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Product Family Approach in E-Waste Management: A Conceptual Framework for Circular Economy

Keshav Parajuly * and Henrik Wenzel

SDU Life Cycle Engineering, Department of Chemical Engineering, Biotechnology and Environmental Technology, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark; henrik.wenzel@kbm.sdu.dk

* Correspondence: kepa@kbm.sdu.dk; Tel.: +45-2117-7608

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Abstract: As the need for a more circular model is being increasingly pronounced, a fundamental change in the end-of-life (EoL) management of electrical and electronic products (e-products) is required in order to prevent the resource losses and to promote the reuse of products and components with remaining functionality. However, the diversity of product types, design features, and material compositions pose serious challenges for the EoL managers and legislators alike. In order to address these challenges, we propose a framework that is based on the 'product family' philosophy, which has been used in the manufacturing sector for a long time. For this, the product families can be built based on intrinsic and extrinsic attributes of e-products as well as of the EoL management system. Such an approach has the potential to improve the current EoL practices and to support designers in making EoL thinking operational during the product design stage. If supported by a better EoL collection, presorting and testing platform, and a family-centric approach for material recovery, such a framework carries the potential to avoid the losses occurring in today's e-waste management system. This, in turn, could facilitate a smooth transition towards a circular model for the electrical and electronic industry.

Keywords: WEEE; end-of-life; design for end-of-life; resource recovery; electronic waste

1. Introduction

1.1. Background

The management of electronic waste (e-waste) is challenged by rapid technological advancement with increasing amounts and diversity of electrical and electronic products (e-products). Resulting low rates of collection and recycling means a significant loss of valuable resources present in e-waste today [1]. With society's increasing focus on resource efficiency, a call for initiatives towards not only improving the material recycling, but also fundamentally changing the way we design product systems and use resources, has been expressed. *Circular economy*, for example, has been conceptualized as an industrial system that aims to avoid waste through design of optimized cycles of products, components and materials by keeping them at their highest utility and value [2]. Given the potential of growth, this concept is becoming increasingly relevant for e-products which is identified as one of the key focus areas by the recent European Union Action Plan for Circular Economy [1]. It is supported by the fact that e-products use critical raw materials, which are not only of higher economic and environmental importance, but also vulnerable to supply disruption. The end-of-life (EoL) options prioritized in the circular model (including reuse and remanufacturing) are also affirmed to bring more resource and environmental savings compared to material recycling [3].

A circular economy, by definition, covers the entire lifecycle of a product, which requires an optimal combination of business model and design strategy for slowing, narrowing and closing of resource loops [4]. Given the complexity of product design and a fast-paced global market of the e-products, a variety of approaches should be considered. Moreover, the current EoL management practices which are based mainly on the Waste Electrical and Electronic Equipment (WEEE) Directive, need to be aligned with the European Commission's Circular Economy Strategy [5]. In order to ensure a smooth transition towards a future system for a circular product lifecycle management, we need a new approach that is simple enough to implement, yet comprehensive and feasible enough to ensure the targeted objectives.

1.2. Product Family Approach

A so-called product family approach (PFA) has been used in the development and manufacturing of a wide range of products – from coffee machine to aircrafts–to provide sufficient variety to the users, while maintaining cost-efficiency and the economies of scale at the same time [6]. According to Meyer & Lehnerd, 1997 (mentioned by Jiao, et al. [7]): "A product family refers to a set of similar products that derive from a common platform, yet possess specific features/functionality to meet particular customer requirements". The main purpose of the PFA has been to address the failure to embrace commonality, compatibility, standardization, or modularization among different products or product lines. Halman, et al. [8] also argued that product families should ideally be built not only on the elements and product architecture, but also on a multidimensional core of assets, which includes processes along the whole value chain (e.g., engineering and manufacturing), customer segmentation, brand positioning, and global supply and distribution.

The increasingly stringent environmental regulations push designers to consider extra features in product family design – including sustainability [9]. Beyond design and manufacturing stages, the previous PFA research has also tried to cover the EoL stage. Kwak and Kim [10], for example, have developed a PFA-based model that identifies optimal strategies for managing EoL take-back and resource recovery, and assessing the product family design in terms of its profitability in EoL management. Kwak [11], more specifically, have modelled the economic and environmental benefits of remanufacturing for a product family.

Two basic approaches (top-down and bottom-up) to product family design exist [6]. The bottom-up (or reactive design) approach has previously been used for redesigning or consolidating a group of distinct products to standardize components in order to improve economies of scales. The latter approach of the product family philosophy can be used for e-products, which are found in hundreds of different product variations. By carefully analyzing the commonalities among e-products, they can be categorized as different families, which in turn can facilitate optimizing their EoL management. Such categorization may also take into account the fate of e-products in their possible EoL pathways. Once these product families are established, they can guide producers to design products to suit the best EoL scenario for a given family. Eventually, this may inspire a 'top-down' (or a proactive platform) approach, wherein the producers themselves start developing products based on these families using e.g., concepts of modular design.

