Assessment of the contribution of preparation for reuse to the goals of a circular economy

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Angaben zur Veröffentlichung / Publication details:

Boldoczki, Sandra. 2021. "Assessment of the contribution of preparation for reuse to the goals of a circular economy." Augsburg: Universität Augsburg.

Assessment of the Contribution of Preparation for Reuse to the Goals of a Circular Economy

Cumulative Doctoral Dissertation
at the Faculty of Business Administration and Economics of the University of Augsburg
submitted in partial fulfillment of the requirements for the degree of
Doctor of Economic Sciences (Dr. rer. pol.)

submitted by

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Augsburg, 2021

First reviewer: Prof. Dr. Axel Tuma

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Date of oral exam: June 17th 2021

List of Scientific Contributions

The following published and submitted scientific contributions are presented within this doctoral dissertation. The articles are sorted following their order of appearance in this dissertation. Rankings relate to the VHB-JOURQUAL3, a journal rating that has been published by the German Academic Association for Business Research (VHB).

Contribution C1 (published in a journal ranked B)

Messmann, L., Boldoczki, S., Thorenz, A., Tuma, A. (2019). Potentials of preparation for reuse: A case study at collection points in the German state of Bavaria. *Journal of Cleaner Production*, 211,1534-1546. https://doi.org/10.1016/j.jclepro.2018.11.264.

Contribution C2 (published in a journal ranked B)

Boldoczki, S., Thorenz, A., Tuma, A. (2020). The environmental impacts of preparation for reuse: A case study of WEEE reuse in Germany. *Journal of Cleaner Production*, 252, 119736. https://doi.org/10.1016/j.jclepro.2019.119736.

Contribution C3 (published in a journal ranked A)

Boldoczki, S., Thorenz, A., Tuma, A. (2021). Does increased circularity lead to environmental sustainability? The case of washing machine reuse in Germany. *Journal of Industrial Ecology*, 1–13. https://doi.org/10.1111/jiec.13104.

Contribution C4 (submitted to a journal ranked C)

Boldoczki, S. (submitted). How to unlock potentials of preparation for reuse: barriers and action recommendations. Submitted to: *Die Unternehmung.*

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Introduction

Introduction

In December 2019, the European Green Deal for the European Union (EU) and its citizens was introduced as an agenda for sustainable growth to transform the EU into a fair and prosperous society with a modern, resource-efficient, and competitive economy (European Commission, 2019). In March 2020, the European Commission published a new Circular Economy Action Plan, which is one of the main building blocks of the European Green Deal and includes measures to stimulate Europe's transition towards a Circular Economy (European Commission, 2020). The realization of these actions will be instrumental in reducing environmental pressures and reaching the Sustainable Development Goals by 2030 (European Commision, 2015). The Circular Economy fosters a transition from a linear "take – make – dispose" economic model to a circular model, where the waste of one process becomes the input to another (Wautelet, 2018). Waste management, therefore, plays a central role in the Circular Economy (Brears, 2018; Ghisellini et al., 2016).

The European Waste Framework Directive (Directive 2008/98/EC) provides requirements for a general framework of waste management and sets basic waste management definitions for the EU. It established a waste hierarchy consisting of prevention, preparation for reuse, recycling, other recovery, and disposal (in that order of priority). The hierarchy's goal is to reduce environmental and health impacts of waste generation and waste management as well as to improve resource efficiency. In order to promote the implementation of the waste hierarchy, the European Waste Framework Directive sets combined reuse and recycling targets to be achieved by 2020 for household waste (50%) as well as construction and demolition waste (70%). Regarding preparation for reuse, no separate targets have been set so far. This shall be changed by December 2024 (Directive (EU) 2018/851, 2018). The latest amendment of the European Waste Framework Directive in 2018 obliged the Member States to report their preparation for reuse rates separately from recycling rates. This is done to calculate separate reuse and recycling targets since data on viable amounts for preparation for reuse is rare and quantitative assessments of potentially reusable wastes are lacking. This currently renders the setting of a feasible quota difficult and constitutes the first research gap this doctoral thesis addresses (contribution C1).

From an environmental point of view, the prioritization of waste prevention is not challenged for any kind product. When it comes to the preferability of reuse compared to lower-ranked waste management options (recycling, energetic recovery, landfilling), this prioritization is questioned in literature for energy-using products (Baxter, 2019). The impacts arising during the entire life cycle of unpowered products are dominated by the production phase, whereas the energy efficiency during the use phase gains importance for energy-using products (Cooper & Gutowski, 2015). Therefore, the assumption that reuse always results in lower environmental impacts needs to be assessed in detail for energy-using products. A detailed environmental assessment of the impacts of reuse compared to lower-ranked waste management options is currently missing. This research gap is addressed by the subsequent contributions (C2 and C3). In literature, it is agreed that actions need to be taken to promote reuse, but a structured review of action recommendations and relevant actors is missing. This structured compilation of action recommendations is given in the last contribution (C4).

This research sets out to provide a comprehensive evaluation of the potential of preparation for reuse to reduce environmental and health impacts. The contributions compiled in this thesis address the following research questions guiding the overall research project:

Q1: What is the theoretical potential for preparation for reuse in Bavaria?

Q2: For which products can preparation for reuse be recommended?

Q3: How environmentally sustainable is preparation for reuse?

Q4: What are success factors for preparation for reuse in Germany and Europe?

This doctoral thesis encompasses an introductory section that structures the research project, delineates some general characteristics of preparation for reuse in the context of Circular Economy research, and provides the methodological background. A total of four scientific publications addressing the research questions constitute section 2. Finally, a summarizing discussion is given, and promising fields for future research are proposed.

1.1 Circular Economy and preparation for reuse

Circular Economy (CE), as an opposing business model to the linear economy, is being proven to have substantial positive impacts on environmental, human health, and social spheres. CE is considered a leader to more sustainable development and an overall harmonious society (Ghisellini et al., 2016). It offers an alternative to the dominant linear economic model by promoting the notion of waste as a resource (Blomsma & Brennan, 2017). Ecosystems serve as a role model for the CE, as nature's biological metabolism likewise works in loops. Naturally, waste is non-existent as all material is effectively recycled. The CE mimics this closed-loop concept to make our economic activities more regenerative, resource-efficient, and sustainable while still being competitive (Wautelet, 2018). At the core of a CE are closed production systems, where resources are reused, and materials are kept at their highest value at all times (Braungart et al., 2007; Kalmykova et al., 2018). Further key aspects are the minimization of waste and the decoupling of economic growth from resource use (Ellen MacArthur Foundation, 2015).

In recent years, the concept of CE has gained the attention of institutions, scholars, and practitioners (Kirchherr et al., 2017; Korhonen et al., 2018). The concept of CE has been evolving since the 1970s, based on different schools of thought such as regenerative design, performance economy, cradle to cradle, industrial ecology, or biomimicry (Ellen MacArthur Foundation, 2013). The first idea of CE dates back to the American economist Kenneth E. Boulding (Ghisellini et al., 2016), who introduced the principle of an open and a closed economy. In his work, he discusses the harmful impact of economic growth on the environment and the limited natural resources available for human activities. He advocates for the closed economy, which is self-contained and demands efficient use of limited resources (Boulding, 1966; Cardoso, 2018).

A central principle of CE is "waste equals food," also described as "cradle-to-cradle design" (Braungart et al., 2007; Wautelet, 2018). This principle demands a design of products and industrial processes that enables the continuous flow of resources within one of two metabolisms (cycles): the biological metabolism and the technical metabolism. Figure 1 shows this distinction as a butterfly diagram based on an illustration by the Ellen MacArthur Foundation (2019).

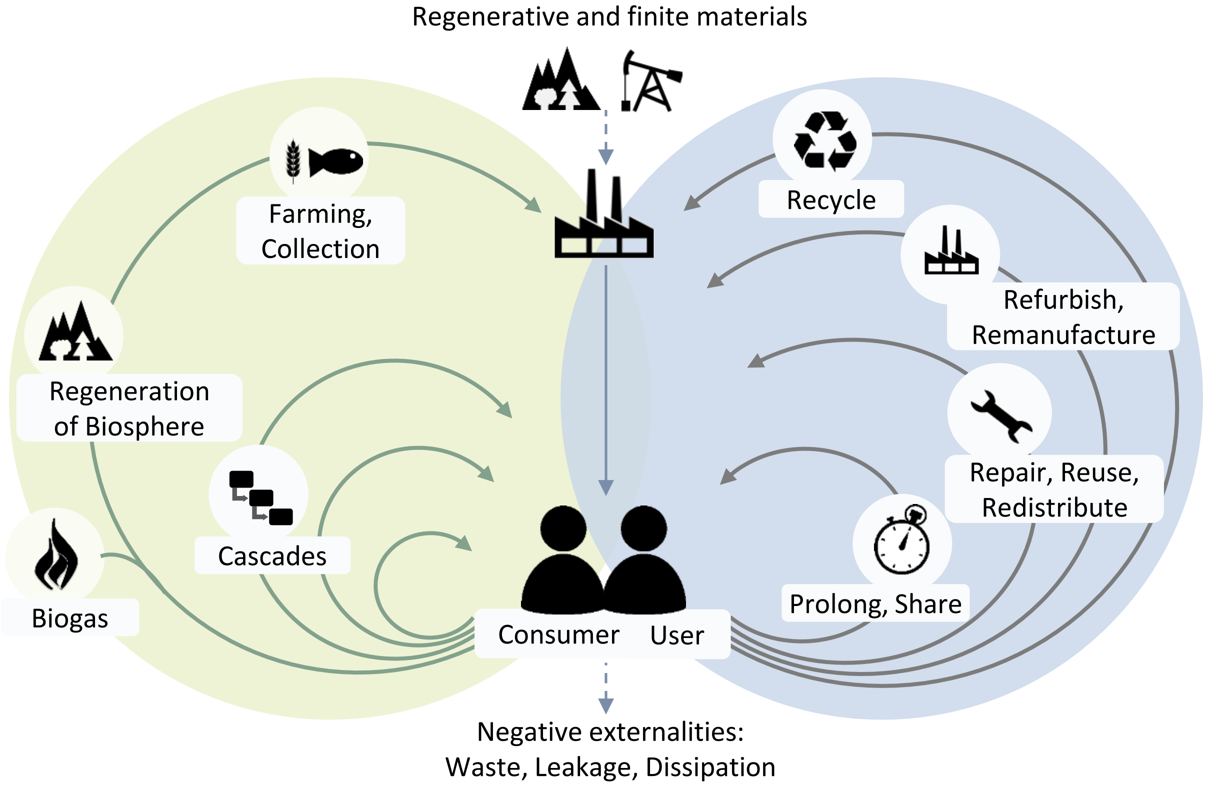

Figure 1: The biological metabolism (products of consumption) and the technical metabolism (products of use) (Beamer et al., 2021)

The green cycle illustrates the flow of biological nutrients (products of consumption). Products that are consumed during their use phase, such as shampoo, or brake pads, should be biodegradable to prevent harm to the environment. Cascading use is to be preferred, but at the end of their life cycle, products of consumption feed back into biological processes and serve as nutrients. Technical nutrients (products of service, e.g., laptops, washing machines) belong to the blue cycle. They are of synthetic or mineral nature and are therefore not biodegradable. The manufacturing of these products is resource and energy-intensive (Boldoczki et al., 2020). Therefore, these products should remain in the use phase for as long as possible. Concepts such as repair, share, reuse, or refurbish can be applied to achieve a lifetime extension. At the end of their lifespan, products should be collected so that the materials can be recycled and reused again as secondary materials in the production phase (Beamer et al., 2021; Braungart et al., 2007).This doctoral thesis analyzes the waste management option of preparation for reuse, which belongs to the second inner cycle within the technical metabolism.

Reuse has become part of the “3 Rs” (reduce, reuse, recycle) and is promoted far beyond the EU by environmental agencies such as the U.S. Environmental Protection Agency (Kahhat et al. 2008) or as part of China’s CE (Zheng et al. 2015). At the same time, the term reuse is utilized generically, comprising more precise terms such as **preparation for reuse** (PfR), repurposing, reconditioning/refurbishing, using second-hand products, or remanufacturing (Ardente et al., 2018). This doctoral thesis follows the definition of PfR by the European waste hierarchy, which is enforced on the national level in Germany by the Law on Closed Cycle Management and Waste (Kreislaufwirtschaftsgesetz, KrWG). It defines PfR as “any recovery operation of testing, cleaning or repair in which products or components of products that have become waste are prepared in such a way that they can be reused for the same purpose for which they were originally intended without further pretreatment” (KrWG, 2012). Waste prevention takes priority in the waste hierarchy for all EU member states. When the owner of a product disposes of it or expresses the will to dispose of it, the product passes the waste threshold and turns into waste (KrWG §3). Beyond the waste threshold, PfR is the preferred waste management option. This is depicted in Figure 2, which puts the European waste hierarchy in the context of a closed-loop supply chain by the example of a washing machine.

