed, then it must be charged to 100% before starting the test run. The UUT should not be connected to the Internet while running the benchmarks, but should be connected to a wireless access point or network switch supporting the highest speed the UUT can handle. Finally, the USB key that was used to install the software should be removed from the UUT and inserted into the controller computer prior to running the full test.

After synchronizing the clocks using the internet, the test run is given a filename and the user clicks the button in the GUI marked "Run full test". This will execute all worklets, which takes approximately 6-7 hours. There is a text based progress indicator shown when clicking on "show detailed status information". Note that the long test duration is only due to the fact that the software is currently running all 47 worklets on each computer to determine how useful and relevant each of them are at testing performance and energy use. In the future, once energy label classes have been identified (e.g., office computer, gaming computer), then subsets of 3-5 worklets which are appropriate to that specific category will be used to quantify the label classes.

Once the test is complete, the user is instructed to insert the USB key with power measurements into the UUT to record the system run data. In this way, the software combines the energy consumption data from the power meter/controller computer with the performance data collected by the UUT.

The computer list of 47 worklets that are used at this development stage of the software testing tool are provided in Chapter 6 of the Software Manual [14]. These worklets are designed to test five different categories of a computer: the CPU, system, memory, disk drive, and graphics.

3.3 The test results

Technical details, such as CPU model, motherboard model, amount of memory, graphics card model, operating system versions and much more is listed in a table. This helps to clearly identify the UUT and gives an overview of the tested hardware.

For each worklet, the performance results are listed in a table giving the assessment of how well the computer did when performing the test. The results also include the power demand measurements (synchronised in time) to compare against the performance measurements, and the overall efficiency result. The worklets have their own measured values of performance, so values such as megabytes per second (MB/s) can have some situations where higher is better and other situations where lower is better. Each graph defines the unit of measured values.

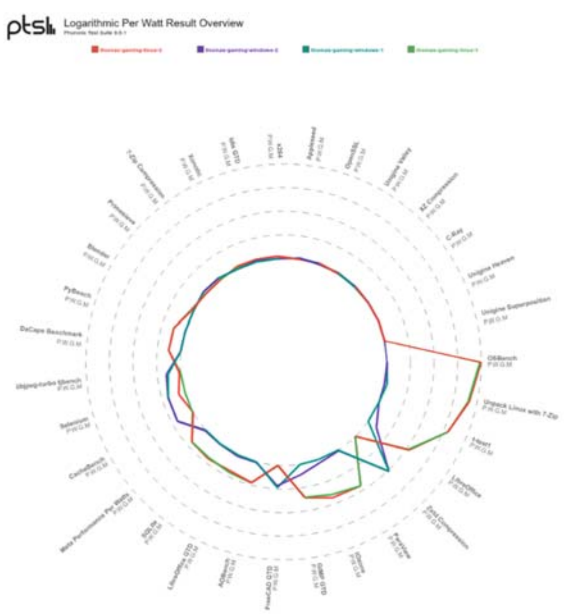

Figure 3. Summary Results Comparison Graph Example [14]

When comparing across different computer systems, the software can produce a circular efficiency plot as shown in Figure 3. In this graph, the more efficient computers are shown in the outside of the concentric circles, thus the larger the area presented, the more efficient the computer.

At the end of the test results report, two graphs are produced which show the "meta efficiency" calculated over all the worklets and the full series of power measurements logged during the test run. The meta efficiency value is created by calculating the geometric mean of the individual efficiency results of each Worklet and represents the combined efficiency result of the UUT. Table 1 presents the test results for four different computers with different operating systems that were tested with all 47 worklets in our development version of the software tool.

Table 1. Meta Efficiency Results from Testing

Computer	Hardware	Meta Efficiency
MacBook Pro 2019	Intel Core i7, 16GB RAM, Intel UHD 630 + AMD Radeon Pro 5300M Graphics	3.82
Windows Desktop 2018	Intel Core i5-7500, 8GB RAM, Intel HD 630 Graphics	2.23
Windows Laptop 2019	Intel Core i5-8265U, 16GB RAM, NVIDIA GeForce GTX 1050+Intel UHD 620 Graphics	2.92
Ubuntu Linux Laptop 2020	AMD Ryzen 7 3700X, 32GB RAM, NVIDIA GeForce GTX 1660 Ti Graphics	3.41

At the time of writing, a number of ICT manufacturers are conducting testing on their own computers with this first version of the software tool. The data collected from this testing will be anonymised and shared with the Commission's Ecodesign and Energy Labelling Consultation Forum. This data will then be used to try to establish appropriate product classes and the best subset of worklets that can be used together to yield the best measure of performance for that product class.

4 Potential policy approach

The opportunities offered by an on-mode benchmarking tool, such as the one described, would help streamline the regulations by removing most if not allowances for different architectural and configuration details, making it easier for compliance reporting by manufacturers and easier for use by market surveillance authorities. Although some allowances may still need to be considered if minimal requirements would be based on the measured energy efficiency index, e.g. to consider features such as expandability, this software tool achieves many of the objectives highlighted earlier, being easy to use, free of charge, scalable and requiring a simple testing set-up.

This new test method opens up the possibility of differentiating computer models based on their energy efficiency when performing under different typical product groups, such as office use, gaming, numerical calculations, video editing, 3-D rendering and so-on. An energy-label for each of these product groups could be based on a different set of carefully selected, appropriate, worklets that emulate how a consumer would use the computer. For example, a computer marketed as a 'gaming computer' could have a label showing prominently the scale measuring the energy efficiency index when running a predetermined set of different worklets which simulate gaming. Under this scenario, the energy label could become a ready-made, platform-agnostic, non-controversial comparison tool to guide consumer choice towards the more efficient computers for their intended use and streamline green public procurement selection procedures. The label must also provide space for capturing non-energy information, via additional indicators, such as, for example, battery durability, expandability, and upgradability.