1.3. Objectives

Realizing the potential for the PFA to expand beyond manufacturing, we investigate its feasibility in the lifecycle management of e-products. In this paper, we introduce a conceptual framework based on the PFA that aims at addressing the challenges in the e-waste management system and helping a smooth transition of the e-industry towards a more circular model. The main objectives of this paper are to

- provide a comprehensive diagnosis of the existing e-management system,
- define the key features of e-products and EoL management systems upon which product families can be defined and exemplify the approach using a variety of product types, and finally
- identify the success factors for the implementation of a framework based on product family.

The remaining part of this paper is divided into five sections: Section 2 describes the methodology used; Section 3 summarizes the diagnosis of the current e-waste management system; Section 4 introduces the concept of PFA for e-waste management; Section 5 conceptualizes the framework circular economy in e- waste management; and finally Section 6 provides the concluding remarks.

2. Methodology

This paper builds on a series of studies carried out over the last three years by researchers at SDU Life Cycle Engineering, University of Sothern Denmark. Stretching between the two topics of e-waste management and circular economy, the studies investigated:

(a) the quantities of e-products and e-waste, their management systems, and the relevant organizational and legislative provisions [12],
(b) product and material flows in the EoL material recovery chain using a handful of case studies [13,14],
(c) the characteristics of EoL products (material composition, component composition, and design features) and economic assessment in order to compare possible EoL options (reuse, refurbishment, and recycling) [15],
(d) the users' perception of possible EoL scenarios for e-products [16], and finally
(e) the role of information exchange for an integrated product lifecycle management of e-products [17].

Based on the findings from these investigations, we first recognize the key issues in the existing e-waste management system. We then evaluate different attributes of e-products and the EoL systems, upon which the potential product families can be built. Finally, we identify the key elements required for the successful implementation of the proposed PFA-based framework for a circular economy in e-industry. The e-waste management system in Denmark is used as a reference, which represents the existing EoL system in the European Union.

3. Challenges in the Current E-Waste Management System

The essence of challenges in the current EoL management of e-products can be captured in the following three points:

(a) A fragmented product lifecycle management system

Although the take-back system intends to cover the whole product lifecycle, the EoL requirements are mainly limited to meeting the collection and the subsequent recycling/recovery targets. In practice, the manufacturing industry exists as a fully separate system, while the EoL management system operates independently. The current setup lacks effective communication and incentive mechanisms that covers all stakeholders in the product lifecycle. This fragmented approach results in the sub-optimization of individual processes in EoL management, but fails to reach the full potential for improving the overall resource efficiency. The current approach limits the producers' responsibility only to documenting the EoL collection and recycling rates. More importantly, the outsourcing of EoL responsibilities to a third party neglects "design for EoL", which is the core theme of the take-back system [18].

(b) A material-oriented (not product-oriented) perspective

The physical implication of the fragmented approach can be found in the current collection and subsequent management infrastructure for EoL e-products. The EoL system is built around material recycling and energy recovery, in which the discarded e-products are treated as a waste stream, not as a collection of EoL products. The European WEEE Directive [19] fails to provide an operational framework to encourage other EoL alternatives (reuse, refurbishment and remanufacturing) except for a subtle and vague call for reuse. The lack of initiatives to keep the products and components alive for a longer time and the unavailability of the spare parts make the alternative EoL possibilities even more unlikely. As a result, values are lost in terms of product and component functionality at the early stage of the EoL management (i.e., disposal and collection) (Figure 1).