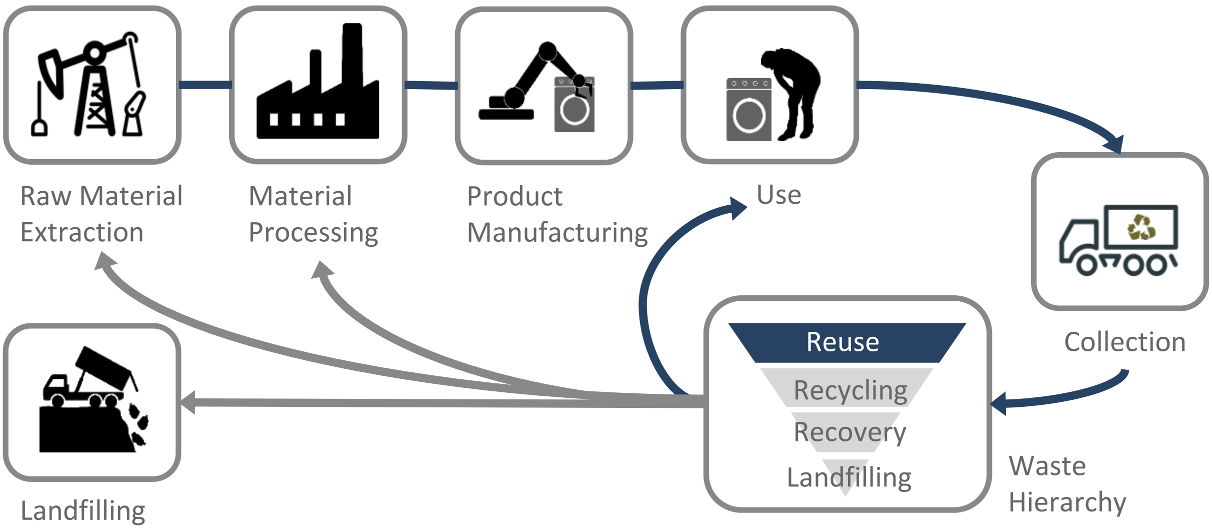

Figure 2. European waste hierarchy in the context of a closed-loop supply chain

PfR requires goods to undergo recovery operations prior to recirculation into the use phase. These operations comprise examination, cleaning, and repairing (KrWG §3). This implies that entire products that have become waste, or components of these, are prepared so that the products can be reused for the same purpose they were conceived (Directive 2008/98/EC, 2008).

Therefore, what distinguishes PfR from reuse is that in the former, a product passed the waste threshold before being prepared to be reused again, whereas in the latter, a product that is not waste is reused again. Both concepts have in common that the original purpose of the product is maintained. In literature, inconsistencies concerning the definition of reuse as well as the inclusion or exclusion of different secondary market production processes in the umbrella concept of reuse such as repair, recondition, refurbish, or remanufacture are recognized (Gharfalkar et al., 2016). Gharfalkar et al. (2016) propose an extension of the "hierarchy of secondary market production processes" developed by Ijomah et al. (2005). In this hierarchy, reuse measures for mechanical and electromechanical products are classified by the five parameters work content, cost, energy requirement, warranty, and performance. Additionally, a potential upgrade of the product (by adding new components or replacing existing components with better-performing ones) is discussed (Ziout et al., 2014). According to Ziout et al. (2014), this could be part of a refurbishing process to improve product functionality and appearance. Figure 3 clusters secondary market production processes according to the abovementioned parameters.

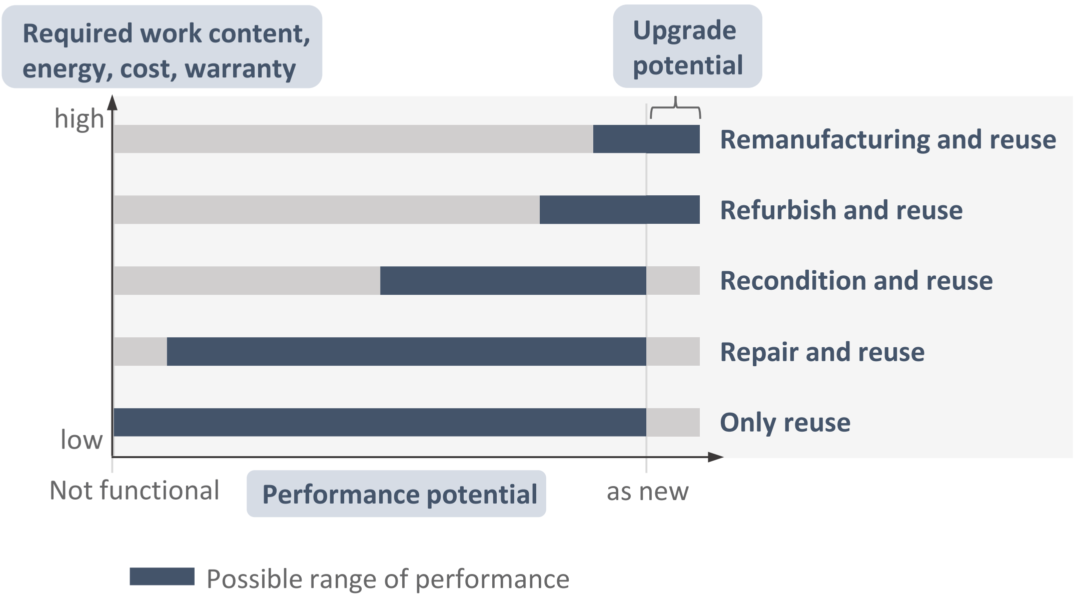

Figure 3. Distinction of secondary market production processes
(own representation based on Gharfalkar et al., 2016 and Ziout et al., 2014)

“Remanufacturing and reuse” requires more work content, cost, and energy but guarantees a product performance that is similar to the original product. It may even deliver a performance that exceeds the original one due to an upgrade. Reuse without any other operation demands almost no work, energy, or cost. However, the product's performance may also be at the lower end of the range, and no warranty is given.

The analyses in this doctoral thesis are based on the assumption that after recovery operations, reused products are able to fulfill their original function with similar performance compared to their first use phase. The parameter of product performance is especially relevant for contributions C2 and C3, where environmental impacts of new and reused electrical and electronic products are compared during their life cycle. In these contributions, the impacts during the use phase depend strongly on energy and water consumption. It is assumed that the energy and water consumption of reused products equals the consumption of the original product. Therefore, reuse operations that include an upgrade are not within the scope of this thesis.

1.2 The relevance of waste electrical and electronic equipment

In 2019, approximately 53.6 million metric tons of waste electrical and electronic equipment (WEEE) was generated globally. This is expected to increase to 74.7 million metric tons by 2030 (Forti et al., 2020). WEEE is the fastest growing waste stream (Mazahir et al., 2019) and comprises a mixture of materials that demand appropriate End-of-Life treatment. Therefore, this waste stream's management is of particular interest for CE and regulated by Directive 2012/19/EU (2012) (Boldoczki et al., 2021). As for household and construction waste, minimum targets for recovery and a combined target for PfR and recycling for different product groups of WEEE are set. These targets support the implementation of the European waste hierarchy in general but do not provide incentives for an increase of PfR in comparison to recycling. As discussed earlier, this will be changed by setting separate targets for PfR. For unpowered products, the preferability of reuse in comparison to lower-ranked waste management options (recycling, energetic recovery, landfilling) is unquestioned. The extend of a potential PfR quota mainly depends on the number of products viable for reuse. For energy-using products, the preferability of reuse needs to be assessed in detail from an environmental point of view. Reuse is only preferable to recycling if the life cycle impacts are smaller than those of a new product. For unpowered products, impacts only arise during the production phase. If these impacts are avoided, life cycle impacts are lower than for a new product. When an energy-using product is being reused, not only the production phase leads to environmental impacts, but also the use phase. During the use phase, the resource consumption (energy and other resources, such as water) of an old product could exceed a newly manufactured product's consumption. In this case, the question arises if the avoided impacts of manufacturing exceed the additional impacts of the use phase. This trade-off needs to be assessed in detail and explains why the waste stream of electrical and electronic equipment requires special attention when the sustainability of a reuse quota is discussed.

1.3 Methodological foundations

The methods applied in this doctoral thesis stem from the research field of industrial ecology. "[Industrial ecology is] the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources" (White, 1994). At the core of industrial ecology is the study of the structure and functioning of the industrial or societal metabolism and their environmental effects (Bringezu & Moriguchi, 2002). Three major analytical methods to study environmental effects of economic interactions are Life Cycle Assessment, Material Flow Analysis, and environmentally extended input-output analysis (Shmelev, 2012). Life Cycle Assessment (LCA) is a method that studies the interaction between society and the environment by quantifying impacts and damages products cause along their life cycle (Udo de Haes, 2002). The method of Material Flow Analysis (MFA) allows disassembling systems into single processes and models the links between material flows and stocks. Input-output analysis is suitable for studying the monetary or physical interactions between economic sectors and regions. The methods LCA and MFA are applied in contributions C2 (LCA), and C3 (LCA and MFA). Thus, a brief introduction is provided in the subsequent sections.

Life Cycle Assessment

Life Cycle Assessment (LCA) is a structured, comprehensive, and internationally standardized method for the assessment of environmental impacts of a product or service along its entire life cycle. It compiles all resource inputs and emissions into water, air and soil, and associates these with a product system or service. Ultimately, the related impacts on the environment, human health, and resource depletion are quantified (ILCD, 2010). The methodological framework for an LCA study is provided by the ISO 14040 and 14044 standards and follows four iterative phases as depicted in Figure 4 (ISO, 2006a, 2006b):

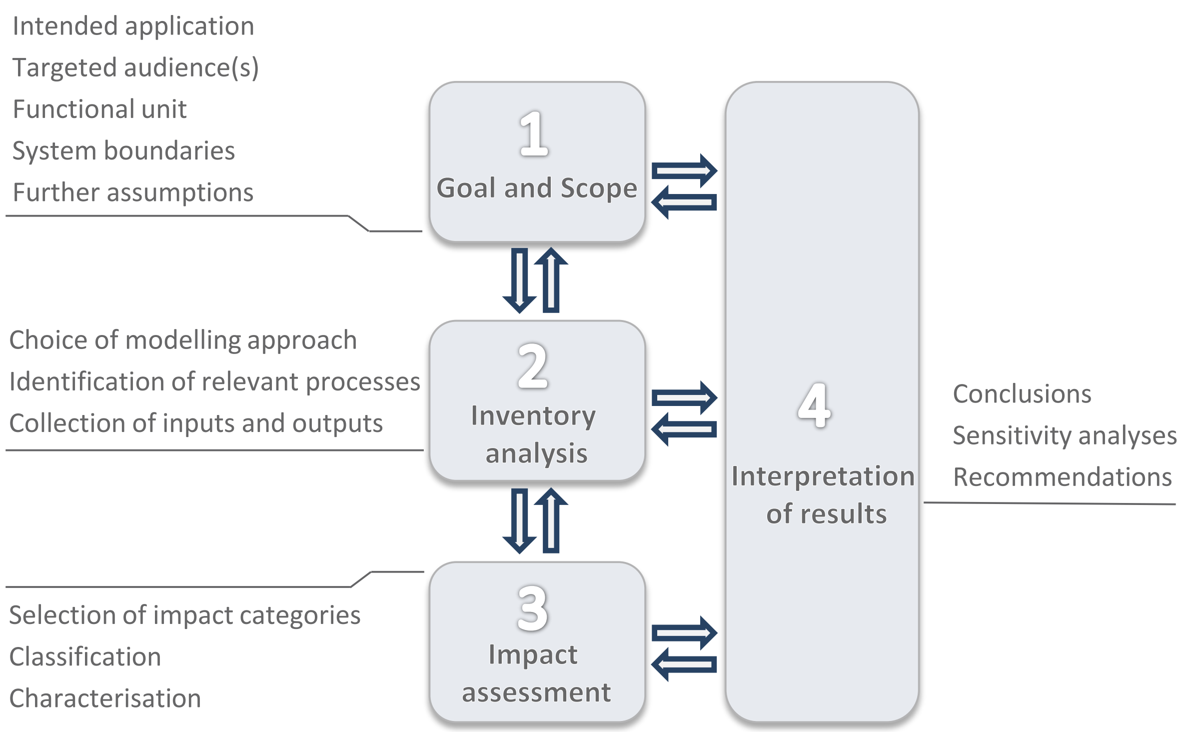

Figure 4. Framework for Life Cycle Assessments (illustration adapted from Frischknecht, 2020)

In the first phase, the goal and scope of the study are specified. The goal definition should precisely state the intended application(s) of the LCA results (ILCD, 2010). The scope of the study is defined by the system boundaries and the functional unit, which describes the quantifiable function(s) provided by the analyzed system (Frischknecht, 2020). The functional unit, therefore, is the reference figure for which the impacts are calculated.