5 Conclusions

Many opportunities would be brought by an on-mode benchmarking tool, duly weighing active and idle states, and the associated energy label for energy efficiency. First, a relevant simplification of Ecodesign regulation, that would be more time-resistant and of easier control for compliance. Secondly, they would provide an indicator to consumers, in a market where only 'computer geeks' are enabled to make an informed purchasing choice. This new EU energy label could also offer relevant additional information, including durability and other resource efficiency criteria. Thirdly, an energy label could simplify public procurement, as required by the Energy Efficiency Directive. Finally, registration of labelled products in the database EPREL (European Product Registry for Energy Labelling) as provided by the European framework labelling Regulation 2017/1369, would provide end-users a quick comparison tool and offer regulators a tool to streamline the requirements evolution.

The development of this tool, a pilot version of which is ongoing, in close collaboration with industry experts will ultimately be proposed to standardisation bodies for review and ideally adoption and maintenance.

6 Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission, GTD, Intertek or CLASP. Neither the European Union institutions and bodies, GTD, Intertek and CLASP, nor any person acting on behalf of any of these organisations may be held responsible for the use of information made available in this paper.

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Sanctioning planned obsolescence practices: Analysis from a legal standpoint

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Abstract

Planned obsolescence is often defined as the assortment of techniques used to artificially limit the durability of a manufactured good in order to stimulate repetitive consumption. Those techniques can take various forms and have multiple consequences that affect both the consumers' financial situation as well as the environment. Indeed, the environmental impact of allowing products (especially electric and electronic devices) with a shortened lifespan to be put on the market can be observed at both ends of the production chain. On the one hand, the increased replacement frequency of affected products accelerates production and leads to the increased extraction of raw materials, in particular non-renewable minerals. On the other hand, the constant renewal of devices that are no longer usable leads to an increase in waste, the disposal of which can be damaging for both the environment and public health.

In the face of such practices, a legal response is necessary. However, very few European countries have adopted a specific legislation prohibiting planned obsolescence. To this day, only France has criminalized this practice. However, the effective implementation of this law is fraught with difficulties. In fact, following a legal complaint regarding the slowing down of mobile phones, the French authorities chose not to retain the offence of planned obsolescence introduced by this legislation but rather to sanction the manufacturer for their lack of consumer information.

This contribution aims to assess the appropriateness of criminalizing planned obsolescence practices in order to establish whether it would be desirable to introduce such a law in other European countries. To this end, the various obstacles to the application of the French legislation will be addressed, in particular the difficulty of establishing a legal definition of planned obsolescence and evidentiary difficulties.

Finally, we will briefly examine what other legal means are either available or desirable to sanction the use of techniques that reduce durability and prevent repair.

1 Introduction

You might be met with incredulity, were you to explain to the general public that the person believed to have coined the phrase "planned obsolescence" and more importantly to have first theorised it, did so in 1932. The fairly recent increase in court cases[1] makes it indeed easy to believe that planned obsolescence is a 21st century phenomenon. However, it is well and truly during the first half of the last century that Bernard London, an American real estate broker, wrote his now famous paper "Ending the depression through planned obsolescence". In the midst of the Great Depression, the most pressing matter was to reduce the U.S unemployment rate and London believed that his plan to "chart the obsolescence of capital and consumption goods at the time of their production" [1] had the potential to "put the entire country on the road to recovery, and eventually restore normal employment conditions and sound prosperity" [1]. His proposed mechanism, however, strayed quite far from what might come to our minds today when we think about practices prone to favour premature obsolescence.

[1] For instance, trials involving Apple took place in Switzerland, Italy and France during these last few years and criminal charges against Epson are currently pending in France.

London's proposal was indeed that of a legal obsolescence. He argued that the Government could assign a lease of life to consumer goods when they were first manufactured. After the allotted time (which had been communicated to the consumer) had expired, these products would be considered as being "legally dead" and would be controlled by a governmental agency and destroyed [1].

Considering the time period as well as the socio-economic context, it seems fair to assume that issues of ecological responsibility were not an integral part of the political decision-making process. Therefore, London's proposed policy, elaborated in response to social inequalities and vowing to create a paradigm shift in the economic system resulting in a more equitable distribution of wealth, was presented exclusively in a positive light.

The publication, in 1960, of Vance Packard's "The Waste Makers" marks the first elaborated, at-length criticism of planned obsolescence from an ecological perspective, with a focus on the quantity of waste generated in the American society. In this context, Packard defines planned obsolescence as a strategy capable of influencing both the design of consumer goods and the perception and behaviour of consumers [2].

2 Defining planned obsolescence

If this initial criticism did not give rise to the introduction of any regulations or policies aimed at curbing this phenomenon, it did however cast a different light on planned obsolescence practices. During the following decades, a number of voices rose against premature obsolescence as various authors[2] tried to define what "planned obsolescence" means and which practices it covers. Maybe one of the most prominent voices, Giles Slade defines planned obsolescence as the assortment of techniques used to artificially limit the durability of a manufactured good in order to stimulate repetitive consumption [3]. This definition seems to have become fairly widely accepted and has since been taken up by the French legislation. To be precise, the Consumer Code defines planned obsolescence as "the use of techniques by which the person responsible for placing a product on the market deliberately aims to reduce its lifespan in order to increase its replacement rate"[4], thus offering the first legal definition of planned obsolescence in Europe.

3 Criminalizing planned obsolescence

A clear circumscription of the concept is particularly important as this law establishes planned obsolescence as a criminal offence. Adopted as part of the 2015 Energy Transition for Green Growth Act, this legal provision is the result of over 10 months of parliamentary debate and is a part of a larger policy aimed at reducing the environmental impact of products [5]. With that goal in mind, French legislators deemed appropriate to render planned obsolescence practices punishable by two years' imprisonment and a fine of up to €300,000. The amount of the fine may be increased, in proportion to the benefits derived from the offence, to 5 % of the average annual turnover, calculated on the basis of the last three annual turnover figures [4]. However, the mere existence of a law doesn't guarantee its effective application and the HOP v. Apple France court case exemplifies that perfectly.