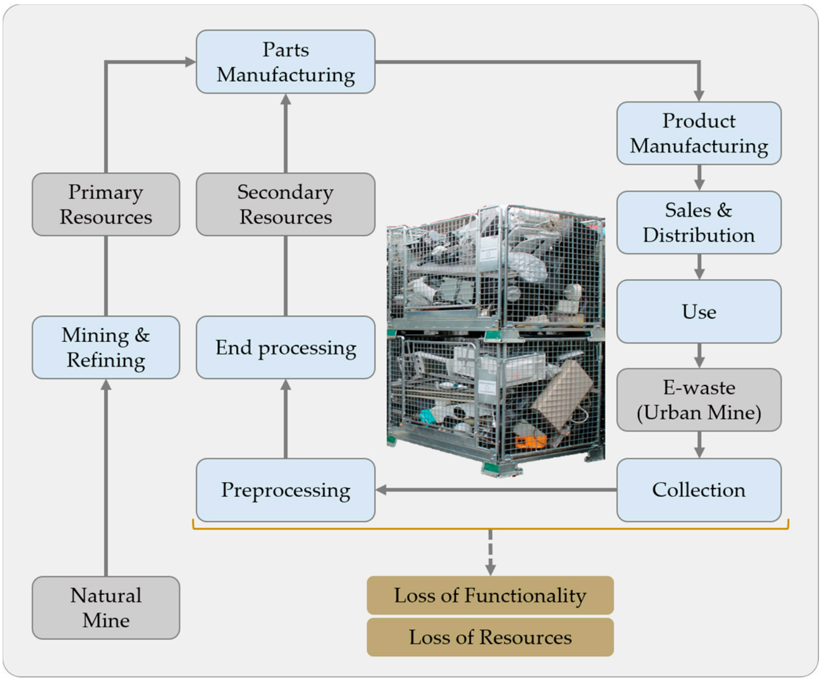

Figure 1. In the current system, the end-of-life (EoL) products are seen as urban mines and the EoL management focuses mainly on material recovery.

(c) A generalized 'one-size-fits-all' approach for managing a diverse stream of products

As defined by the WEEE Directive, e-waste includes all types of electrical and electronic products (e-products), which make it a complex stream, in terms of both design features and material compositions of the products [19]. Despite the complexity, the vast majority of EoL e-products just follow the same EoL management chain, often kicked off by a shredding preprocessing with the aim of liberating materials from each other in order to separate them in individual material streams being as pure as possible. This one-size-fits-all type of approach misses the opportunity of harnessing values in EoL products in terms of their product and component functionalities, which a more differentiated approach, better tailored for the characteristics of individual EoL product categories, could potentially harness. A more differentiated and product-centric approach has been suggested by, for example, the International Resource Panel [20], but the evidence of their implementation is not visible in the case of e-products. The challenge has been, among others, to find technological and legislative solutions that respect the product diversity, as well as the EoL management practices.

4. PFA in E-Waste Management

The e-waste collection and consequent material recovery processes in the European Union are loosely based on the 'categories' defined by the WEEE Directive, which lay the foundation for the existing EoL system. The member states define their own systems where the EoL products are collected in different collection fractions [21]. The existing practices mainly target material recycling and energy recovery, and the categorization is not consistent across all member states [15,22]. Besides the categories defined by legislations and local EoL management systems, other approaches to categorize e-products (and thus e-waste) exist (see examples in Table 1). Though the objective is to contribute towards improving the overall resource efficiency of the EoL system, there are inconsistencies among these approaches in terms of their basis for the classification and their goals. A standardized classification of e-products covering the diverse product types and their EoL options has been lacking.

Table 1. Examples of different approaches used in categorizing e-products.

Categories & Fractions Based On	Types *	To Support
Size, functionality, use of products [23]	10	Documentation & EoL treatment of e-products
EoL processing infrastructure [19]	6	
EoL treatment options [24]	5	Collection and material recovery
Functionality [22]	58	Documentation and EoL management
Material composition [25]	4	Active disassembly
Mechanical properties & chemical composition [26]	-	Product design and recycling processes
Metal content and EoL quantities [27]	6	EoL management

* Number of categories or fractions to which e-products are assigned to.

A possible solution to these issues is a more comprehensive categorization of products based on the product family philosophy. A product family can be a group of products that share some commonalities that are of significance in the product EoL management. More importantly, these families can also facilitate the implementation of 'design for EoL' thinking by providing producers an insight into the product EoL options and their linkage to different product attributes. In the following, we identify the key attributes of e-products as well as the EoL system in order to lay a foundation for defining product families.

(a) Intrinsic Product Attributes

i. Functionality

Product functionality has been an obvious basis for defining product categories, as it provides information on product characteristics. In most of the cases, products designed to achieve a particular functionality can be expected to have a similar product architecture. It means they share significant commonalities in terms of components used and their material compositions. As exemplified in Figure 2, robotic vacuum cleaners (RVCs) produced by five different brands were found to have very similar distribution of weight share among their components and the material compositions were also found to be consistent [14]. Also exemplified are the best-suited possible routes for the material recovery for each groups of components.

Nevertheless, not all products with the same functionality may belong to the same family. Some products may have entirely different product attributes (including shape, size, design features, and resource profile) even though they offer the same service. For example, these attributes of an RVC can be different from that of a conventional vacuum cleaner, which is bulkier and consists of different sets of components (e.g., cables and vacuum pipes). One the other hand, some products may serve two entirely different purpose, but can be similar in terms of product architecture and in terms of which EoL pathways are optimal for harnessing their residing functional and material values. For example, an electric kettle and an electric iron both usually consist of plastic casing, a heat exchanger, a thermostat, and a cable for the power supply. These two products, therefore, can have similar strategies for product refurbishment or component and material recovery. Therefore, it is also important to take into account another product attributes such as the components' material composition and design features.