In the second phase, data for all processes related to the analyzed system is collected in a life cycle inventory (LCI). The life cycle inventory comprises all inputs (resources, intermediates) and outputs (waste, emissions) of the analyzed system that arise during all life cycle stages included in the system boundaries and connects these to form a product system that can fulfill one or more quantifiable function(s) (Frischknecht, 2020). The way processes are identified within system boundaries differs considerably between the consequential and the attributional modeling approach[1] (ILCD, 2010). In the case of multifunctional product systems, the compiled inputs and emissions need to be attributed to the systems function(s) based on allocation rules[2]. Thereby, all relevant flows for the provision of the functional unit are identified.

In the third phase, impacts of the compiled life cycle inventory are assessed. First, impact categories need to be selected to suit the goal definition of the LCA. Then, inventory results are grouped according to their effect(s) on the environment (classification) and multiplied with the relevant impact factors to calculate their contribution to a midpoint (characterization) (see Figure 5). The impact category Climate Change is expressed in kg CO_2-equivalents. Therefore CO_2 is the reference substance for this impact category. All substances contributing to Climate Change are weighted according to their impact on Climate Change in comparison to CO_2. This defines the characterization factor (Frischknecht, 2020). For the classification and characterization of the inventory results, life cycle impact assessment methods are provided by experts. These methods exist on midpoint and endpoint level. Midpoints are the first outcome of a life cycle impact assessment and constitute impacts, which are calculated based on scientifically established cause-effect chains. Endpoints are the second outcome of a life cycle impact assessment and result from a further aggregation of the midpoints. They constitute damages to areas of protection (commonly human health, natural environment, and natural resources) (ILCD, 2010). In the contributions of this thesis, the life cycle impact assessment method ReCiPe 2016 is applied. ReciPe 2016 provides results for 18 midpoints and three endpoints (Huijbregts et al., 2016).

[1] In attributional modeling, all activities that can be related to the analyzed system are attributed to it, while in consequential modeling all activities that are expected to be a consequence of a decision related to the analyzed system are included (ILCD, 2010).
[2] Allocation should be based on the physical relations between different by-products of a product system (e.g. mass), if this is not applicable other relations between the products should be taken into account (e.g. economic value) (Frischknecht, 2020).

As an LCA study follows an iterative process, the preceding steps can be repeated multiple times until the model is finalized. Finally, the results are interpreted in relation to the objectives of the study. This is done to derive robust conclusions and recommendations (Frischknecht, 2020; ILCD, 2010).

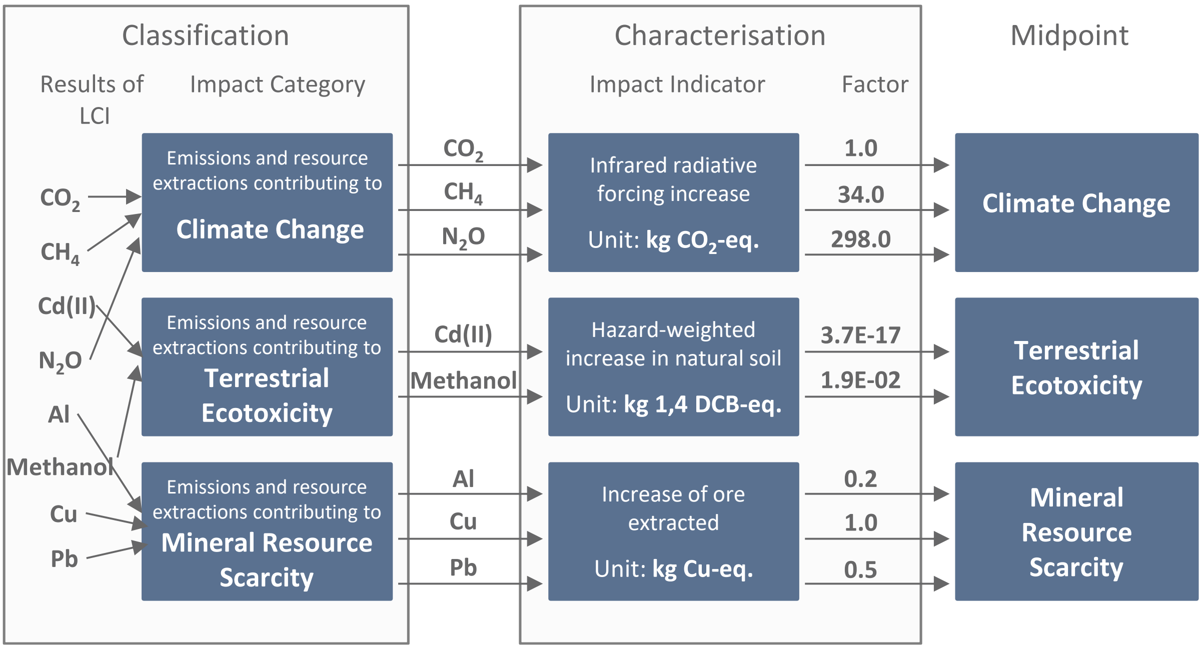

Figure 5. The process of classification and characterization in life cycle impact assessment (own representation based on Hutner, 2017 and Huijbregts et al., 2016). Note: characterization factors are based on the ReCiPe 2016 hierarchist method; for terrestrial ecotoxicity the characterization factors for the emission compartment agricultural soil are depicted

Material Flow Analysis

Material flow analysis (MFA) is a tool to analyze the transformation, transportation, or storage of materials within a system defined in space and time (Brunner & Rechberger, 2004). It is based on accounts in physical units of materials (goods or substances). It can be applied to evaluate systems of different scales (e.g., the whole economy or parts of it, regions, industrial plants, or households). The creation of an MFA consists of the stages of goal setting, system definition, balancing, evaluation and interpretation, conclusion, and presentation (Baccini & Brunner, 2012). An MFA system is typically represented as a process flow diagram. It always consists of the system boundary, one or more processes, and material flows between processes. Some of these processes can also have stocks of materials (see Figure 6). A physical exchange between the system and its environment happens via flows that cross the system boundary.

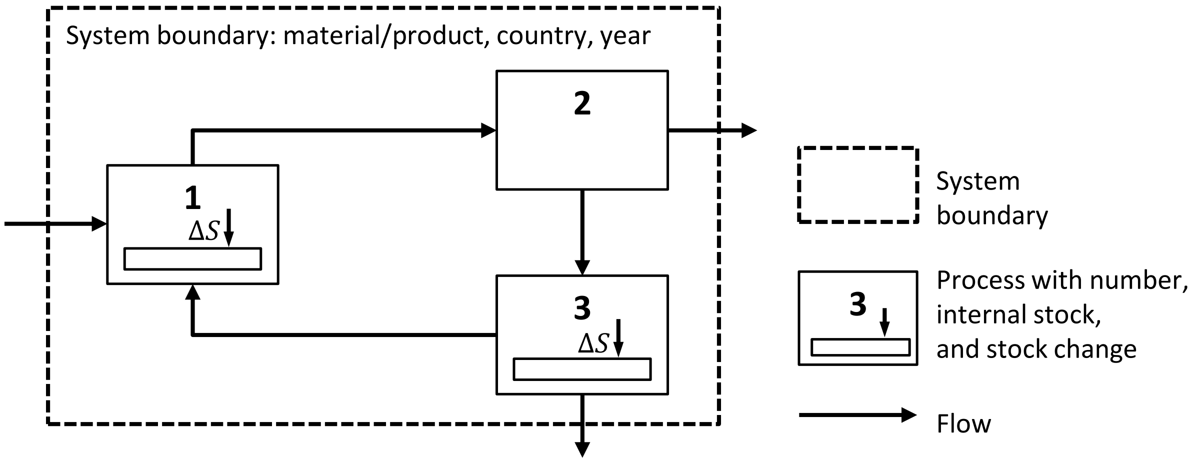

Figure 6. Generic MFA system

The principle behind all MFA approaches is mass conservation: All inflows into a system over a certain period equal all outflows over the same period plus the stock changes (Allesch & Brunner, 2015). Stock changes $\Delta S(t)$ are therefore calculated as the difference between inflows $I(t)$ and outflows $O(t)$:

$$\Delta S(t) = \big(I(t) - O(t)\big) \cdot dt \qquad (1)$$

MFA models can either be static (to analyze flows at a certain point in time) or dynamic (to analyze the changes of stocks and flows over a time interval) (Chen & Graedel, 2012). Dynamic MFA uses historic development patterns of physical stocks and flows to create scenarios for the future. The main difference between both models lies in the inclusion of stocks in society (Elshkaki et al., 2005). Dynamic MFA models are commonly described as dynamic stock models and explicitly consider in-use stocks' role in past, present, and future material use (Pauliuk et al., 2017). For quantifying in-use stocks, two methods exist: the flow-driven approach and the stock-driven approach (Müller et al., 2014). In the flow-driven approach, in-use stocks are calculated based on historic consumption (inflows). In contrast, in the stock-driven approach, the in-use stocks are predefined, and inflows are calculated based on the need to compensate the outflows and balance the stock change (Helbig, 2018). Dynamic stock modeling is frequently applied to study metal cycles (Müller et al., 2014), but is also present in WEEE management (De Meester et al., 2019; Lau et al., 2013; Miller et al., 2016; Parajuly et al., 2017). MFA is therefore suited to monitor the stocks and flows of electronic products, including their End-of-Life pathways within an economy.

An important concept within dynamic stock modeling are age-cohorts, which describe the fraction of an in-use stock that enters this stock at a certain point. An in-use stock is therefore always composed of different age-cohorts. Each age-cohort is assigned an expected lifetime or a lifetime distribution that determines when the cohort leaves the current stock. Future waste streams result from past production, and the relationship between inflows and outflows is defined by lifetime distribution functions (Elshkaki et al., 2005; Van der Voet et al., 2002). The dynamic stock model introduced in contribution C3 is stock-driven. The model is solved recursively, starting in the first model year. First, the outflow of the current stock is calculated based on the given service-life curve, either defined by a probability density function $pdf(t,t')$ of the life curve over the usage time $(t - t')$, or as its integral, the distribution function $\Phi(t,t')$. The outflow $O(t,t')$ of a cohort that is produced in period t' can be described as:

$$\mathrm{O}(t,t') = \mathrm{I}(t') \cdot pdf(t - t'), \text{ with } \int_{t'}^{\infty} O(t,t')\,dt = I(t') \qquad (2)$$

Where $I(t')$ is the inflow of the cohort in period t'.

The entire outflow $O(t)$ that leaves the stock in period t is described as:

$$\mathrm{O}(t) = (I * pdf)(t) = \int_{t_0}^{t} I(t') \cdot pdf(t - t')\, dt' \qquad (3)$$

Assigning a lifetime distribution function to an inflow corresponds to the mathematical operation of calculating the convolution (see equation 3, with “*” denoting the convolution). This approach is also called the population balance model. Equation 4 represents the numerical integration since it is rarely possible to solve this convolution analytically (Müller et al., 2014), and in practice, mostly discrete data points are given.

$$O(t) = \sum_{\tau = t_0}^{\mathrm{t}} I(\tau) \cdot pdf(\mathrm{t} - \tau) \qquad (4)$$

Subsequently, the stock change $\Delta S(t)$ between the actual stock $S_{set}(t)$ and the remaining stock $S(t)$ is determined by subtracting the remaining stock in period t from the stock that needs to be met in this period as follows:

$$\Delta S(t) = S_{set}(t) - S(t) = S_{set}(t) - \int_{t_0}^{t} (I(\tau) - O(\tau))\, d\tau \qquad (5)$$

The inflow $I(t)$ then results from the difference between the stock that needs to be met and the remaining stock from the previous year:

$$I(t) = \Delta S(t) \qquad (6)$$

1.4 The research project at a glance

This section gives an overview of the contributions compiled in this doctoral thesis. Each contribution is briefly described and positioned within the research project. In addition, a short summary of each contribution and the answered research questions is provided.