When faced, in 2018, with criminal charges against Apple France, French authorities led a two year-long investigation which concluded that "some iOS updates were likely to lead to a slowdown of mobile phones. It is precised that these updates included a dynamic power management feature that could, under certain conditions, such as the presence of old batteries, slow down the performances of iPhones' models 6, SE and 7. The impossibility to revert to the previous version of the operating system would have forced many consumers to change the battery or even buy a new phone" [6]. On the basis of those conclusions the authorities chose to retain a lack of consumer information (as the risks tied to the updates hadn't been disclosed by Apple) rather than to apply for the first time the planned obsolescence offence. This court proceeding ultimately resulted in a plea bargain ("*transaction*" under French law), Apple accepting to pay a €25 million fine and to publish a press release on its website for a month [6].

The reasons that may hinder the effectiveness of a legal norm are many and varied. It is therefore a question of reviewing the elements of the planned obsolescence offence and trying to understand how they may pose difficulties in the application of this law.

4 Elements of the planned obsolescence offence

Upon reading Article L-441-2 of the French Consumer Code, it appears that at least three elements must be present for the offence to be deemed to have been committed and for a criminal penalty to be imposed.

2 Such as Giles Slade, Serge Latouche and Thierry Libaert.

First of all, there must be a reduction of the product's lifespan (or lifetime, both terms being used indifferently). This lifespan reduction must be deliberate and it must pursue the goal of increasing the replacement rate.

4.1 The reduction of product lifespan

4.1.1 The result of an assortment of techniques

The numerous studies that have been carried out on the issue of planned obsolescence have defined different types of obsolescence and although there is currently no clear consensus on the practices that the notion of planned obsolescence covers, we can nonetheless cite the following distinctions as examples:

- Technical obsolescence: this type of obsolescence is usually defined as the fact, for a given product, to become obsolete while remaining functional, following the arrival on the market of a new product that better fulfils the desired functionalities or offers new ones [7,8]. This type of obsolescence appears not to be totally deliberate but simply results from technological innovation [8]. However, some other authors [9] choose to define technical obsolescence as the loss of function of a product due to the limited lifespan of one of its essential and irremovable components. This also includes the introduction of a device designed to limit the lifespan of the product as a whole after a certain number of cycles or uses. This seems to be a marginal point of view and those kinds of practices are more commonly referred to as "planned obsolescence in a strict sense" [8], "direct obsolescence" [7] or "evolutionary obsolescence" [10].
- software obsolescence or incompatibility obsolescence: it includes, in particular, the failures occurring when updating the operating system, the limitation of the duration of technical support, format incompatibility between old and new versions of the software and incompatibility between devices [9,11].
- indirect obsolescence: this terminology refers to all the techniques used to prevent repair, as for instance, the short-term availability of spare parts, excessively high repair costs or the design of certain consumer goods limiting repair possibilities.

The notion of planned obsolescence can therefore refer to a multitude of practices. However, it has simply been decided to enshrine in law that the lifespan limitation should result from the use of "techniques", without any further clarification as to what those techniques might actually be. This decision is the result of lengthy debates between the French parliamentary chambers. Indeed, an earlier version of the text of the law, proposed by the Senate, included the following sentence: "Such techniques may include the deliberate introduction of a defect or fragility, programmed or premature shutdown, technical limitation, impossibility of repair due to the impossibility to disassemble the device, unavailability of essential spare parts, or incompatibility" [12]. According to some senators, this non-exhaustive list of the different types of planned obsolescence had the merit of avoiding any ambiguity and could have guaranteed the full effectiveness of both the objective of combating planned obsolescence and the sanction attached to it. They believed that if the notion of planned obsolescence remained vague, it would not be operational and may lead to legal uncertainty [12]. However, the chosen wording and the definition of the offence in general terms make it possible to cover a broader range of practices and to take into account possible marginal practices.

Finally, it should also be noted that this is a "conduct crime" ("*infraction formelle*" under French law), meaning that the mere implementation of techniques aimed at reducing the lifetime of a product is an infringement as such, independently from any concrete result [9].

4.1.2 The notion of product lifetime

This element implies the definition of a usual or expected lifespan in order to be able to assess its possible limitation. However, the lifetime of a product may also refer to various notions, the main ones of which are briefly outlined below. As there is no coordinated effort yet, at the international level, to standardize the terminology related to product lifespan [10.13], the choice has been made to use the French wording (as the law is written in that language) and to provide a free translation. The lifetime of a manufactured good can refer, essentially, to four main ideas as defined by the French Agency for Environment and Energy Management (ADEME) [10].

- The normative lifetime (*durée de vie normative*) is defined as "the average operating period measured under specific test conditions" [10]. There are indeed reliability tests established by various organizations to determine the average time a device will operate, for instance before the first failure [9]. This lifetime can be assessed in terms of elapsed time or in terms of number of cycles, depending on the product [10].
- The duration of use (*durée d'usage*) is the period of time during which "the product is used, in working order and ready for use, by a given user"

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[10]. The duration of use is therefore specific to a particular user or household and excludes cases where an appliance, theoretically still functional, would be kept but not used, as a device stored in this way cannot be considered ready for use [10].

- The holding period (*durée de détention*) "corresponds to the time elapsed between the acquisition of a new object by a first consumer and its passage to the state of waste, whatever its working condition. It thus includes the possible repair and reuse and takes into account possible storage periods. In other words, it is the total lifespan of a given good, from its new acquisition to its disposal" [10].
- The existence time (*durée d'existence*) is a concept close to the holding period since it considers the time between the end of the manufacturing process of a product and its disposal or recycling. But, contrary to the holding period, it includes on the one hand, the time between the end of production and the purchase, on the other hand, a possible reuse of the product after it is discarded [10].