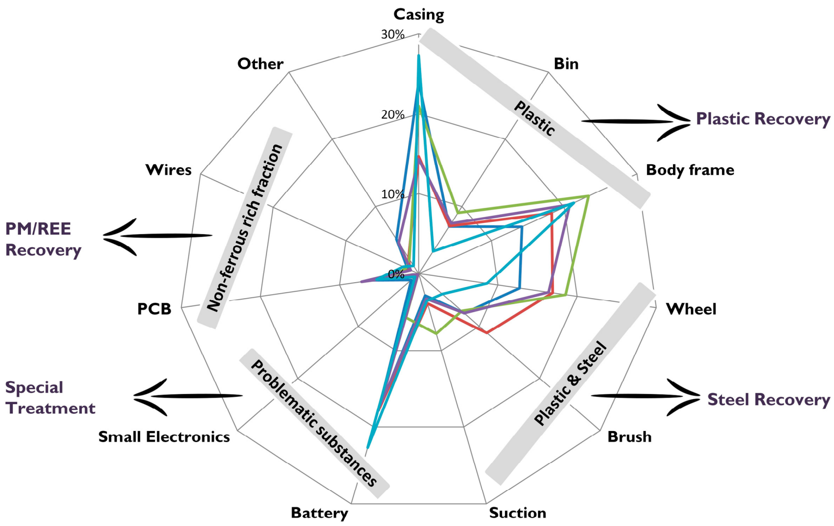

Figure 2. An example of commonalities within the different brands of robotic vacuum cleaners based on [14]. The diagonal of the cobweb plot represents % weight share of each component. The arrows suggest the best possible EoL pathways for the give groups of components [PM/REE = Precious metal/Rare earth element].

ii. Material Composition:

Material composition is probably the most influential product attribute that governs the success of the EoL processing, at least within the existing EoL infrastructure that focuses on material recycling. In processing plants, the e-waste is loosely divided into two streams (plastic-dominant and metal-dominant). This provides a simple basis for the primary processing and the subsequent material recovery chain. However, the processing of these two streams is not considerably different in the commonly practiced shred-and-separate approach. This generalized practice can be singled out as a key factor responsible for the significant gap between the overall recycling rates of plastics and that of metals.

An elaborated understanding of material composition of e-products allows us to establish the resource footprint of products, which provides a scientific basis for defining product families. Our case studies show that the metal-dominant products are more suitable for mechanical size reduction followed by a set of sorting steps. The well-established recycling infrastructure and material value allow efficient recycling of base metals such as steel, aluminum, and copper. Plastic-dominant products in the shredding process, however, result in large share of mixed plastic streams with different polymer types, grades, and colors—reducing the probability of being recycled. Besides base metals and plastics, most of the products consist of components and materials (e.g., printed circuit boards, small electronics, glass, ceramics etc.) that require special attention due to either their high material value or the content of potentially hazardous substances.

In Figure 3, we exemplify the distribution of select e-products based on their material composition grouped into these three groups: base metals, plastics, and other components. The illustration provides a simple guide for finding the best-suited material recovery pathways. For example, products close to the left edge (e.g., window cleaner) are plastic-rich and are therefore not best suited from intense shredding. Moreover, products lying towards the top vortex (e.g., mouse) contain significant share of other components such as PCBs, which are more suitable for recovery with manual dismantling. On the other hand, products close to the lower-right vortex (e.g., microwave oven), which are metal-rich, are suited for shredding after the removal of components such as power cables.