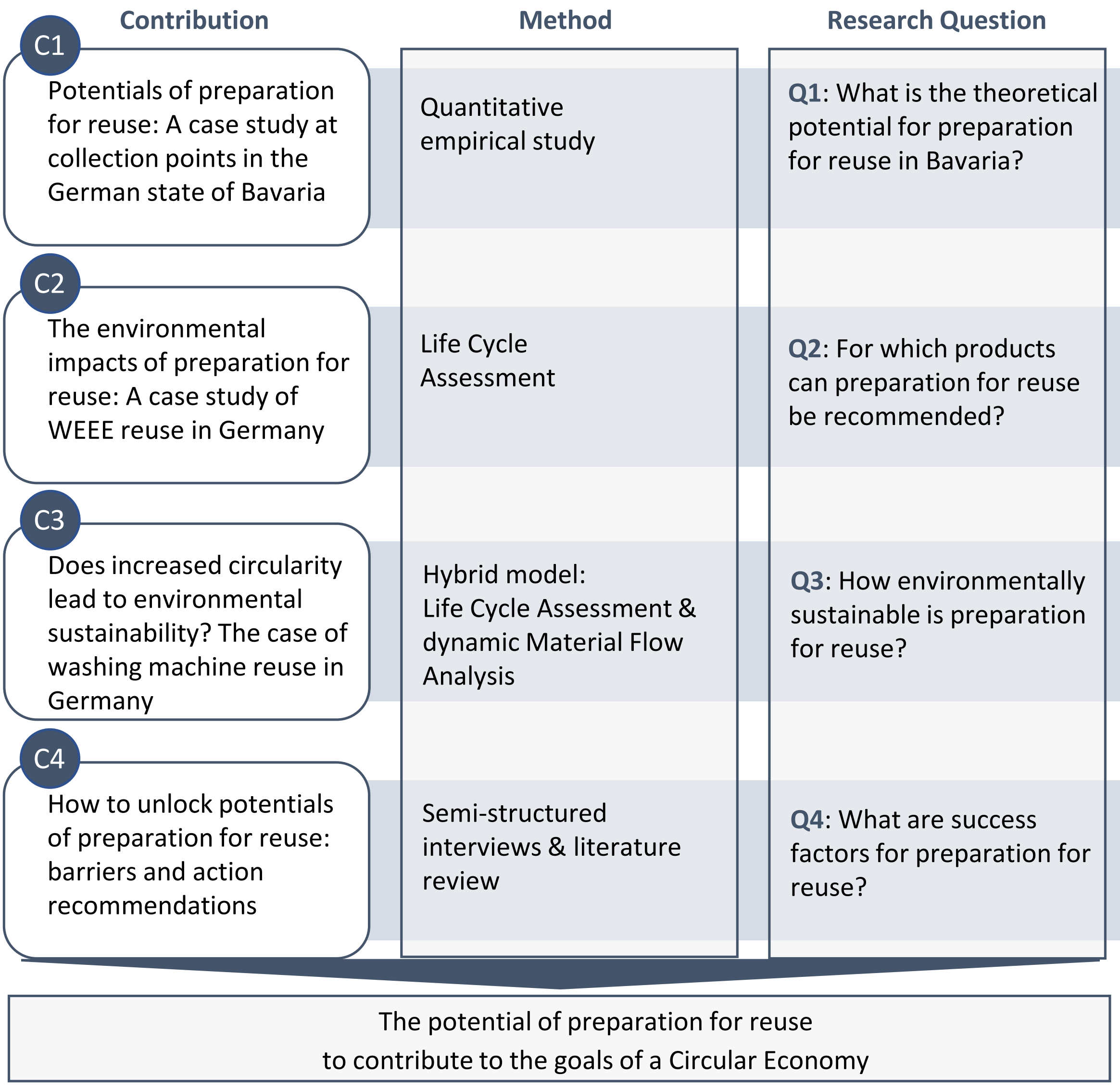

Figure 7. Research concept

Figure 7 illustrates the research concept and assigns the addressed research questions (Q1-Q4) to each contribution (C1-C4). The quantitative empirical study conducted in C1 builds the basis for further research and provides data on potential amounts viable for PfR in Bavaria. The second contribution focuses on WEEE and, based on LCAs, determines for which products reuse leads to environmental benefits compared to recycling. In the third contribution, the method of LCA is combined with a dynamic MFA to assess the overall environmental impacts if a certain reuse quota is implemented in Germany, for the example of washing machines. In the last contribution, the market attractiveness for PfR operators is evaluated based on semi-structured interviews, and a literature review is conducted to derive action recommendations that address the barriers to reuse. Overall, this research aims to provide a comprehensive assessment of the waste management option PfR towards its capability of contributing to the goals of a Circular Economy.

First, a lack of quantitative assessments of potentially reusable wastes is observed. Several organizations such as ComputerAid, RREUSE, ACR+, and the European Environmental Bureau support a PfR target of 5% as suggested by the European Parliament (Esenduran et al., 2016). In 2017, the European Commission re-investigated the possibility to set separate PfR targets for WEEE. However, they concluded that this is unfeasible at the current stage due to insufficient knowledge about quantities of WEEE that could be prepared for reuse in the EU and requirements for reverse logistics (European Commission, 2017). To provide aid for the formulation of a PfR quota by politics and support the selection of effective actions to increase the processed amounts of waste, Messmann et al. (C1) assess potentials for reuse and compile respective data for the German state of Bavaria. Based on the quality of the goods and the causes of damages, the theoretical potential for PfR is quantified for the waste streams WEEE, used furniture, and used leisure goods. Subsequently, action recommendations that yield the highest potential for avoiding damage to goods and therefore increasing the reuse potential are delineated.

Second, the assumption that reuse always results in lower impacts needs to be assessed in detail for energy-using products. To fill this research gap, Boldoczki et al. (C2) conduct comparative LCAs for four white goods (washing machine, refrigerator, range, freezer) and four small electric devices (PC, printer, monitor, laptop). These eight devices account for 68% of all collected WEEE in Germany by weight. The research results, therefore, allow for generalizable recommendations. In a first step, the impacts of average reused products are compared to average new products in order to assess the saving potentials of reuse. Since the findings show that the reuse of white goods cannot be recommended unconditionally, further assessments are conducted in a second step. Based on the energy efficiency of the products and the expected usage durations, product-specific recommendations for reuse are delineated. Therefore, the results support environmentally-conscious consumer decisions about acquiring a new versus a second-hand product and enable End-of-Life decision-making in terms of the separation of reusable devices at collection points.

Third, Boldoczki et al. (C3) present a hybrid dynamic stock model to assess the environmental impacts of the implementation of a reuse quota. As described in section 1.1, PfR is considered as one CE strategy within the technical metabolism that maximizes resource efficiency and is supposed to have a positive impact on environmental, human health, and social spheres. Kondo & Nakamura (2004) imply losses in employment induced by the lifetime extension of products. In contrast, the majority of other studies show positive economic and social implications of reuse (job creation, accessibility of cheap products) (González et al., 2017; O'Connell et al., 2012; Pini et al., 2019). However, the environmental preferability of reuse compared to lower-ranked waste management options has not been studied on a large scale so far. Helander et al. (2019) assess current approaches for the evaluation of CE activities towards their capability of capturing environmental sustainability. They find that none of the indicators holistically evaluate net environmental pressure and suggest complementing present CE management indicators with environmental indicators related to the respective CE activity. Boldoczki et al. (C3) address this research gap and evaluate the environmental sustainability of PfR in a case study on washing machine reuse in Germany. A dynamic stock model is introduced to quantify future product stocks and flows in dependency on reuse targets. In a second step, LCA data from contribution C2 is included to assess the environmental implications of increased reuse. The combination of a dynamic MFA and LCA shows how the composition of stocks and flows (with respect to the products energy efficiency) change in the future if different reuse targets are applied and which environmental implications result due to the changing stocks and flows. The hybrid approach thereby delivers detailed information on the implications of policy decisions in multiple impact categories.

Boldoczki (C4) rounds off the research project by identifying success factors for PfR. Many case studies exist that show barriers to PfR and derive possible solutions, but no comprehensive review of action recommendations has been compiled so far. In this contribution, first, relevant actors along the supply chain are identified, and the market attractiveness for PfR operators is assessed based on the concept of the reverse five market forces (Stindt et al., 2016). Subsequently, a structured literature review yields 26 action recommendations. Each measure is assigned to relevant actors as well as the effect towards improving market attractiveness for PfR.

2

Contributions

2.1. Contribution C1: Potentials of preparation for reuse: A case study at collection points in the German state of Bavaria

Title: Potentials of preparation for reuse: A case study at collection points in the German state of Bavaria

Authors: Messmann, L., Boldoczki, S., Thorenz, A., and Tuma, A. (University of Augsburg)

Published in: Journal of Cleaner Production 211 (2019) 1534-1546

Abstract: This research addresses the second priority of the waste management hierarchy and the demand for a circular economy. First, we develop a methodology for the quantitative assessment of potentially reusable wastes. Second, based on empirically retrieved primary data following the developed methodology, this study quantifies a theoretical potential for the preparation for reuse of Waste Electric and Electronic Equipment (WEEE), used furniture, and used leisure goods in the German state of Bavaria. We find that between 13% and 16% of these waste streams could immediately be prepared for reuse, depending on the type of waste. A further potential of 13% and 29% could be unlocked through changes to the mode of collection, storage and the overall treatment of wastes at Bavaria collection points. Most notably, 86% of identifiable damage causes of WEEE are attributed to a lack of sufficient weatherproof roofing. Conclusively, we derive four key action recommendations for unlocking existing potentials.

Keywords: Circular Economy, preparation for reuse, reuse potential, transfer station, waste management

DOI: 10.1016/j.jclepro.2018.11.264

2.2. Contribution C2: The environmental impacts of preparation for reuse: A case study of WEEE reuse in Germany

Title: The environmental impacts of preparation for reuse: A case study of WEEE reuse in Germany

Authors: Boldoczki, S., Thorenz, A., and Tuma, A. (University of Augsburg)

Published in: Journal of Cleaner Production 252 (2020) 119736

Abstract: According to the European waste management hierarchy, preparation for reuse (PfR) is preferable to recycling. From an environmental point of view, reuse is beneficial, if the impacts that arise during a certain usage duration of a reused product are smaller than those of a new product. If this is not the case, reuse is not beneficial to recycling. This study explores potential benefits of PfR compared to other waste management options for four white goods (washing machine, refrigerator, range, freezer) and four small electric devices (PC, printer, monitor, laptop) by the use of Life Cycle Assessment. These eight devices account for 68% by weight of all the collected waste electrical and electronic equipment (WEEE) in Germany. The results show that the assumption that reuse is preferable to recycling does not apply to every case. Especially the impact categories of global warming, water consumption and cumulative energy demand are strongly dominated by the use phase of white goods, therefore a reuse of inefficient devices should be avoided. The results show that a reuse of products with an European energy efficiency rating of D and C is not recommended for any of the analyzed products. For small electric devices, the use phase is less dominant in comparison to the production, therefore reuse leads to significant saving potentials in almost all impact categories. A comparison of energy efficiency classes allows for product-specific decisions, whereas the assessment approach based on average devices yields for generalizable recommendations. Therefore, the results support environmentally conscious consumer decisions about the acquisition of a new versus a second-hand product and enable End-of-Life decision making in terms of the separation of reusable devices at collection points.

Keywords: environmental saving potential, Life Cycle Assessment, preparation for reuse, WEEE, waste management

DOI: 10.1016/j.jclepro.2019.119736

2.3. Contribution C3: Does increased circularity lead to environmental sustainability? The case of washing machine reuse in Germany

Title: Does increased circularity lead to environmental sustainability? The case of washing machine reuse in Germany

Authors: Boldoczki, S., Thorenz, A., and Tuma, A. (University of Augsburg)

Published in: Journal of Industrial Ecology (2021) 1–13

Abstract: This study investigates under which circumstances increases in circularity through the reuse of use-phase-intensive electrical and electronic equipment lead to environmental benefits. We combine dynamic Material Flow Analysis (dMFA) and Life Cycle Assessment (LCA) to assess a Circular Economy strategy towards its environmental sustainability on midpoint and endpoint level. The hybrid approach measures long-term implications of policy decisions in multiple impact categories and shows the need to comprehensively evaluate Circular Economy activities. We apply the approach to the strategy of setting reuse targets in a case study on washing machines in Germany. As a consequence of a reuse target, the product portfolio changes over time. The resulting stocks and flows are calculated in a dMFA, and attributed with the respective LCA-based environmental impacts. We present cumulated impacts between 2015 and 2050 for scenarios with different reuse targets for 18 midpoints and three endpoints of the impact assessment method ReCiPe 2016, and the cumulative energy demand. The latest proposal of a 5% reuse target results in average impact reductions of 1% compared to "business as usual". An increase of reuse up to 87% results in an average impact reduction of 9%, ranging from an increase of 1% (*water consumption*) to a decrease up to 26% (*land use*). This shows that even high reuse rates only have a limited leverage on reducing environmental impacts and that it is therefore necessary to include detailed environmental assessments in a holistic evaluation of Circular Economy activities. This article met the requirements for a gold-gold JIE data openness badge described at http://jie.click/badges.

Keywords: environmental policy, dynamic material flow analysis (dMFA), Life Cycle Assessment (LCA), industrial ecology, reuse, WEEE management

DOI: 10.1111/jiec.13104

2.4. Contribution C4: How to unlock potentials of preparation for reuse: barriers and action recommendations

Title: How to unlock potentials of preparation for reuse: barriers and action recommendations

Authors: Boldoczki, S. (University of Augsburg)

Submitted to: Die Unternehmung

Abstract: This paper reports on success factors and action recommendations for preparation for reuse (PfR) of Waste Electrical and Electronic Equipment (WEEE). Relevant actors along the value chain of PfR are identified. Based on semi-structured interviews, the market attractiveness for PfR operators is evaluated from a German perspective. The results show deficits in access to viable products, barriers to market entry and remarketing of reused goods, intense competition for reused goods, and impeding interdependencies with the primary market. Second, a literature review is conducted to derive action recommendations that address the barriers to reuse. The action recommendations are distinguished by the type of instrument into the categories information (six measures), legal framework (eight measures), organizational structure (seven measures), and process change (five measures). Each measure is assigned to the relevant actors and the effect towards improving the market attractiveness for PfR. Based on the number of references in literature, the main success factors for PfR are derived. Those are value-conserving logistics, public relations work, the introduction of an umbrella brand, and cooperation between collection points and repair or sales platforms. This structured overview serves as a guide for decision-makers as to which recommendations for action should be given priority and implemented.