Once these definitions have been established, it is necessary to determine which kind of "lifetime" is affected when it comes to planned obsolescence. In its report on the legal definition of planned obsolescence, the Government states that practices aiming to reduce product lifespan occur at the normative lifetime level and result in a limitation of the duration of use [13]. It goes on to specify that this means that cases of planned obsolescence involve "practices aimed at limiting the duration of use right from the product's design stage" [13]. The mention of techniques implemented at the design stage, even though such a requirement is not contained in the law, is regrettable since it excludes a number of planned obsolescence practices.

In addition, there are many testing standards and it is not clear how to identify which ones should be used. This results in a vague lifespan notion that could serve as an argument that the law is not sufficiently precise to allow a criminal sanction to be pronounced, in application of the legality principle (*nullum crimen, nulla poena sine lege certa*) which requires legal provisions to be sufficiently precise in regards of what is criminalized [14,15]. The incriminated manufacturers could thus argue that the law does not clearly indicate which standards the lifespan of their products had to meet.

4.2 A deliberate lifespan reduction

The limitation of the product's durability must be deliberate. This means that the manufacturer must have acted with intent. Proof of such intent can be particularly difficult to provide and will require to appeal to experts able to identify the techniques used to implement a given type of planned obsolescence [16] and capable of demonstrating that "a particular industrial choice cannot be justified by reasons other than a desire to intentionally reduce the product's lifespan" [17]. In cases where a device, such as a chip for instance, has been introduced into a consumer good in order to stop its proper functioning after a certain number of uses, it is indeed conceivable that an expert report will succeed in establishing such an intention. However, this form of planned obsolescence in a strict sense seems to remain quite rare. In other cases, such as indirect or incompatibility obsolescence, it is likely that the only possibility of proving the intent to limit durability would be to rely on possible whistle-blowers or former employees who are in a position to reveal relevant facts [16,17].

Establishing this intent is therefore not an easy task, but it is not yet the biggest hurdle, as it seems that the law also requires to establish evidence of the motive.

4.3 The aim to increase the replacement rate

The law lays down the condition that the reduction of the lifespan of a product must pursue the goal of increasing its replacement rate. This point is poorly addressed even though it represents a major obstacle to the applicability of this legal provision. Indeed, it is almost impossible to prove such a motive as, as stated by Vasseur and Sauvage [9], the judge cannot read minds in order to know the motivations underlying the choices operated by the manufacturers. These authors argue however, that the judge could be able to "deduce this motive from the mere deliberate reduction of the product lifespan, thus increasing the effectiveness of the law" [9].

As things stand, we still have to wait for a court to rule on this issue in order to know how the question of the motive will be assessed.

5 Conclusion

It follows from the above that barriers to the application of this law can essentially be grouped into two different categories. Either the notions used are not sufficiently precise, which in the criminal justice context can have particularly important consequences, or the elements of the offence are arduous to prove. It therefore cannot be denied that the application of the legislation criminalizing planned obsolescence practices contains its fair share of difficulties.

The European Parliament having adopted a resolution on a longer lifetime for products [18], stressing the importance of tackling practices that limit the durability of consumer goods, other countries may nonetheless want to follow France's example and criminalize planned obsolescence. If this were to be the case, it is indispensable to clearly define and unify the concept of product lifetime. Furthermore, the inclusion of the existence of a particular motive as a constituent element of the offence should be avoided. However, even with such adjustments, the planned obsolescence offence is likely to remain difficult to prove, except in the marginal cases of planned obsolescence in a strict sense. This is not to say that criminalizing planned obsolescence practices is meaningless. Indeed, as it is sometimes pointed out [17], the adoption of such a law has a symbolic value. It shows that the State recognises the issues raised by the excessively short lifespans of certain goods and that it disapproves of it. Another argument is that such a legal provision may have a deterrent effect on manufacturers [17]. While this may be the case in the first few years after its entry into force, the more time passes without the law being applied, the more it loses its general deterrence capacity. That theory has been developped in the 18th century by Cesare Beccaria, when he stated that what most surely prevents crimes is the certainty of punishment, and not its severity [19].

While the effectiveness of criminalizing planned obsolescence practices is therefore debatable, this does not mean that there are no other means of punishing companies that limit the durability of the goods they produce. As we have seen, a lack of consumer information constituting a deceptive commercial practice by omission has been held against Apple [6]. In Italy, the antitrust authorities have also sanctioned Apple and Samsung for dishonest commercial practices [20]. Some countries thus already have in their legal arsenal the means to sanction practices of planned obsolescence without the need for a specific offence.

Furthermore, the European Parliament resolution cited above [18] also underlines the importance of a number of measures designed to promote the durability of manufactured goods and to provide more accurate information to the consumers. In that spirit, the French anti-waste law for a circular economy introduces various regulations (some of which will already come into force in January 2021) designed to encourage the extension of product lifespan. Examples include the introduction of a reparability index, consumer access to information on the availability of spare parts and the obligation for manufacturers to provide information about the length of time that software updates will be supported by an appliance. Then, on January 1st 2022, an extension of the legal warranty for devices that have undergone repair will come into force, as well as measures enabling the use of 3D printing for the repair of products [21].

In order to consider what other measures might be possible, reference should be made to the white paper published by the HOP association, which contains fifty proposals for sustainable consumption and production aimed at public decision-makers [22].

Assessing the effectiveness of these policies requires hindsight and an in-depth analysis beyond the scope of this article. However, they have the merit of intervening upstream and could play an important role in the prevention of planned obsolescence practices. Such regulations are thus likely to offer a good complement to the sanctions regime - which could find different foundations depending on the national legal regimes - in the fight against the limitation of product lifespan.

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The Future of Regulatory Information Technology in our Climate Emergency – How Products will Shop for People.