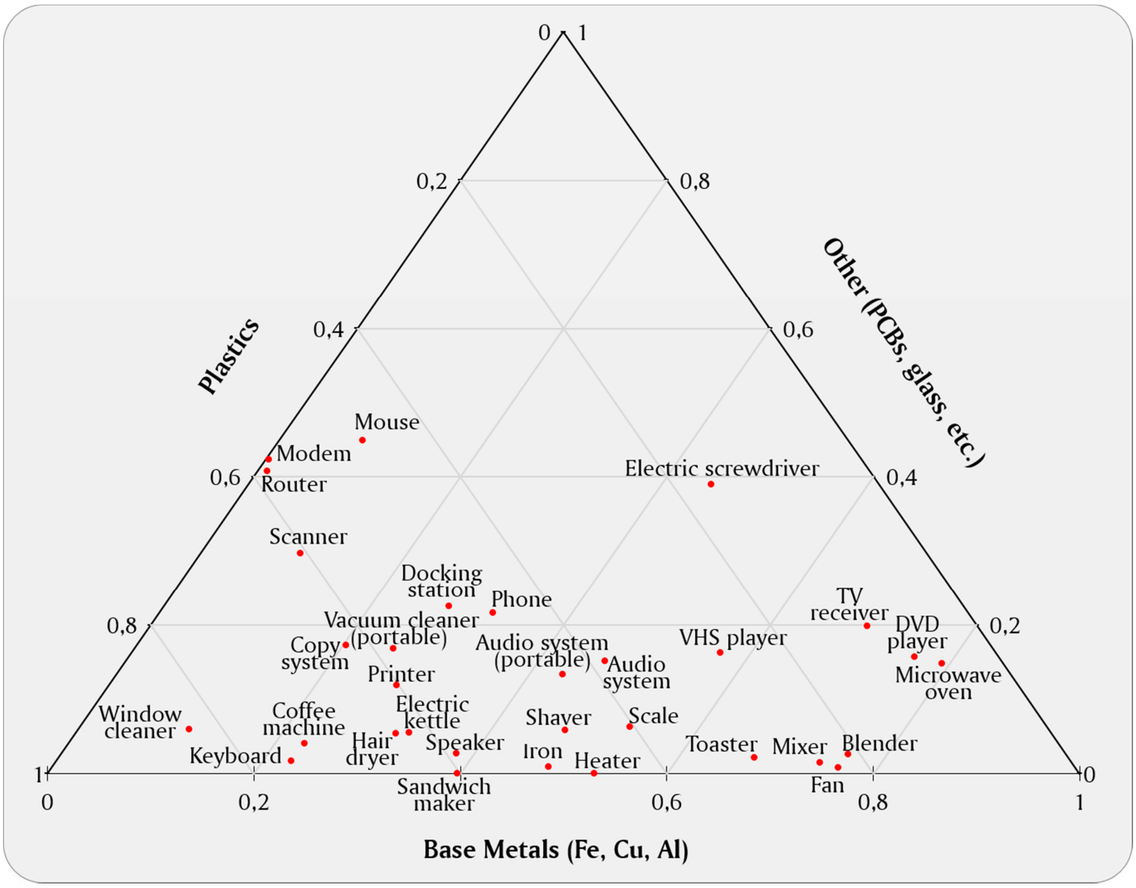

Figure 3. Illustration of the diversity of material composition in household e-products based on the empirical data from [15]. Each axis shows the content of a material type in a ratio between 0 and 1.

iii. Product and Design Features

Along with the material composition, features of a product and its design choices also play a crucial role in the EoL resource recovery process. Examples of the product design's impact on resource recovery have been illustrated in our previous case studies [13,14]. Moreover, design features such as number and placement of different components and the type of fasteners used in a product can facilitate or hinder the possibilities of refurbishment and remanufacturing [17]. For an example, a higher number of components and assemblies in a product could mean a complex product assembly, which has direct implication in the dismantling of the product for repair or recycling. While defining product families, these factors need to be taken into account as well.

The legal definition of e-products covers product types varying from refrigerators to toothbrushes. This variation requires different strategies for EoL collection and handling of these products. Table 2 illustrates the diversity of e-products in terms of their component composition, and identifies the possible EoL management pathways for the products. In the table, we identify the key components in select products and group them under the two broad categories 'potentially reusable' and 'suited more for material recovery'. Further, we have divided the components based on their occurrence in common e-products, which can be related to the repair and remanufacturing possibilities, and the potential for modularization. Finally, it shows how the components can lay the foundation for the material recovery process. A comprehensive characterization and categorization of products based on the components, their resource profiles and the preferred EoL recovery options can serve as the key for the presorting platform suggested in Section 5.2.

Table 2. Component-level composition of select e-products and their relation to possible reuse and recycling options.

Product Type	Potentially Reusable Components				Components Suited More for Material Recovery						
	Universal Components		Common Components		Plastic-Rich	Metal-Rich		High-Value		Special Components	
	Power Cables	Switches	Electromotors & Transformors	Displays	Casings & Body Frames	Casings & Body Frames	Other	PCBs	Other	Batteries	Other
Audio System	*		*	*	*	*		*	*		
Blender	*	*	*		*		*				
Coffee machine	*	*			*		*				
Copy System			*		*	*					*
Docking Station					*	*		*	*		
DVD-Player	*			*		*		*	*		
Electric Kettle	*	*			*		*				
Electric Screwdriver		*	*		*	*				*	
Fan	*	*	*		*	*	*				
Hair Dryer	*	*	*		*		*				
Hair Trimmer	*	*	*		*		*				
Heater	*		*		*	*					
Iron	*				*		*				
Keyboard					*	*		*			
Microwave Oven	*		*	*		*		*	*		*
Mixer	*	*	*		*	*	*				
Modem	*				*			*			
Mouse					*			*			
Personal Computer	*					*		*	*		*
Phone				*	*			*	*		
Portable Cassette Player		*	*		*	*		*	*	*	
Portable Vacuum Cleaner		*	*		*			*		*	
Printer	*		*		*			*			*
Router	*				*			*			
Sandwich maker/Grill	*						*				
Scale				*			*	*		*	*
Scanner	*		*		*		*				*
Shaver		*	*		*			*		*	*
Speaker	*		*								*
Toaster	*					*	*				
TV receiver	*					*		*			
VHS Player	*		*	*	*	*		*	*		
Window cleaner		*	*		*						