Keywords: barriers preparation for reuse, success factors, action recommendations, reuse of electrical and electronic equipment, WEEE

1. Introduction

Preparation for reuse (PfR) constitutes the second priority of the European waste hierarchy, followed by recycling, other recovery, and disposal. It yields social, environmental, and economic benefits (Boldoczki et al., 2020; González et al., 2017; O'Connell et al., 2012; Pini et al., 2019). PfR is preferable to recycling because the value is conserved, and therefore resource efficiency is maximized (Kalmykova et al., 2018). This is especially relevant for products with resource-intensive upstream processing, such as Waste Electrical and Electronic Equipment (WEEE) (Braungart et al., 2007). In the EU, 8.4 kg of WEEE per inhabitant is collected annually (Eurostat, 2020a). Of the collected WEEE, 97.8% are recycled. However, a case study from Belgium shows that only 32% of the materials are recycled towards high-end applications whereas 68% is lost in low-end applications, landfill or incineration (De Meester et al., 2019; Eurostat, 2020b). This shows that for recycling of WEEE not only highly energy intensive recycling processes are required, but also a considerable share of primary resources is not recoverable. Therefore, it is of high interest to increase the share of PfR for this specific waste stream.

Various management practices for WEEE can be observed within Europe (Ongondo et al., 2011). The success of PfR varies greatly, even among countries with an identical legal basis concerning reuse operations (Johnson et al., 2015). In Europe, the Directive on Waste Electrical and Electronic Equipment (Directive 2012/19/EU) regulates WEEE collection. It establishes the concept of extended producer responsibility (ERP) for WEEE. ERP puts the responsibility for the financing of collection, recycling, and end-of-life disposal on producers. However, incentives initiated by ERP mainly focus on material recycling and are rarely involved in PfR operations (Kunz et al., 2018; Zacho et al., 2018). In Germany, the Law on Closed Cycle Management and Waste (Kreislaufwirtschaftsgesetz, KrWG) enforces the waste management hierarchy on a national level. The handling of WEEE is additionally regulated by the Electrical and Electronic Equipment Act (ElektroG). The act governs sales, return, and environmentally sound disposal of WEEE and implements ERP. Consumers are obliged to collect WEEE separately from household waste. They can discard WEEE at municipal collection points, public depot containers or via pick-up systems operated by municipal disposal services. They can also return WEEE to the distributors upon sale of a new piece of equipment or via take-back systems offered by producers or resellers of electrical and electronic equipment. A representative survey, conducted by the German Environment Agency (Umweltbundesamt, UBA), identifies municipal collection points as the main disposal route, with a share of 37% of the respondents using this return option (Schmiedel et al., 2018). A recent case study on the potentials of PfR states that 113.114 t of WEEE arise annually at Bavarian collection points alone, of which up to 87% are theoretically viable for reuse (Messmann et al., 2019). The preeminence of collection points compared to other disposal routes is also observed in Denmark (Parajuly and Wenzel, 2017) and England (Curran et al., 2007; WRAP, 2011). Charitable institutions handle the major part of municipally collected waste processed for PfR but the overall amount of goods undergoing recovery operations for remarketing is minimal (Sander et al., 2013; Schomerus et al., 2014). Johnson et al. (2015) and Queiruga and Queiruga-Dios (2015) identify a strong need for a distinct reuse quota. While already 93% of collected WEEE is recycled in Germany, the share of WEEE being prepared for reuse is below 2%, despite its higher priority within the waste hierarchy (Eurostat, 2020b). In 2017 the European commission re-investigated the possible setting of separate targets for WEEE to be prepared for reuse but concluded that it is unfeasible at the current stage due to insufficient knowledge about quantities of WEEE that could be prepared for reuse in the EU and requirements for reverse logistics (European Commission, 2017). In literature, several approaches exist to fill the lack of data about potentials for PfR (Bovea et al., 2016; Curran et al., 2007; Messmann et al., 2019; Parajuly and Wenzel, 2017; WRAP, 2012). All studies agree that a considerable reuse potential exists, and therefore, the implementation of a binding PfR target for WEEE can be expected in the future. Spain took a pioneering role among Europe as the first country to implemented a binding PfR target for large EEE (3%) and small IT and telecommunication equipment (4%) (Ministerio de Agricultura alimentaciòn y medio Ambiente, 2015). Several organizations such as ComputerAid, RREUSE, ACR+, and the European Environmental Bureau support a PfR target of 5% as suggested by the European Parliament (Esenduran et al., 2016). With the current share of PfR of WEEE of less than 2% it is necessary to take action and follow an effective strategy to promote PfR.

In literature, it is agreed that actions need to be taken to increase the share of PfR, but a structured review of action recommendations and best practice examples is missing. As part of a research project by the Bavarian State Ministry of the Environment and Consumer

Protection, this study sets out to consolidate findings of previous studies on success factors and barriers of PfR. The aim is first to assess barriers to the implementation of PfR and then derive action recommendations that address these barriers. In the following semi-structured interviews and a structured literature review are conducted in order to answer the following research questions:

- What are success factors for PfR in Germany and Europe?

  RQ1. What are the barriers to preparation for reuse in Germany?

  RQ2. What action recommendations can be identified in literature and how can they be classified and prioritized?

A complete process of PfR contains the components identification, recovery, and re-provision on the market (Sander et al., 2019). Before a good can be re-provided on the market, it is required to undergo recovery operations. These operations comprise examination, cleaning, and repairing (KrWG §3). Barriers that currently hinder preparation for reuse and restrict access to sufficient volumes of reusable goods are legal hurdles (CIWM, 2016; Cole et al., 2019; European Commission, 2015; González, 2013; Johnson et al., 2015; Kissling et al., 2013; Löhle et al., 2016; Ongondo et al., 2011; Sander et al., 2013), a lack of consumer awareness and information (CIWM, 2016; Cole et al., 2019; European Commission, 2015; Löhle et al., 2016; Neitsch et al., 2010; Sander et al., 2013), missing cross-sector engagement and organizational structures (CIWM, 2016; Johnson et al., 2015; Löhle et al., 2016; Neitsch et al., 2010; Sander et al., 2013; Spitzbart et al., 2009) as well as insufficient infrastructure (Broehl-Kerner et al., 2012; European Commission, 2015; Neitsch et al., 2010; Sander et al., 2013).

To structure action recommendations within the (reversed) supply chain, potential actors need to be known. Based on Hostmann et al. (2005) and expert discussions within the project steering board, stakeholders are classified according to their influence and involvement. Figure C4-1 shows the flow of influence and the exchange of information among the different stakeholders. As discussed above, waste management is strictly regulated by European and national legislation (Gollakota et al., 2020). The legislator influences all subjacent levels. Public authorities implement the legal framework on the subsequent level. On the third level, commercial and non-commercial actors can be distinguished. A study of the German Federal Environmental Agency identifies manufacturers and repair facilities as commercial actors of the supply chain municipal disposal and social-charitable institutions as non-commercial ones (Schomerus et al., 2014). Associations, such as the German used Electronic Appliances Register (EAR foundation), function as mediators between all levels.

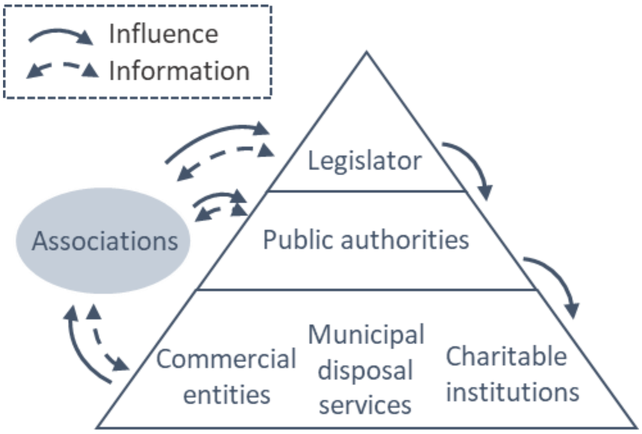

Figure C4-1. Actors of PfR operations classified by influence and involvement. The top-level represents the greatest area of influence, the width represents the level of involvement in PfR processes.

2. Method

The study's structure is illustrated in Figure C4-2. The research approach follows seven subsequent steps in three phases (A-C). The first phase (A) clarifies the research aim and operationalizes the research question into two distinct fields of interest: barriers to PfR and action recommendations to overcome these barriers. Phase B begins with the contextualization of research (step B2, Introduction). The identification of barriers is based on the framework of the reverse five market forces (based on Stindt et al. (2016)) and is assessed by semi-structured interviews. Action recommendations to increase the share of products undergoing PfR are derived from a structured literature review (both step B2). In the third research phase (C), action recommendations are classified according to the previously gained findings concerning the actors and barriers of PfR. Based on each action recommendation's potential to overcome barriers and the relevance in literature, the main success factors for PfR are derived.

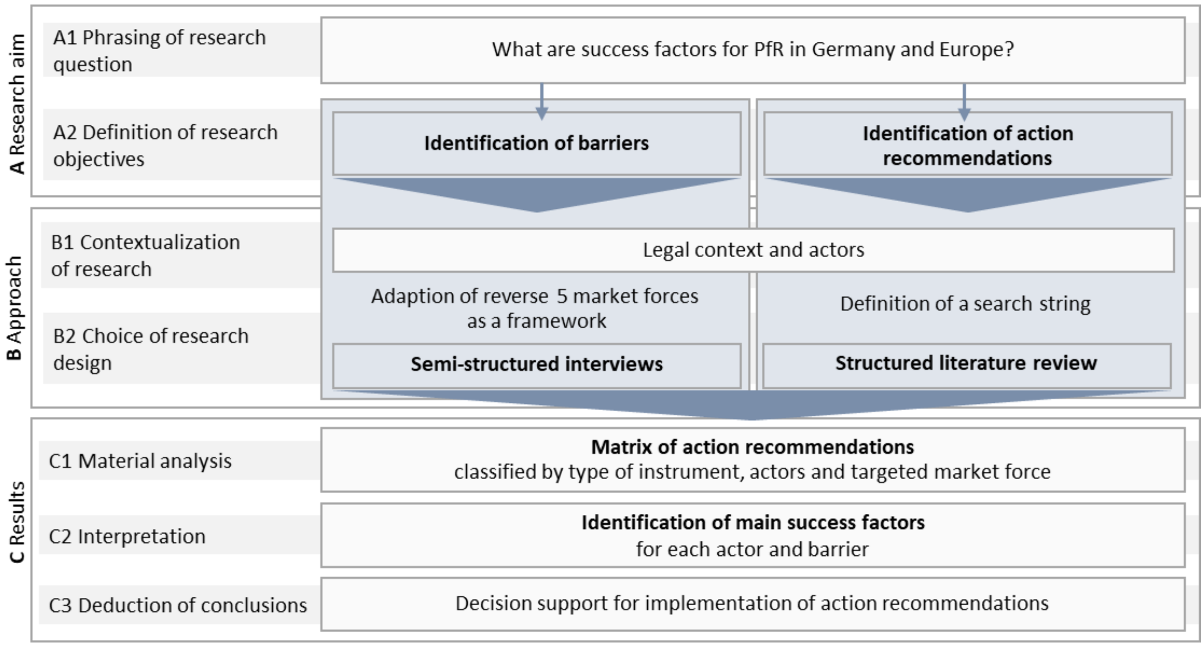

Figure C4-2. Research approach for the identification of success factors for PfR

Identification of barriers

In order to evaluate action recommendations and measures, information on characteristics, mechanisms, and interdependencies of the market must be retrieved. The Reverse Five Forces (R5F) offer a framework for evaluating the attractiveness of take-back markets for goods and groups of goods and various actors in a structured manner (Stindt et al., 2016). The framework of the R5F is based on Porter's Five Forces. Porter's Five Forces is a widely accepted model that identifies and analyzes five competitive forces that shape every industry and helps determine an industry's weaknesses and strengths (Porter, 1979, 2008). The model can be applied to any sector of the economy to understand the level of competition within the industry and improve a company's long-term profitability. Nevertheless, the model cannot be directly applied to markets for recoverable products and has therefore been adapted by Stindt et al. (2016). Stindt´s R5F take the perspective of original equipment manufacturers (OEMs). Since the main actors of PfR operations are non-commercial ones, the R5F are tailored to the case of PfR based on discussions within the project steering board and iterative pre-tests with a subset of interviewees (see Appendix C). Figure C4-3 depicts the R5F with adapted subordinate attributes that determine the power of each force. The three necessary steps for a successful PfR are located within these forces. The identification of goods suitable for PfR is described by attributes within the force access, operations of PfR are included in the market entry, and re-provision of the goods on the market is covered by the remarketing. Competition and interactions with the primary market are forces that allow a more extensive assessment of the take-back market.