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Abstract

Nowadays, more than ever, effective policy and Regulation is necessary. However, regulators, Standards bodies and businesses lack a co-ordinated technology vision encompassing the production and consumption of requirements. Regulations and Standards are delivered in formats that are not designed to facilitate early warning to, and easier workflow in, impacted businesses. Quality is conformance to all requirements, and the ones that make companies interesting and attractive have little to do with legal compliance and more to do with leadership and social purpose, including solving the Climate Emergency. Whatever way companies define words like 'sustainable' and 'good corporate citizen', it will be up to buyers (consumers and B2B) to decide if they like everything they uncover about a business. Citizens will upload their values to the internet and allow that information to be used to find sellers that come closest to matching those values with businesses' virtues. Products will shop for people.

1 Introduction

The Climate Change Emergency is real and based on solid science [1]. The Coronavirus has reinforced the value and legitimacy of science, scientific leaders and science-based advice. The Pandemic has brought home the reality of shared humanity, forced us to slow down and think about a new normal. The killing of George Floyd was filmed as it happened and broadcast worldwide. It sparked a wave of anti-racist outrage. Pandemic downtime has given us time to prioritise the things that matter. Things have to change.

When science is relegated, it results in people believing that humans walked with dinosaurs [2], that vaccines cause autism, that the moon landings were faked, that climate change is a hoax, and that ingesting bleach might be curative.

Good leadership leads to good policy, regulation and compliance. It leads to jobs, commerce and the availability and affordability of goods and services. And not at the expense of human or environmental health. The best businesses are well organised and always years ahead of the law. Compliance with the law never made a company interesting or particularly worthy of being sustained with our hard-earned money. Compliance with the law, in our experience, is not relied on for competitive advantage by well-run companies.

Our planet is fragile, perhaps the Coronavirus will help us realise this in significant and lasting ways. Finite resources have to be protected. The activities carried on by complex supply chains must be regulated to ensure that production and consumption of goods and services, whatever the political frameworks, serve to do no social harm and specifically reverse global warming. In fact, the world is already being re-regulated. Since 2000, global regulatory growth charts show a steady incline at about 25 degrees.

2 Machine Readable Regulations & Standards

Scientists and engineers are increasingly challenged to be creative in anticipation of tighter and tighter Regulations and Standards in the interest of society at large. They must invent more energy efficient ways of manufacturing more energy efficient products, and ways to eliminate chemicals and substances that seriously damage human and environmental health. They must design longer lasting products, more easily repaired, better packaged, easier to disassemble and recycle, while not compromising safety. Business must reduce waste at every step in the product lifecycle and measure impacts on the environment, and on Climate Change in particular, in increasingly stringent ways. All of this is regulated and impacted by emerging Standards.

In addition to its readable content, a document can also have 'meta-data', which is a machine-readable set of data, describing the content in the document. Meta-data would define the structure of the document and show, for example, where to find a product category or an activity in scope. Understanding the structure of the content of Regulations and Standards in this way, would allow businesses, large and small, to more easily cope with a high volume of this necessary regulation.

Meta-data of legal publications can be extracted manually by adding markup or through artificial intelligence, but without a coordinated approach to defining this structure, compliance will always be a difficult problem for businesses to solve. Publication on an international level also presents the difficulty in translation of documents, which could also be simplified by a more structured approach.

Regulators, unlike the industries they regulate, do not, in our view, sufficiently concern themselves with the way in which the requirements they produce are consumed by the ultimate consumers - businesses. Even if some requirements are left deliberately open to interpretation, perhaps as a result of expensive and deeply sophisticated lobbying, many requirements are straightforward and can now be produced in a more machine readable format called Requirements Interchange Format (RiF), a markup format developed under The Object Management Group® standards consortium [3] RiF (Requirements interchange Format) allowing faster and tighter integration in the automotive industry which uses a rapidly evolving jigsaw of requirements management software tools.

The question is whether in a climate emergency Governments and even Standards Development Organisations should be working not only to produce, but to smooth the absorption by businesses of necessary Regulations and Standards.

Despite a globally shared climate emergency there is no international cooperation to solve this in a harmonised way. Such an ambition or collaboration doesn't exist.

Expecting companies to get by using a combination of employee internet search, consultants, lawyers, spreadsheets, industry association communications, email and homegrown or adapted databases is to not understand one very important way to reduce the burden of necessary regulation. It requires standing in the shoes of business people, and trying to do their job. It means understanding what the emerging software tools look and feel like, catering for the interconnected jobs processing requirements.

Specifically, we call on Governments and Regulators and Standards Development Organisations to re-invigorate efforts to produce machine readable texts so that key information can automatically be absorbed by receiving software - basic information such as addressees, scopes to product categories, product exemptions and exclusions, chemicals, substances & materials, definitions, relevant dates, requirement types, detailed requirements where possible, impacted business activities, and some other common aspects, such as instrument types, official titles, and so on. Begin with things that can and ought to be automatically updated after subsequent amendments.

On the consumption side there will be significant advantages from these small but important publishing improvements, arising from the objective of helping businesses get early warning of the proposed Regulations & Standards relevant to them, depending on whether their product categories or activities are in scope or not. This addresses the common problem experienced by many companies that discover very late that they have to comply with something they didn't know about.

3 Business as Usual

Perhaps contrary to popular belief, the idea clearly expressed by Milton Friedman in 1970 [4] that *'the social responsibility of Business is to increase its profits'*, is very much alive.

Friedman is quoted nowadays by way of implying that the world has moved on, and that corporations take social responsibilities as seriously as shareholder value.

Even a strict reading of his analysis and advice in that famous New York Times Article would not preclude any amount of activity aimed at keeping employees and customers engaged and motivated provided it serves the real purpose of the business, to increase shareholder value. Such activity is justified, wrote Friedman, to *'generate goodwill as a by-product of expenditures that are entirely justified in its own self-interest'*.

Friedman says that spending money to reduce pollution is perfectly legitimate as long as it is *'in the best interests of the corporation'*, and not just *'to contribute to the social objective of improving the environment.'* And this might mean going even further than the law requires, provided the ultimate aim is served.