Besides the above-mentioned intrinsic product attributes, external factors also influence the EoL of a product and therefore need to be taken into account. In the following, we identify the attributes related to EoL management and therefore are worth considering while defining product families.

(b) Extrinsic Product Attributes

i. Maturity Level and Expected Lifespan

As the history of electrical and electronic products goes back more than a century and given the constantly evolving technology, the e-products that are available today have a varying degree of maturity in terms of product design and expected lifespan. The expected lifespan, which in general becomes more predictable with the increased maturity of products, may influence the fate of EoL products. For example, matured products tend to have more standardized components that are commercially available as spare parts, meaning a higher possibility for reuse and refurbishment. On the other hand, the features of relatively new products that are still evolving can vary across different brands. Such products are also likely to be 'outdated' earlier because of the rapid technological advancement—reducing the reuse possibilities. A microwave oven can be considered to have a higher maturity level, which is less likely to be affected by the advancing technology compared to a smartphone. The EoL fate of a product can be more predictable with its maturity, which from a producer's perspective, may mean a greater opportunity for implementing design for EoL strategies.

ii. Price Range

Price of a product can arguably have the most significant impact on reuse, refurbishment, and remanufacturing possibilities. If the price is higher, users will be more likely to repair their product (e.g., a television) compared to a low-priced product (e.g., an electric kettle), which will most likely be discarded when it stops functioning properly. The price factor also comes into play combined with the weight and size of a product. In general, size and weight seems to have a direct correlation with the price and lifetime of the products (e.g., longer life of ovens compared to hair dryers) with some exceptions (e.g., a laptop). An example can be seen in Figure 4, which shows the price and weight of 45 different e-products in the Danish market. The prices are the average of ten samples for each product collected (in January 2017) from a website (www.pricerunner.dk) that compares the price of different products. The weight of the products are taken from our previous study [12].

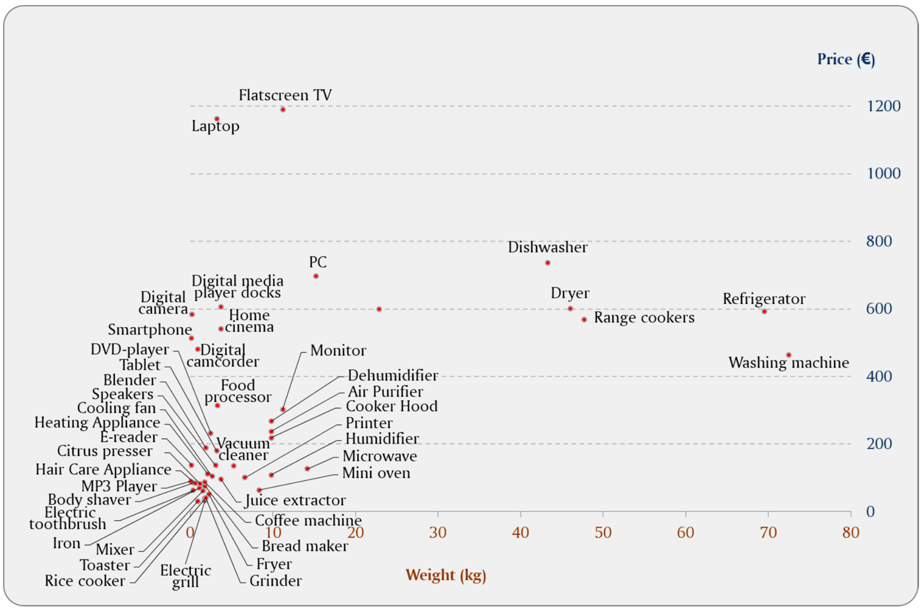

Figure 4. Comparison of average market price and weight of select products.

We have also observed that very few of the products with higher price range and lower weight range (e.g., smartphones, tablets, gaming console) were present in the collected e-waste, and notably, these are also the most sold products through user-to-user online platforms for used items [15]. This is an important insight for an EoL system and policy makers who seek to cover the whole range of products in the promotion of reuse, refurbishment and remanufacturing.