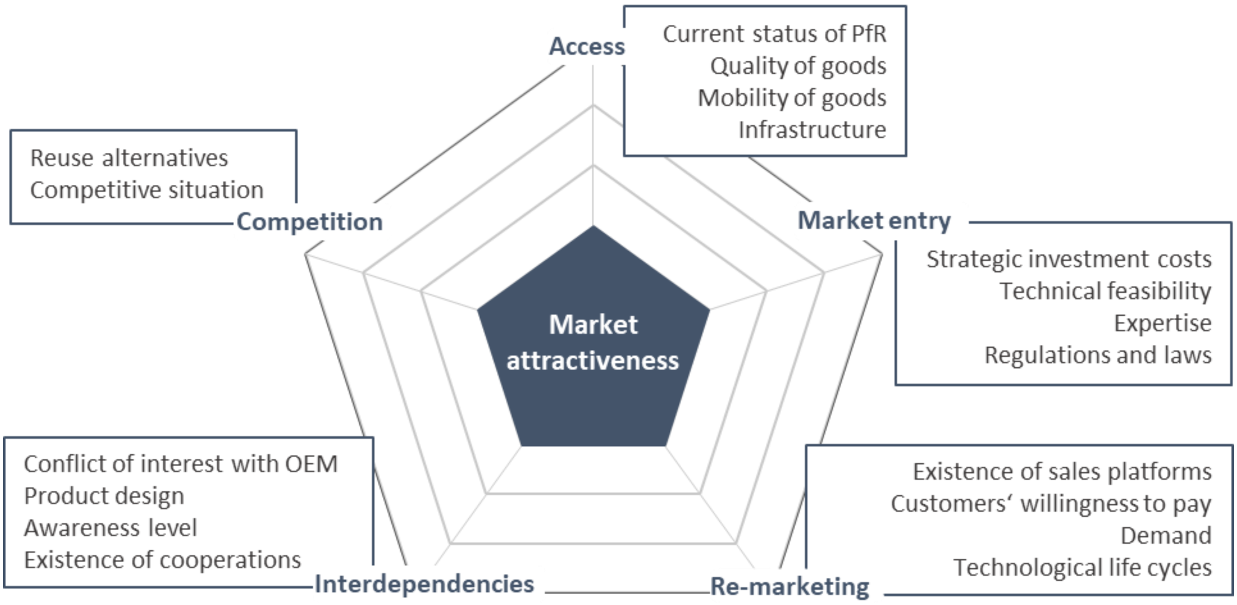

Figure C4-3. The Reverse Five Forces (R5F) of PfR

A set of attributes defines each force. For example, the force of access is assessed by the status quo of PfR, quality of available products, mobility of products, and infrastructure for collection. The scale ranges from 1 (not prevalent) to 5 (optimal condition). In terms of access, this optimal design would provide unrestricted access to reusable goods. The difference to the optimal value (5) represents the potential, which can be exploited by different instruments and actions. The evaluation of the attributes is conducted through semi-structured expert interviews. The interview guide is provided in Appendix B. The experts stem from the areas of waste management, repair networks, remarketing, and science, thus covering the entire spectrum of the R5F. A list of the interviewees and documentation of interview results are provided in Appendix C and D to E, respectively. The individual assessments are equally weighted and aggregated to form the status quo of the PfR market's attractiveness.

Identification of action recommendations

The material collection is carried out in careful database research, for which the online catalog of Google Scholar and Web of Science are selected. A Google search is performed to identify scientific and other types of formal reports that are not published as peer-reviewed journal articles. Literature in English and German language is included, and the Boolean search string is therefore applied in both languages. The search was finished on 20 January 2021 and employed the following search string:

("preparation for (reuse OR re-use)" AND (action OR recommendation OR "success factor" OR "best practice") – for English results

("Vorbereitung zur Wiederverwendung" AND ("Empfehlung" OR „Handlungsempfehlung" OR „Maßnahme" or „best practice") – for German results

In order to be referenced in this study, an article needs to meet the following criteria:

- ❖ The article is written in English or German.
- ❖ The article targets preparation for reuse.
- ❖ The article includes at least one action recommendation.

The final sample comprises a total of **22 articles** that are analyzed in this study with respect to the research questions. Appendix A shows the list of identified publications, according to the scope and type of article. The referenced studies are given an additional number in square brackets (in lexicographic order, see Appendix A) to distinguish them from other references and ease their citation in tables and other lists.

3. Material evaluation

First, the current market situation for PfR of WEEE is presented. Subsequently, action recommendations are derived. Action recommendations target either one or more of the barriers identified by the R5F. For each of the R5F approaches for improvement are presented.

3.1 Market analysis

Experts were asked to assess small and large WEEE individually. The results of the market analyses are shown in Figure C4-4 as a web chart. Each axis represents the assessment of the status quo of the respective market force. In the following findings of the semi-structured interviews are summarized for each market force.

	Status Quo	
Forces	Large	Small
Access	2.18	2.94
Market entry	2.23	1.88
Re-marketing	2.85	2.48
Interdependencies	2.41	2.03
Competition	2.50	2.55

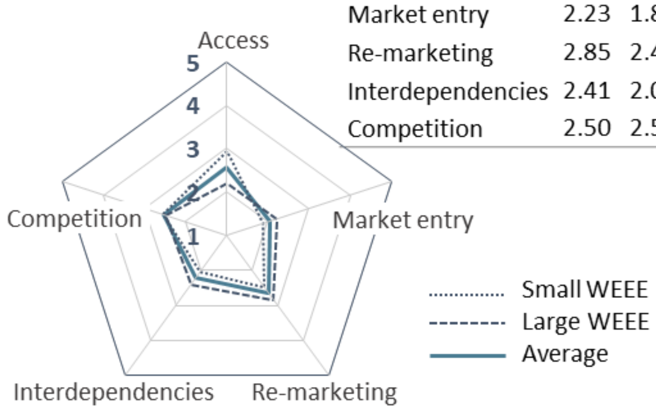

Figure C4-4 Evaluation of market attractiveness for PfR of WEEE

Access to goods is rated with 2.24 (large WEEE) and 3.05 (small WEE) out of 5 points, indicating room for improvement. A recent case study quantifies the amount of accessible products for PfR in the German state of Bavaria. The study states that up to 44% of WEEE arriving at municipal collection points could be prepared for reuse with reasonable effort. Currently, less than 2% of this potential is prepared for reuse. While 14% would directly be suitable for PfR, another 29% can be realized with improvements in the collection mode. More extensive interventions in existing collection systems, market mechanisms, consumption patterns, and legal requirements are needed to enable PfR for an additional 42%. Only 13% is regarded as inapt for PfR (Messmann et al., 2019). Regarding mobility of the goods, a distinction can be made between household appliances, which have limited mobility, and other WEEE. Smaller WEEE can be easily transported, facilitating access to goods but also enabling illegal collection and export. This leads to improper recycling, lower domestic reuse rates, damage to health, and increased environmental impacts abroad (Kissling et al., 2013). The collection of large household appliances is challenging due to their restricted mobility. Easy access to collection points plays a crucial role in this regard. Besides, the collection mode has a significant impact on the quality of the goods, as, for example, improper transport or insertion into containers can lead to damage.

The need for high investment in the expansion of reuse facilities restricts market entry into the secondary market. In addition to trained employees' expertise, reprocessing of WEEE also requires appropriate technical equipment and availability of spare parts. This is even more prevalent for small products (1.88 points) than for large WEEE (2.23 points). Also, especially for large household appliances, the requirements for size and design of storage areas must be met. These factors lead to high strategic costs for PfR. According to German law, the processing of WEEE must be conducted by primary treatment facilities (§ 21 ElektroG). Thus, PfR can only take place at certified recycling centers (LAGA, 2017). If legal conditions are met, repair options also depend on the technical feasibility. Electrical appliances are becoming increasingly complex, and repair options are limited.

Remarketing depends on sales platforms' existence and is evaluated comparatively well, with close to 3 points on average. IT equipment can be sold nationally or internationally, whereas large household appliances are mainly traded regionally due to low mobility. No or poor remarketing opportunities arise for certain small household appliances such as electric toothbrushes or shavers due to hygienic aspects (Broehl-Kerner et al., 2012). Demand for secondary electrical appliances exceeds supply in some places but fluctuates widely (Kissling et al., 2013). A strong correlation between existing demand and well-known manufacturer brands can be observed for major household appliances and consumer electronics. Branded products have a higher perceived product value and thus increase customers' willingness to pay. Short innovation cycles, characteristic of IT and consumer electronics, lead to a time restriction for secondary products' remarketing. After a certain time, compatibility with other devices and software is no longer guaranteed, or technology has progressed so quickly that there is no more demand for a specific product. This psychological obsolescence hinders remarketing in the case of IT devices. These problems are negligible for large household appliances (NABU, 2016). On the other hand, planned obsolescence ensures a constant number of returns for manufacturers but conflicts with waste prevention goals. For the most part, existing markets are already well developed but have further development potential in terms of nationwide distribution networks (Broehl-Kerner et al., 2012). One competitive advantage of secondary markets is the availability of spare parts or old technologies whose technological life cycles have already passed, and they can thus no longer be acquired on the primary market. This niche can be tapped by offering them on secondary markets.

In the course of remarketing WEEE, strong interdependencies with external actors arise, especially for small WEEE (2.03 points). If secondary products partly serve the market, this can lead to a decline in demand for primary products. Successful remarketing of WEEE may result in conflicts of interest with manufacturers (Kissling et al., 2013). One way to counteract this competition is the strategic involvement of manufacturers. They are legally obliged to ensure take-back and proper recycling of their products. In this context, the EAR foundation serves as a joint coordination body for manufacturers (stiftung ear, n.d.). By integrating product take-back into the corporate strategy, the market entry of other players is prevented. In addition to joint coordination points, cooperation between collection points and repair or sales platforms is crucial to the success of PfR and has not been sufficiently developed to date. Cross-linking existing channels and awareness among the population for reuse possibilities still hold significant potential for improvement. Consumers' responsibility lies in the return of old appliances, whereas manufacturers can already start at the product design stage. The Ecodesign Directive already aims for an increased eco-friendly product design. Manufacturers' efforts to "design to repair", which facilitates the reparability and thus reusability of products, have not yet emerged.

From PfR operators' perspective, potential competitors for WEEE are recycling facilities interested in metallic raw materials. In this context, the attractiveness of PfR compared to other forms of treatment is related to the current raw material prices (NABU, 2016). Competition is prevalent but is not evaluated as the most pressing restriction.

3.2 Action recommendations

First, a descriptive analysis shows that 18 out of 22 identified studies are published as reports, three as journal articles, and one as a conference proceeding. The majority of the studies are written in German and set the regional focus to Germany or Austria. This leads to the conclusion that PfR is a topic that is mostly discussed on a national or regional level. Action recommendations for PfR have not yet been the focus of a scientific discourse but are rather investigated by administrative bodies or associations such as federal environmental agencies or nature conservation authorities. A total of 26 action recommendations are derived from the articles. The action recommendations can be distinguished by the type of instrument, and each belongs to one of the four following categories:

- Information
- Legal framework
- Organizational structure
- Process change

Table C4-1 shows an overview of all identified measures, clustered according to the type of instrument, targeted market forces, and actors. Six measures belong to the category of information and aim to raise awareness among the population and eliminate barriers to PfR that exist due to information deficits. Additionally, the willingness of stakeholders to actively participate in PfR is targeted. The provision of information alone is not sufficient to overcome all barriers to PfR. However, in addition to more practical measures, it is necessary to bring about behavioral changes (González 2013). A total of eight measures targets the legal framework. The goal of all measures in this category is to set legal conditions that facilitate the implementation of PfR and reduce existing obstacles. Changes to the legal framework are primarily the legislator's responsibility and characterized by a long-term planning horizon. Seven measures concern the organizational structure and have an effect on a supraregional level (comprising several municipalities). Improved organizational structures enhance collaboration between all actors, which allows synergy effects to be exploited. The category of process change comprises five action recommendations which, due to their more regional character, particularly address collection points and municipalities. By implementing these measures, process changes can be brought about in the short term.