Today, the suspicion is that still the overarching aim of many corporations is to increase shareholder wealth, and these *'motivational'* activities are carried out in the service of that aim, not at its expense. Accusations of greenwashing and virtue signalling abound.

Look to the Articles of Incorporations of some of the best performing 'Sustainable' companies. We will read something along the lines of *'The purpose of this corporation is to engage in any lawful act or activity for which a corporation may be organised under the general corporation law of [Country]*.' And on it goes. The foundations upon which such companies are built and sustained are devoid of social purpose.

In his open letter to CEOs, Larry Fink, CEO of BlackRock [5] is, he admits himself, following behind the tide of public opinion rather than leading it, when he insisted in 2018 *that 'society is demanding that companies both public and private, serve a social purpose'*. Climate Change is mentioned only once, and then among other *'broad structural trends'* that affect *'potential for growth'.*

In August 2019, likely as a response to Fink, the American Round Table published, with much self-congratulatory ado, a *'Commitment'*, *a 'Statement on the Purpose of a Corporation'*, signed by 181 top CEOs, not, we think, because the primacy of creating shareholder value was at an end, but rather because the language used in previous communications was not sophisticated enough to reflect the fact that many CEOs realise how deeply the attainment of the primary goal is now bound up with paying sufficient attention to stakeholders other than shareholders. In the mercifully short document titled *'Our Commitment'*, There is no specific mention of Climate Change just an anodyne reference to a need to *'protect the environment by embracing sustainable practices across our businesses'.* Yes, one could argue that 'protecting the environment' includes Climate Change, but the thing is that Climate Change is so overwhelmingly serious that it ought to be called out specifically in order to remove any doubt about the collective responsibility of business.

'Delivering value to our customers', *'Investing in our employees'*, *'Dealing fairly and ethically with our suppliers'*, *'Supporting the communities in which we work'*, & *'Generating long term value for shareholders'* are the highlights. Nothing to see here, just business as usual.

We hear you Larry - say the CEOs - *'we urge leading investors to support companies that build long-term value by investing in their employees and communities.'* And Larry signed it too.

Even if the democratic process and Government is unable to solve urgent problems, this is not sufficient reason according to Friedman to insist that the responsibilities of business should be expanded, just because it might be *'a quicker and surer way to solve pressing current problems'*.

The problem for us today is that Climate Change is not just another pressing current problem. And because there is insufficient co-ordinated international political leadership leading to effective policies, regulation, standards and compliance, business leaders, to protect their future, are looking to themselves to find a solution.

The pressure has been mounting, and in Jan 2020, Larry Fink's annual letter to CEOs made ten specific references [6] to Climate Change. In bold letters he states - ***'Every government, company and shareholder must confront climate change'.*** Unlike Friedman he calls on governments to do more to protect the environment.

Already his second paragraph is devoted entirely to Climate Change - *'Climate change has become a defining factor in companies' long-term prospects. Last September, when millions of people [7] took to the streets to demand action on climate change, many of them emphasized the significant and lasting impact that it will have on economic growth and prosperity – a risk that markets to date have been slower to reflect. But awareness is rapidly changing, and I believe we are on the edge of a fundamental reshaping of finance.'*

Larry Fink is under pressure. Millions of people are demonstrating in Sept 2019, but again he is responding to the *'changing demands of society'*. *'Indeed, climate change is almost invariably the top issue that clients around the world raise with BlackRock'* he says.

'Over the next few years, one of the most important questions we will face is the scale and scope of government action on climate change, which will generally define the speed with which we move to a low-carbon economy. This challenge cannot be solved without a coordinated, international response from governments, aligned with the goals of the Paris Agreement.'

'While no framework is perfect, BlackRock believes that the Sustainability Accounting Standards Board (SASB) provides a clear set of standards for reporting sustainability information across a wide range of issues, from labor practices to data privacy to business ethics.

For evaluating and reporting climate-related risks, as well as the related governance issues that are essential to managing them, the TCFD [Task Force on Climate Related Financial Disclosures] provides a valuable framework.'

The level of overall 'Quality' required of companies is rising, and growing in complexity as they take on an ever increasing, sophisticated range of regulatory and voluntary requirements in order to remain eligible for consideration and support by investment firms like BlackRock.

4 Businesses with Social Purpose

'Brand X. They have customers. They have the past. They have an old business model, They're a commodity. They have to be cheaper [no not always]. *They are the status quo. In recessions, their customers leave and go to the cheapest.* [no not always]. *They have changed very little and can't remember why they started.*

'Brand Why' They have fans. They have the future. They have a new business model. They are special. They can charge a premium [no not always]. *They are respected. Their fans love them. They are proud of them. In recessions their fans stick with them. They are changing what they set out to.'* [8]

A Benefit Corporation is a specific type of for-profit legal entity, with limited liability, but with social purposes written into its Articles of Incorporation. 36 US States provide the possibility to begin corporate life as a Benefit Corporation or to become one. Five US States are currently working on Benefit Corporation legislation. Relatively few countries outside the US have a similar legal entity.

Benefit corporations set out to do more than earn a profit. Key aspects are -

- Pursuit of the "Triple P" bottom line (profit, people and the planet);
- Consideration by directors of more than just the interests of the shareholders when considering what is in the best interest of the corporation; and
- Regard to both short and long-term interests by directors of the corporation, including benefits that may accrue to the corporation from its long-term plans.

Patagonia Works became California's first Benefit Corporation on the day the law took effect, January 3, 2012.

"Benefit corporation legislation creates the legal framework to enable mission-driven companies like Patagonia to stay mission-driven through succession, capital raises, and even changes in ownership, by institutionalizing the values, culture, processes, and high standards put in place by founding entrepreneurs." [9]

There is some confusion between a 'Benefit Corporations' and a 'Certified B Corporation' (often referred to as a 'B Corp').