(c) EoL Attributes

The efficiency of EoL resource recovery depends largely on the available infrastructure and method used for EoL processing of e-products. Moreover, the requirements of the recycling industry and materials markets influence how e-waste is processed in the material recovery chain, which we have illustrated in our case studies [13,14]. Such realities, which are beyond the technical feasibility of resource recovery, also need to be taken into consideration while defining product families.

The EoL fate of a product also depends on the possibilities for reuse, refurbishment, and remanufacturing, which are shaped by technical factors (e.g., availability of knowledge and resources needed for repair), as well as socio-economic aspects of product use. For example, the trend of reuse and repair are found to be more common in countries with low income [28]. Environmental awareness and grassroots movements such as Repair Cafés (https://repaircafe.org) can also have impacts on how users perceive the EoL possibilities of a product [29]. Though such trends may seem less significant, given their popularity, they have the potential to influence the EoL fate of e-products.

One or more of the above-mentioned attributes related to product and EoL can be identified as the commonalities across the various types of products and can be used to build the platform for defining product families. Once the product families are defined, the most suitable EoL pathways can be identified for each family, based on which EoL strategies can be defined for the products belonging to that family. Along with the legislative provisions, more targeted guidelines for product design can be developed that address the 'design for EoL' requirements for each product family based on the product as well as the EoL attributes.

5. A Framework for CE

Defining product families based on the product and EoL attributes will only be the first step towards implementing CE in the e-industry. It will require a fundamental change in today's e-waste management systems, with the prerequisite being to perceive e-waste as 'EoL products' and not as an 'urban mine'. To support this fundamental change in perspective, an improved collection system for the EoL products will be needed in place of the current waste collection system that sees the EoL products only as a source of secondary materials. Further, a system for presorting and testing of the EoL products (preferably at the collection point) can support the possibility of utilizing the remaining functionality of the products and their components. Finally, such a system—if supplemented with a family-centric approach for material recovery processing-can improve the overall resource recovery. The potential for improved material recovery using a more customized processing has been suggested by previous studies [20,26,30]. Figure 5 illustrates the envisioned system, the components of which are described in the following subsections.

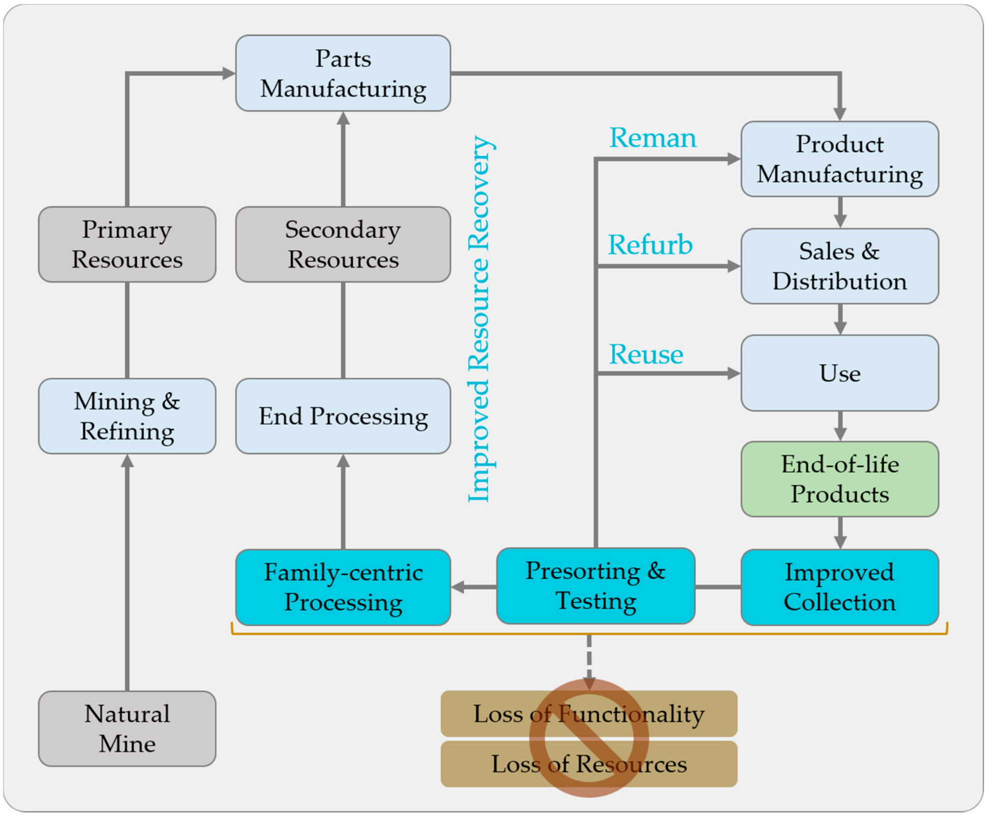

Figure 5. The envisioned system based on a product family approach for the lifecycle management of e-products.