Table C4-1. Identified action recommendations by type of instrument, targeted market forces, and actors

		Market Force					Actor					
Instrument	Title	Access	Market entry	Remarketing	Inter-dependencies	Competition	Legislator	Public authorities	(non-)-commercial	Associations	# mentions	References
Information	Public relations work	x		x			x	x	x	x	14	[2],[3],[4],[6],[7],[9],[11],[12],[13],[15],[16],[18],[19],[22]
	Employee qualification	x	x						x	x	12	[1],[2],[3],[7],[9],[11],[13],[15],[16],[18],[19],[22]
	Advertisement			x					x	x	11	[2],[4],[5],[8],[9],[11],[15],[16],[17],[19],[22]
	Liability and warranty		x				x	x			9	[2],[3],[9],[14],[15],[16],[19],[21],[22]
	Information sharing	x	x	x	x	x			x	x	4	[2],[15],[19],[22]
	PfR Ranking	x	x	x	x	x		x		x	1	[15]
Legal framework	Design to repair				x		x				8	[4],[6],[7],[9],[13],[16],[15],[22]
	Repair manual		x				x				7	[1],[9],[15],[16],[17],[18],[22]
	Incentive system	x	x	x	x	x	x	x			5	[2],[6],[9],[15],[22]
	Illegal collection	x					x	x			5	[6],[7],[8],[15],[16]
	Deposit system	x					x				4	[4],[8],[9],[21]
	PTF certification		x				x				4	[9],[14],[20],[21]
	VAT reduction			x			x				1	[9]
	Public procurement			x			x	x			1	[9]
Organizational structure	Umbrella brand			x					x	x	14	[1],[2],[3],[5],[7],[9],[11],[14],[15],[16],[17],[19],[21],[22]
	Cooperation				x				x		14	[2],[3],[5],[7],[9],[11],[12],[14],[15],[18],[19],[20],[22]
	Alternative sales structures			x					x	x	7	[5],[9],[12],[13],[15],[19],[22]
	Project support		x	x			x	x			6	[3],[4],[14],[15],[19],[22]
	intra-municipal second-hand store			x					x		4	[9],[15],[19],[22]
	Mobile testing unit		x					x	x	x	2	[2],[21]
	Upcycling			x					x		1	[4]
Process change	Value-conserving logistics	x							x		16	[1],[2],[3],[5],[6],[7],[8],[9],[12],[13],[15],[16],[18],[19],[21],[22]
	Separate collection	x							x		11	[2],[3],[9],[11],[15],[16],[17],[19],[20],[21],[22]
	Transport	x					X	x	x		9	[1],[2],[9],[10],[13],[15],[19],[21],[22]
	Secure data deletion			x					x		8	[3],[6],[7],[8],[9],[16],[21],[22]
	Collection mode	x						x	x		4	[2],[9],[15],[19]

INFORMATION

Within the category “information”, the measure of public relations work is mentioned most frequently. Successful public relations work aims to improve access to high-quality goods as well as remarketing conditions. By raising awareness among the population for the potential reuse of products, more conscious handling of goods can be achieved. This leads to an improved quality of collected goods. Additionally, public relations work helps build up a positive image of second-hand goods and strengthens sales. A first step is to create transparency regarding the processes of PfR (González, 2013). Presentations and campaigns with informative brochures and flyers or contributions by regional media address a more extensive customer base for PfR products and inform about drop-off and sales opportunities for second-hand goods (Broehl-Kerner et al., 2012). Public relations work and the dissemination of information about the positive impacts of PfR on the environment are all actors' responsibilities. Within this category, the second and third most relevant action recommendations by the number of references are employee qualification and advertisement. Qualification of employees forms the basis for the implementation of PfR. On the one hand, trained employees are needed for sorting and identifying reusable goods at municipal collections points (Spitzbart et al., 2009). On the other hand, PfR operations of WEEE require specific knowledge to carry out standard measures such as functional tests or safety checks. These activities can be performed independently by in-house employees after training by a master electrician or with the help of a manual for less complex goods (Broehl-Kerner et al., 2012). Commercial or non-commercial actors or associations can organize these training or workshops. Access to suitable goods for PfR can be expanded through a qualified examination of the disposed of goods (Sander et al. 2013). Also, market entry of PfR operators requires both legal and technical knowledge in the implementation of PfR. Reuse facilities should effect the active promotion of reused products. The goal is to build up a positive image of reused goods and draw attention to environmental impact reduction and resource conservation through reuse (Spitzbart et al., 2009). Reuse facilities can increase their brand awareness by participating in regional events, social media presence, and their own homepage. In addition, targeted marketing campaigns explicitly address different customer groups such as "antique/vintage, green, thrifty" (Sander et al., 2013). Particularly in the case of WEEE, uncertainties concerning liability and warranty issues inhibit this equipment's reintroduction into the market (Sander et al., 2013). Clarification of existing requirements and laws as well as pragmatic approaches facilitate the market entry for practical businesses. For example, a used appliance's warranty can be shortened to one year in the general terms and conditions. Further shortening is not allowed (Broehl-Kerner et al., 2012). Educational and informational measures include standardized procedures for collection, processing, and remarketing, as well as an easily understandable fact sheet on liability and warranty. In terms of implementation, both the legislator and public authorities can initiate changes. Supraregional exchange of information targets stronger networking activities among reuse facilities and associations and further disseminates best practice examples. Improved information exchange has a positive effect on all aspects of PfR, as the actors benefit from the experience already gained by others, and solutions to existing obstacles can be sought jointly (Sander et al., 2013). Exchange of experience can take place both at network meetings and via internet platforms and results in new structures of cooperation (Broehl-Kerner et al., 2012). The recommendation of a PfR ranking among municipal reuse operators is mentioned only once. Supraregional PfR rankings create incentive systems for municipalities and reuse facilities. The design offers a wide range of possibilities and can influence all aspects of the market. Examples include rankings of reuse quotas, best practice examples, or incentives for efficient pick-up or drop-off systems (Neitsch et al., 2010). The initiative to implement and publicize ranking systems origins from public authorities and associations.

LEGAL FRAMEWORK

According to §4 (1) ElektroG, manufacturers are required "[...] to design their electrical and electronic equipment in such a way as to facilitate, in particular, the reuse, dismantling and recovery of waste equipment, its components, and materials […]“. NABU (2016) points out that this is merely a design requirement. §4 (2) ElektroG specifies that manufacturers should not adopt design features or manufacturing processes that prevent reuse. However, these are "weak" legal instruments (NABU, 2016). Thus, there is a need for a stronger binding force concerning product design and reparability, which the legislator must define. The provision of information relevant to the reuse and treatment of WEEE is already required by law under §28 (1) ElektroG. However, stricter implementation of the law is required, so that reuse facilities receive information electronically or in the form of manuals. The responsibility of implementing this requirement lies with manufacturers (NABU, 2016; Neitsch et al., 2010). The aim is to facilitate market entry for reuse facilities and repair companies. Besides those two most commonly mentioned measures, the introduction of an incentive system and the prevention of illegal collection are frequently proposed. An incentive system for the implementation of the waste hierarchy can, for example, be subsidies from municipal administration. In this context, a legal target (e.g., a PfR quota) is necessary to differentiate PfR from recycling (Neitsch et al., 2010). Separate PfR targets combined with monetary or reputational incentives have a positive impact on all aspects of PfR. The legislator and authorities are primarily involved in the implementation of incentive systems. Illegal waste collection restricts access to goods for commercial actors, public utilities, and social-charitable institutions, acting in compliance with the law. The goal is to either prevent illegal actors from collecting through stricter regulation or integrate them into regular waste collection systems (Neitsch et al., 2010). As a best practice example, the EU-funded project "Trans-Waste", completed in 2013, addresses both the risks of improper disposal and the opportunities of cross-border waste management. Further measures concerning the legal framework are the introduction of a deposit system to increase the return rate of used goods and the facilitation of certification procedures for PfR operators. A legally required deposit can be charged on the purchase of certain goods, which is refunded upon "return for the purpose of resource-friendly disposal" (González, 2013). An innovative extension of the deposit system can be achieved through the use of RFID chips. This allows product routes to be tracked and important information on repair or recycling to be stored directly in the chip and retrieved autonomously when the good arrives at a collection point (O'Connell et al. 2013). According to §3 (24) ElektroG, initial treatment includes "the primary treatment of WEEE in which the WEEE is prepared for reuse or freed from pollutants and recyclable materials are separated from WEEE, including preparatory actions related to this; initial treatment also includes the recovery processes R 12 and R 13 according to Annex 2 to the Closed Substance Cycle Waste Management Act”. According to this definition, preparatory operations such as sorting, dismantling and storage can only be conducted by primary treatment facilities (PTF). Thus, every collection point would need a PTF certification. However, in literature there are controversial interpretations of the certification obligation according to ElektroG; these are explained in detail by NABU (2016). On the one hand, strict legal requirements are necessary to enable all actors to operate in a legally secure manner. On the other hand, complicated certification processes should not prevent PfR. This recommendation for action aims to reduce the legal hurdles and increase legal certainty for the players involved and is intended to facilitate market entry into PfR. Implementation is the responsibility of the legislator. The last two recommendations are mentioned once in literature, and both aim to improve remarketing possibilities. The current tax system does not encourage the reuse of goods. After goods are depreciated, they no longer have value for accounting purposes, and repairs become unprofitable (González, 2013). To counteract this type of economic activity, goods from PfR can be promoted through a reduced VAT rate or the possibility of tax depreciation (NABU, 2016). Such subsidies initiated by the legislator increase the demand for secondary goods and thus have a positive effect on remarketing. Also, the consideration of used goods in public procurement increases remarketing opportunities (NABU, 2016). On the one hand, public authorities can give preference to used goods over new goods through their initiatives. On the other hand, they can be obliged by the legislator to cover a predefined proportion of their requirements through secondary goods (Neitsch et al., 2010).

ORGANIZATIONAL STRUCTURE

With 14 mentions each, the introduction of an umbrella brand and increase in cooperation are the most relevant measures within this category. A (supra)regional umbrella brand improves remarketing conditions and forms a basis for implementing further action recommendations. It enables a uniform appearance of reuse facilities, which creates a recognition value that customers associate with quality standards and which they trust. In addition, the umbrella brand provides a basis for advertising measures and thus increases awareness of reuse facilities (Neitsch et al., 2010). The implementation includes uniform processes (from collection to remarketing), transparent cachets, an appealing "corporate design," and a joint marketing strategy of participating reuse facilities (Sander et al., 2013). In addition to reuse facilities, associations can also be involved in establishing the umbrella brand. "Currently, only very few reuse companies are able to map the entire logistics and process chain in their own company; the majority is dependent on cooperation with other companies" (Spitzbart et al., 2009). Cooperation between municipal disposal services and repair and distribution networks leads to a financial alleviation of the actors, as individual companies can specialize. Besides, cooperation makes it possible to balance regional differences in demand, repair capacities and remarketing opportunities. In addition to the positive effects on profitability, cooperation strengthens the PfR segment compared to competing processes and products (Neitsch et al., 2010). More detailed design options of cooperation models are discussed by NABU (2016). Seven to four articles recommend the subsequent measures. The implementation of alternative sales structures and specifically an intra-municipal second-hand store target remarketing opportunities. By expanding sales structures, standard remarketing concepts, such as sales areas directly affiliated with repair stores, are supplemented with alternative models. The success of remarketing depends on accessibility and the level of awareness. Repair stores are usually located outside of pedestrian and shopping areas, depriving them of walk-in customers. Second-hand stores that specialize only in remarketing and do not require space for sorting r repair tend to be more centrally located and thus reach a larger group of customers (Spitzbart et al., 2009). To enable supraregional remarketing, sales via own or external internet platforms are a good option (Spitzbart et al., 2009). In particular, distribution via one's own internet presence becomes more lucrative through a joint presence of several reuse facilities or higher-level associations, as there is strong competition from some large sales platforms (e.g., eBay) (NABU, 2016). Another opportunity is an intra-municipally operated second-hand store. This can be considered as a preliminary stage or supplement to an umbrella brand in the sense of an operationally active network of reuse facilities (NABU, 2016). Supplied by the collection of several municipalities, it is characterized by a significantly more diverse range of secondary goods and enables balancing services and logistics. Besides, remarketing benefits from supraregional marketing and thus an increased level of awareness. Government subsidies and organizational support from public authorities and legislators offer the opportunity to bridge the often difficult start-up phase of PfR operators (Neitsch et al., 2010). Both one-time grants and ongoing grants in the areas of "research & development, operational and network development, education and training, quality assurance, support of the running operation of networks and reuse operators in the start-up phase, know-how development and -exchange, and public relations [...]" (Neitsch et al., 2010) are necessary to promote "repair networks, swap circles, flea markets, give-away exchanges [...]" (Neitsch et al., 2010) in addition to start-ups and repair cafés that are already establishing themselves (Sander et al., 2013). Subsidies for these activities can, on the one hand, facilitate market entry of new actors and, on the other hand, strengthen remarketing opportunities. The least frequently mentioned measures in this category are the use of a mobile testing unit and options for upcycling rather than just repairing. An autonomous mobile testing unit "comprises a variable number of up to four or, if necessary, more test stations for testing the safety (DIN VDE 0701) and functionality of entire electrical appliances and replacement components" (Broehl-Kerner et al., 2012). The goal of the testing unit, which can be used intra-municipally, is to facilitate market entry for WEEE reuse facilities and thus increase the reuse rate. Especially in rural regions, the acquisition of infrastructure for the testing and repair of WEEE is not necessarily worthwhile due to lower collection volumes. Costs for a mobile testing facility that is deployed on specific days at the respective municipalities can be borne jointly and, also, a more flexible collection and on-site testing can be realized. Broehl-Kerner et al. (2012) describe the structure, possible applications, and other advantages of the mobile testing unit. Upcycling, e.g., by remanufacturing products, consists of more comprehensive measures than mere repair (Dekker et al. 2004). In some cases, this improves the product properties, resulting in increased performance, higher equipment safety, or an extension of the service life, leading to an increase in the value of the products (LAGA, 2009). Thus, remanufacturing of used goods significantly strengthens the possibilities of remarketing. Implementation can be carried out directly by reuse facilities.

