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].

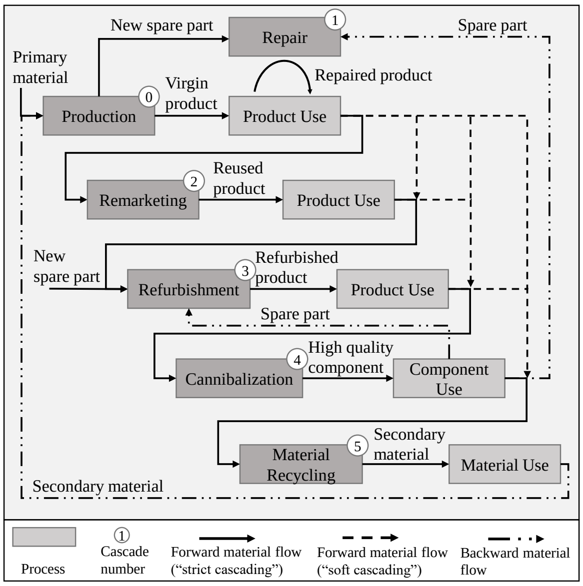

Figure 1: Cascade use of electronics

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

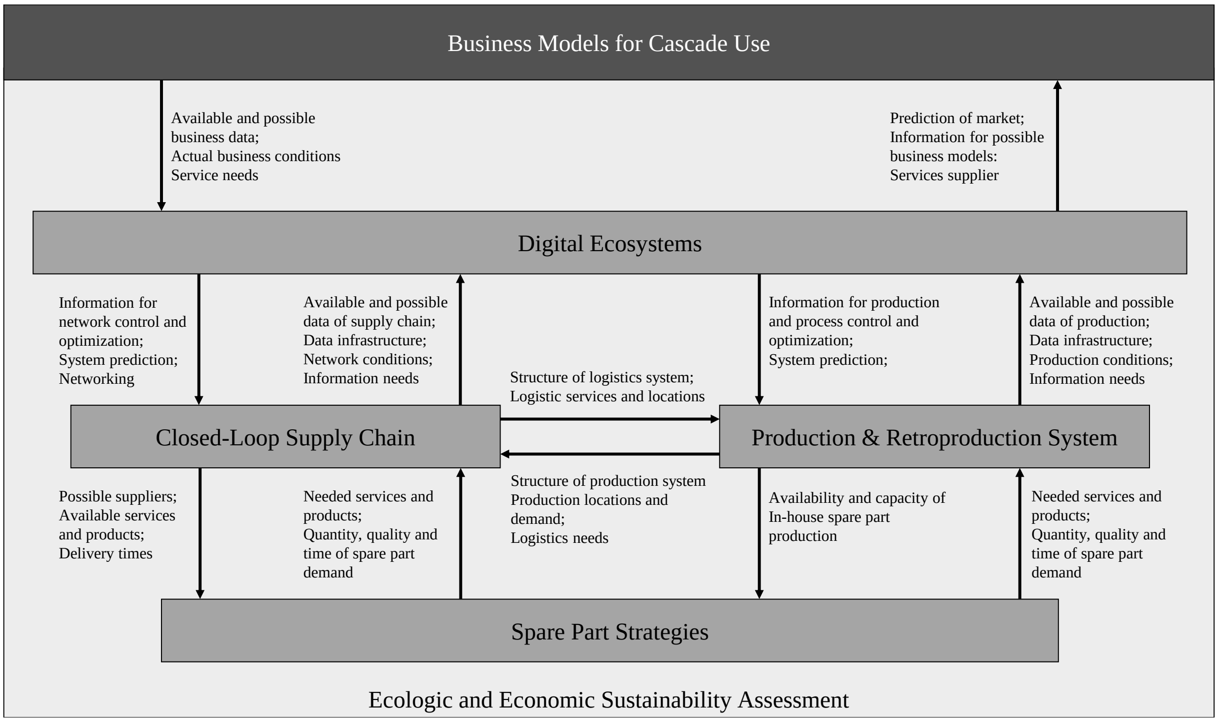

Figure 2: Interdisciplinary research framework to develop circular business models for cascade use of electronics

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 interdependencies 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

Acknowledgment

This paper evolved of the research project “EffizientNutzen” (data-based business models for the cascade usage and extended product usage of electr(on)ic products) which is funded by the Federal Ministry of Education and Research (033R240C).

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