"Certified B Corporation" is a certification much like LEED for buildings, or Fair Trade for coffee. [10] There are more than 3,300 Certified B Corporations across 150 industries in 71 countries.

Benefit Corporations may also achieve Certified B Corporation status from B Lab [11] which is a not for profit company that awards the B Corporation certification to any company that meets certain strict criteria, whether or not incorporated as a Benefit Corporation.

It should be noted that where a company applies to become a Certified B Corporation, B Lab will request that the Articles of Association (Incorporation) are amended to include social purposes. The idea is to balance purpose with profits.

The importance of the B Lab certification is that it provides verification to a high standard by a third party of meeting requirements on a broad range of commitments to community, planet, and shareholders. Without such third-party verification there is no objective assessment of the performance of a company incorporated as Benefit Corporation.

5 Leadership

Leaders, from wherever, are citizens, and good citizens, according to William James have *'a sense of duty and responsibility to the common good'*.

Certified B Corporations are first and foremost a community of leaders. And these leaders feel acutely the lack of political leadership across a whole range of social issues. Where Climate Change is concerned, politics is failing. To quote Friedman, *'the problems are too urgent to wait on the slow course of political processes.'*

Leaders require courage. *'We mean courage to include any physical valor yes, but also integrity and perseverance ... we mean doing what is right, even when one has much to lose.'* [12] According to French philosopher Compte-Sponville, *"Without courage, we cannot hold out against the worst in ourselves or others."* [13]

And, of course, leaders by definition have followers. That's the idea, to bring other business leaders along, where they move away from primacy of shareholder value to a bell rung clarity that their own particular business exists to make a profit yes, but where shareholder value is not the only goal.

We are seeing now the emergence and support for the *'constructive charismatic'*, the leaders that *'seek power to help others'*. Such leaders have *'an unconscious motive to use social influence, or to satisfy the power need, in socially desirable ways, for the betterment of the collective rather than for personal self-interest'*.[14]

In 2018 Patagonia changed its Mission to *'We're in business to save our home planet'*. Its previous vision was *'Build the best product, cause no unnecessary harm, use business to inspire and implement solutions to the environmental crisis'*.

Essentially because the degree of seriousness of the environmental crisis increased, Patagonia doubled down on their purpose.

'To qualify as a Certified B Corp, a firm must have an explicit social or environmental mission, and a legally binding fiduciary responsibility to take into account the interests of workers, the community and the environment as well as its shareholders. A company must also amend its articles of incorporation to adopt B Lab's commitment to sustainability and treating workers well. In addition a B Corp must pay an annual fee based on revenues, biannually complete a B Impact Report (a lengthy questionnaire that measures social and environmental impact), meet B-Lab's comprehensive social and environmental performance standards and make that B Impact Report public, in order to receive the certification from B Lab.' [15]

Certified B Corps include a mix of private and public companies. Patagonia is privately owned, while existing Certified B Corps have gone public, like Laureate and Silver Chef. Publicly traded companies have also achieved B Corp Certification, such as Natura. Many other Certified B Corps are subsidiaries of publicly traded companies, such as Ben & Jerry's and Sundial Brands (owned by Unilever) and New Chapter (owned by Proctor & Gamble), Innocent (owned by Coke).

New stories are being written, the endings yet unknown. BP CEO Bernard Looney demonstrates leadership and a good deal of courage, expressing BPs new purpose *'to become a net zero company by 2050 or sooner, and to help the world get to net zero.'* And stating, *'to deliver that, trillions of dollars will need to be invested in replumbing and rewiring the world's energy system. It will require nothing short of reimagining energy as we know it.'* [16] The story is of BP leadership passing to a young inspirational leader promising to do something extraordinary, almost impossible. How will the story end?

6 Matching Buyer Values with Seller Virtues

What if buyers were able and willing to take a values-selfie and intentionally upload to the internet a description of their values, including the causes they support, so that products made by matching corporations can find them. In other words, the match is made between our values and the proven virtues of corporations. In this way the commercial transaction goes far deeper than an exchange of goods or services for money. Now as self-aware buyers we have become an active supporter of a corporation and its leaders, not just its products and pricing.

Even if we do not already consent to giving information for this purpose, Yuval Noah Harari claims that Google, Amazon, Apple and Facebook know us better than we know ourselves. We know the adds find us. Will it not be better when we citizens willingly share certain information about ourselves and the causes we care about, as opposed to passively having it harvested surreptitiously. The difference is we will intentionally share very specific information to enable the right products from the right companies to find us.

And what if B Lab Certification (or equivalent) was to support such a matchmaking exercise, addressing the trust deficit highlighted in the 20th Annual Edelman Trust Barometer, 2020 which concluded that across 28 markets neither Government, Business, NGOs or Media were seen as both competent and ethical. Wow! Yes.

In China, Confucian virtues, with a focus on education and leadership was compulsory study for 2000 years. One of the four or five central virtues espoused by Confucius was '*Jen*', translated variously as humanity or human heartedness or benevolence. *'If you want to make a stand, help others make a stand, and if you want to reach your goal, help others reach their goal.'* [17] Such advice resonates strongly today for anyone seeking to support the businesses they admire, the businesses trying hardest to change the world, precisely in the ways they want to see it changed most. Mind you, Confucius was likely as interested (if not more interested) in the support, rather than some mutually reinforcing stand or goal.

Ethical Shopping is on the increase and this is happening against a background of capitalism coming under fire. In the same Edelman Trust Barometer report, 65% of respondents agreed that *'Capitalism as it exists today does more harm than good'*.

The views of employees are hugely important. Given a choice, people definitely want to work for leaders and companies they admire.