5.1. Improved Collection Systems

The waste management system in a CE should seek to create values from the EoL products, unlike the conventional system that focuses on reducing the cost of collection and disposal [31]. The e-waste management system needs to expand to cover reuse, refurbishment, and remanufacturing possibilities of all product types [15]. If EoL products are to be prepared for reuse, the way e-waste is collected also needs to change fundamentally. E-products, especially those with monitors and other impact-sensitive parts need to be handled carefully. If broken, such products not only diminish the possibilities of reuse, but also influence the ease of recycling, and thus increase the cost of handling. Moreover, they could create challenges in logistic as well as the management of potentially hazardous substances such as lead in cathode ray tube (CRT) monitors and mercury in the light tube of liquid crystal display (LCD) monitors. A better collection platform can prevent such damages to products during the EoL collection.

Depending on their types, many e-products retain a resale value and therefore can have a good business case for reuse, if they are brought to the second-hand market. Often used products with such potential remain at households in the form of hibernated stocks. An improved EoL collection system should target the remaining functionality of not only collected products, but also the hibernated stocks. For example, products with high reuse potential but with short lifespan (e.g., mobile phones) should be acquired as soon as possible once the users stop using them. Strategies such as door-to-door collection and/or monetary incentive for the users to deliver potentially reusable products can be effective in such cases. A timely door-to-door collection may help to preserve the functional value of such products in this fast-paced technological development, which may become obsolete by the time it would be otherwise discarded of. If handled by trained personnel at the doorsteps, any potential physical damage can also be avoided during the collection of the reusable items. It can also preserve the remaining functionality from being lost to factors such as rain and snow in the current

EoL collection setup [15]. Users were also found to prefer the option of their EoL e-products being collected at their doorsteps [16]. While implementation of such collection options for select product categories has the potential to capture the reuse value, it will require further investigation to confirm the cost effectiveness.

5.2. Presorting and Testing Platform

Along with the improved collection system, it is essential to have a presorting platform for the different types of collected EoL products. Such platforms can be established either at the collection points (e.g., civic amenity sites) or at the preprocessing facility depending on the logistic requirements. Such sorting platforms can be supplemented with a testing facility, which will identify potentially reusable products and components. The main purpose of such a platform will be to divert EoL products towards the most preferred EoL pathways including reuse, refurbishment, remanufacturing, and recycling. Such a platform can be run manually, or given the feasibility, use automatic systems with the help of visual recognition techniques. Further, relevant information for this purpose can also be planted in the product itself by the producer (e.g., using barcodes or radio-frequency identification (RFID) technology) and can be used as platforms for product sorting.

5.3. Family-Centric Processing

Our case studies [13,14,17] have shown the losses occurring in the resource recovery chain due to the generalized processing and the mismatch between product features and their EoL handling. The efficiency of resource recovery processes varies with the material compositions and design features of the EoL products. For example, while shredding could be a good option for metal-rich products such as a microwave oven, shredding of EoL RVCs results in high losses of electronic components as well as the high value plastics [14]. A disassembly-based treatment has been found to be more efficient in the recovery of precious metals and plastics from EoL products compared to generalized processing based on size reduction [32].

A family-centric processing will prioritize soft dismantling of EoL products in order to create component concentrates (as opposed to the generalized shredding that creates material recyclates). Each component concentrates can be then sent to respective downstream processing for the optimal resource recovery. Such an approach will help reduce the loss of materials caused by shredding and improve the purity of recyclates, which in turn will lead to better recovery of resources in the recycling chain.

6. Concluding Remarks

The current e-waste management system suffers from losses in the form of materials as well as product and component functionality, which occur during the collection and processing of EoL products. In part, these losses can be attributed to the diversity of the e-products but also the generalized approach to handling them. A more robust system of categorizing e-products carries the potential of improving the EoL material recovery and facilitating reuse, refurbishment, and remanufacturing. We identify the attributes upon which product families of e-products can be built for a better EoL management. Moreover, we identify the three key improvements in the EoL management chain in order to avoid the material and functionality losses, namely: (a) an improved collection system; (b) a presorting and testing platform; and (c) a family-centric processing of EoL products. The framework is based on the philosophy of a 'product family', and if supported by these three key upgrades in the existing EoL management system, they can serve as a potential solution for achieving circularity in the e-industry.

We acknowledge that this study is limited to identifying the attributes for defining product families, which does not offer concrete examples of product families. We believe it will require a more in-depth study of each of the identified attributes in order to come up with such concrete suggestions, which will be the focus of our future work.

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