'Social mission is even more important when it comes to recruiting. At business school recruiting events, it is almost obligatory that companies describe their LEED-certified workplaces, LGBT-friendly human resource practices and community outreach efforts.' [18]

The *'Vote Every Day'* campaign of B Lab specifically encourages people to work only for companies they respect, and to be demanding - *'buying from, working for* *and doing business with B Corps we vote for what we believe in'.*

An Edelman Study [19] concluded that in 2017 1 in 2 people were belief driven buyers. Of belief driven buyers 67% bought a brand for the first time based on its position on a controversial issue. 65% will not buy a brand because it stayed silent on an issue it had an obligation to address.

By 2018 belief driven buying had increased to nearly 2 of 3 buyers. And Edelman declared this mainstream around the world, spanning generations, and income levels. Almost incredibly 53% believed that Brands could do more to solve social ills than governments. And 60% said *'Brands should make it easier for me to see what their values and positions on important issues are when I am about to make a purchase'.*

Wholefoods in the US, and Waitrose in the UK are leaders in providing ethical produce and a specific type of shopping excellence, where customers understand that, often for a premium, the painstaking way of doing business with supplier partners is worth the effort because business is ultimately about Community and not just about making money.

'The UK ethical food and drink sector's ongoing popularity is set to continue, as sales of ethically certified food and drink are projected to rise by 17% to reach £9.6 billion between 2019-23' [20].

Zalando describes itself as *'Europe's leading online platform for fashion and lifestyle'*. On May 27th, 2020 it announced that by 2023 it would be compulsory for brands on its platform to follow Sustainable Apparel Coalition [21] Standards that make them increasingly sustainable. The idea was born out of a desire by the SAC to make the whole industry more sustainable, across an index of issues like Climate Change, use of resources, workers' rights, and so on. The Higg Co. was spun out of SAC and is a technology play. If companies are measured and scored, then they can be compared, and in theory this would allow at least a limited matching of buyer values with virtues of Zalando brands.

In addition to SAC there are other sustainability certifications that may be stepping-stones on a journey of becoming ever more sustain-worthy. Perhaps these various sustainability certifications may be mutually exclusive, and companies will have to pick one over the other. Who then will decide which one is better if it comes to a choosing between the products of two variously certified companies? Who, or which organisation is trustworthy enough to act as the oracle in such a case.

Eco-age is a UK consulting company in the fashion space that gives companies like 'Reformation' numerical scores against a target, across 12 headings, all under the sustainability umbrella. In 2019, the equivalent of an 'A' grade (setting new standards) was achieved by Reformation for Climate Action, and Packaging. A 'B' grade (Leadership) for Use of Chemicals, and Communications. A 'C' grade (Best Practice) for 7 headings, Corporate Governance, Human Rights, Operational Environmental Management, Training and Education, Community and Giving, Supply Chain Traceability, and Product Environmental Footprint. Under Employee Diversity and Inclusion, it scored 1 out of a maximum 17, so a 'D' grade (basics in place).

Not everyone can afford to be virtuous. But we can take comfort from the studies that have shown that many will take their new climate related responsibilities seriously. Even under conditions of anonymity, studies showed that one quarter to one third of participants refused self-gain at group expense. Which brings to mind the Christian notion of the responsibilities that come with privilege, *'to whom much is given, much will be required'* (Luke 12:48), and the Marxist notion, *'from each according to his abilities, to each according to his needs'*.

If moral identity formation is a component of the education system, then self-reflection is necessary. It can be taught. As one's moral identity forms, one begins to see oneself as *'this or that kind of person; as a person who is committed to this standard and that cause; as a person who is or is not likely to do certain things.'* [22] One of those things then, whenever possible, is to exercise integrity at the moment of choice, always preferring to support corporations worthy of being sustained because their virtues match one's values and causes. If only one could know which ones.

A 2019 Nosto survey [23] of 1000 consumers in the UK and 1000 in the USA reported that 45% of survey respondents say it is difficult to know which fashion companies are truly committed to sustainability, while only 23% of them say they have a generally good idea of what fashion brands mean when they say they are committed to sustainability. 50% said they would prefer to buy sustainable products but only 29% said they would be prepared to pay more to support brands committed to sustainability.

If climate education in schools and across reliable media can help us understand why and how we take a stand, then ultimately the technologies will emerge that allow products made by companies we admire to find us. The fact that the most attractive initiative for respondents in the Nosto survey, at 74%, was improved sustainability labelling shows a hunger for ethical decision making.

Online shopping with the physical infrastructure for delivery from anywhere to anywhere is already in place to support value-based buying. Although it may be that an overriding desire to shop local will restrict choice.

This depends on the hierarchy of values and the weighting given to each.

Various organisations on the Internet are capturing user preferences in open and hidden ways. Consumers are becoming more aware of the reasons why personal information is being harvested and the law is catching up to protect citizens from unwitting exploitation.

What does not yet appear to exist are trusted platforms that bring everything together allowing buyers to support companies they love to sustain, with technology playing a central role in the match-making.

With expected mounting pressure on Climate, and advances in technology, especially AI, it will be more about buyers deciding if companies are worth sustaining, as opposed to companies telling us they are sustainable.

We need education, activism, and the right algorithms to bring tidal change.

7 Transparency, Audit, Trust

We believe that in the increasing urgency of a Climate Emergency World, strategic requirements management platforms will emerge. They will leverage artificial intelligence to automate the flow of actionable information from governments, regulators and Standards bodies directly to impacted products and activities.

An artificially intelligent 'mind of the product', for example, will know its regulated essence and attributes, and detect emerging trends and requirements in a way that feeds early and directly into product development and business strategy.

Requirements that owe their origin to self-imposed social purpose, will be integrated into such platforms so that business decisions can demonstrate consideration of all relevant requirements and be amenable to third party audit, supported by integrated evidence of compliance.

All this, taken together, will form an essential mechanism for the problem of trust to be addressed, supporting from one side the consideration of buyer values, and on the other side transparency into seller virtues, with certification and trusted third party validation, so, finally, products can shop confidently for the people they love.

And products too should exercise integrity at the moment of choice.

8 Literature

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