PROCESS CHANGE

A large proportion of damage to goods arises due to handling at collection points. 54% of WEEE are damaged by storage and another 6% by pre-treatment. Protecting WEEE from adverse weather conditions by covering collection areas can prevent up to 86% of damage during storage. Improper storage and pre-treatment represent another critical source of damage. The latter results from compacting goods or cutting cables (Messmann et al., 2019). To address these problems, suitable logistics must be developed to ensure a space-saving, flexible and damage-free process chain (Neitsch et al., 2010). The action recommendation of value-conserving logistics is mentioned most frequently throughout all categories. One starting point is to switch from bulk containers to equipment-specific, value-preserving container systems (such as mesh boxes) that can be combined and stacked in different sizes, as well as changes in filling and unloading techniques (Spitzbart et al., 2009). As already required by the ElektroG, value-conserving logistics is within the reuse facilities' remit and has a high potential to increase quality and thus access to reusable goods. A similarly import process step is the separate collection of reusable goods. The viability of PfR should best be checked directly at the point of handover (Sander et al., 2013) since later separation leads to a strongly reduced quality of the goods (Neitsch et al., 2010). Separation can be performed directly at the point of collection by two vehicles in case of collection systems or by qualified personnel by drop off at collection points in case of bringing systems. Appropriate weather-protected areas are to be provided at collection points for this purpose. The space requirement at collection points can be kept as small as possible through consultation with reuse facilities and regular collection of reusable goods (Sander et al., 2013). According to the ElektroG, WEEE must be collected so that subsequent reuse is not hindered; this includes transport in the course of the collection and further transport to downstream reuse facilities. However, current collection and transport methods do not meet value retention requirements (Broehl-Kerner et al., 2012). By using appropriate collection containers, damage during transport can be avoided. In addition, compressing goods, reloading collection containers, and emptying containers by pouring should be refrained from (NABU, 2016). Especially for ICT devices, secure data deletion poses an important success factor for remarketing. Reuse facilities have so far been exempt from the obligation to delete personal data. Nevertheless, for reasons of both data protection and professionalism, it is recommended that reuse facilities implement procedures that take data protection into account (Löhle et al., 2016). The proven quality of PfR processes through certified data destruction helps to dissolve the negative public perception of the reuse sector and has a positive effect on remarketing (Kissling et al., 2013). The last recommendation within the category of process change is the optimization of the collection mode, which improves access to used goods. The accessibility of collection points represents a central factor for citizens (Sander et al., 2013). The collection system can be improved by integrating additional drop-off options, such as the introduction of collection systems with separate collection of reusable goods or a higher container density, as well as the optimization of existing systems, by extending or adjusting opening hours at collection points. The organization of these improvement measures is to be specified by the authorities, whereas the implementation is the responsibility of reuse facilities.

4. Discussion and conclusion

This paper identifies relevant actors, evaluates barriers to PfR by an analysis of the market attractiveness based on the reverse five forces, and derives action recommendations for PfR from literature. Action recommendations are grouped into four categories information, legal framework, organizational structure, and process change, according to the type of instrument. Additionally, the influence of each measure on the reverse market forces and relevant actors are mapped out. The relevance of each measure is evaluated based on the number of references from literature. For further prioritization, an evaluation of the personnel and financial effort required to implement each measure and the potential quantities of WEEE that could additionally be prepared for reuse after the implementation of each measure needs to be assessed. So far, only a limited amount of best practice examples exists.

The market analysis shows substantial barriers within the market entry for reuse operators, the access mainly to large WEEE in sufficient quality, and strong interdependencies with external actors as successful remarketing of WEEE may result in conflicts of interest with manufacturers. To overcome these barriers, a range of action recommendations are proposed in literature. The analysis of all 26 identified action recommendations reveals the main success factors for each actor. The legislator influences all other actors in the field of reuse operations and defines the scope of action. Public authorities commonly implement the legislation on a regional level. Concerning these actors, the most pressing success factors for PfR of WEEE are raising awareness among the population for potential reuse of products through public relations work and clarifying uncertainties concerning liability and warranty issues. The actors involved directly in PfR operations are commercial reuse businesses, OEMs, municipal disposal services, and social-charitable institutions as non-commercial actors. Public relations work should also be pursued from these actors. A particular focus is to be set on preventing damage to potentially reusable goods by implementing value-conserving logistics, the introduction of an umbrella brand and increased cooperation between municipal disposal services and repair and distribution networks. Associations function as a mediator between all actors. They should mainly focus on public relations work and advertisement for reuse, the implementation of an umbrella brand, and qualification programs for employees.

A limitation of this work is a missing assessment of action recommendations' feasibility concerning the associated costs and benefits. Further work could focus on this aspect. The currently available best practice examples do not provide information on the related costs of implementing single measures. Quantification of the additional realizable volumes of WEEE reuse is hardly feasible for the categories information and legal framework. A case study from the German state of Bavaria finds that through the measures “employment of value-preserving boxes instead of bulk cargo containers” (Transport), “early separation of reusable devices” (separate collection), “employment of weatherproof and value-preserving containers,” and “prohibiting pre-treatment” (both value-conserving logistics) close to 30% of WEEE arising at municipal collection points could additionally be prepared for reuse. This shows a significant potential of the recommended measures to increase the share of PfR. As discussed before, the implementation of a binding PfR target for WEEE can be expected in the future for Germany and other European countries. To meet a future PfR quota, it is necessary to follow an effective strategy to increase the share of PfR. This structured overview serves as a guide for decision-makers as to which recommendations for action should be given priority and implemented.

Funding

The Bavarian State Ministry of the Environment and Consumer Protection supported this work as a part of a research project titled “Estimation of the potential of selected waste streams for the Preparation for Reuse” [grant number 71 f-U 8743. 1-2015/3-4- BAF01UKZA-69459].

Role of the funding source

Provision of resources for research activities.

Declaration of competing interest

None.

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Appendix

Appendix A. Overview on referenced articles

No	Author(s)	Year	Geographical scope	Type of article
[1]	Arold et al.	2008	Europe	Report
[2]	Broehl-Kerner et al.	2012	Germany	Report
[3]	Fitzpatrick & Hickey	2016	Belgium, Ireland, UK	Report
[4]	González	2013	Germany	Report
[5]	Jepsen & Vollmer	2015	Germany	Report
[6]	Kissling et al.	2013	Global	Journal article
[7]	Kissling	2011	Belgium, UK	Report
[8]	Lambert et al.	2014	Germany, Sweden	Report
[9]	Löhle et al.	2016	Germany	Report
[10]	Luger et al.	2010	Germany	Journal article
[11]	Meissner & Pladerer	n.d.	Austria	Report
[12]	Milios & Dalhammar	2020	Sweden	Journal article
[13]	Miller et al.	2017	Europe, Focus on Ireland	Report
[14]	NABU-Bundesverband	2013	Germany	Report
[15]	Neitsch et al.	2010	Austria	Report
[16]	O'Connell & Fitzpatrick	2013	Global, Focus on Ireland	Report
[17]	O'Connell et al.	2010	Europe, Focus on Ireland	Conference Proceedings
[18]	Rreuse	2013	Europe	Report
[19]	Sander et al.	2013	Germany	Report
[20]	Sander et al.	2019	Germany	Report
[21]	Schomerus et al.	2014	Germany	Report
[22]	Spitzbart et al.	2009	Austria	Report

Appendix B. Interview guide

Market Force	Attributes	Description	Rating: 1	Rating: 5
Access	Current status of PfR	Share of goods currently being prepared for reuse	Current share of reuse <20%	Current share of reuse >80%
	Quality of goods	Quality of the goods arriving at collection points	Very poor quality	Very good quality
	Mobility of goods	Transportability of the goods	Good is big, heavy and hard to transport	Good is small, lightweight and easy to transport
	Infrastructure	Accessibility and number of collection points	Few collection points, poor accessibility	Many collection point, good accessibility
Market entry	Strategic investment costs	Investment requirements for PfR (costs for personnel, space, infrastructure)	High investments required (a lot of personnel, large areas)	Low investment required (few personnel, small area)
	Technical feasibility	Complexity, spare parts availability, etc. (theoretical possibility of repair)	High effort required to prepare good for remarketing	Good is not complex and can be easily prepared
	Expertise	Required expertise of the personnel to perform PfR	Employees need special training/expertise	No special knowledge is required
	Regulations and laws	Regulations in the area of PfR (e.g. certifications, warranty and guarantee)	Regulations hamper PfR operations	Laws and regulations favor PfR operations
Remarketing	Existence of sales platforms	Existing sales platforms (number, size, regional distribution, networking)	Design of sales platforms limited remarketing	Design of sales platforms is optimal
	Customers' willingness to pay	Customers' willingness to pay for secondary goods compared with primary products	Willingness to pay is significantly lower than for new products	Willingness to pay is very high (>80% of new price)
	Demand	Demand for second-hand products	Very low demand (oversupply)	Very high demand (any secondary good can be sold)

	Technological life cycles	Time span in which secondary products can be marketed (with regard to the state of the art)	Good has very short life cycle, is quickly obsolete	Good can still be marketed over a long period of time
Interdependencies	Conflicts of interest with OEMs	Conflicts of interest with manufacturers due to remarketing of secondary goods	There are strong conflicts of interest	There are no conflicts of interest
	Product design	Aligning product design for potential repair and reuse	Good is not repairable/rebuildable	Good is easily repairable and modular, for example.
	Awareness level	Awareness of consumer responsibility towards reuse	The level of awareness is very low	The level of awareness is very high
	Existence of cooperation	Existing cooperation between collection points and repair stores / sales platforms	No cooperation exist	Many cooperation exist
Competition	Reuse alternatives	Existing alternatives to PfR(e.g. recycling, energy recovery).	Many alternatives exist	No alternatives exist
	Competitive situation	Number, structure, concentration of competitors or rivals	There is strong competition	There is no competition

Appendix C. Documentation of interviewees and dates

Interviewee	Professional background	Date of interview
Lukas Messman	Resource Lab, University of Augsburg	16 May 2017
Sandra Boldoczki	Resource Lab, University of Augsburg	16 May 2017
Isabella Wagner	Resource Lab, University of Augsburg	16 May 2017
Petra Hutner	Resource Lab, University of Augsburg	16 May 2017
Dietmar Lange	Waste management Munich	14 June 2017
Werner Bauer	ia GmbH - Municipal consulting and knowledge management	22 June 2017
Christian Daehn	State office for environment, Dep. 31: Circular economy strategies and systems	26 June 2017
Jürgen Beckmann	State office for environment, Dep. 31: Circular economy strategies and systems	26 June 2017
Günther Langer	Waste management Munich	27 June 2017
Prof. Dr. Axel Tuma	Chair of Production & Supply Chain Management, University of Augsburg	27 June 2017

Appendix D. Results of market analysis for large WEEE

	Current status of PfR	Quality of goods	Mobility of goods	Infrastructure	Strategic investment costs	Technical feasibility	Expertise	Regulations and laws	Existence of sales platforms	Customers' willingness to pay	Demand	Technological life cycles	Conflicts of interest with OEMs	Product design	Awareness level	Existence of cooperation	Reuse alternatives	Competitive situation
Expert 1	1	2	3	3	2	3	1	3	3	4	4	4	2	3	4	2	2	4
Expert 2	1	2	3	3	2	2	2	1	2	3	4	2	3	2	3	3	2	4
Expert 3	1	2	3	3	3	2	1	2	1	3	4	2	3	1	4	2	2	3
Expert 4	1	2	3	3	2	3	2	1	2	3	4	2	3	2	1	1	2	3
Expert 5	1	2	2	4	2	3	4	2	3	4	3	4	1	4	3	3	1	1
Expert 6	1	3	1	3	2	4	5	2	1	4	3	4	3	2	2	1	4	4
Expert 7	3	3	1	3	2	3	2	1	2	3	3	4	2	3	3	4	3	1
Expert 8	1	3	1	4	5	3	3	2	1	2	3	3	1	2	2	2	5	1
Expert 9	2			3	2	2	2	2	3	4	3	3	2	3	2	4	1	2
Expert 10	1	2	1	2	1	1	1	1	1	1	2	3	2	2	2		2	3
Mean	1.3	2.3	2.0	3.1	2.3	2.6	2.3	1.7	1.9	3.1	3.3	3.1	2.2	2.4	2.6	2.4	2.4	2.6
Minimum	1	2	1	2	1	1	1	1	1	1	2	2	1	1	1	1	1	1
Maximum	3	3	3	4	5	4	5	3	3	4	4	4	3	4	4	4	5	4
max. Difference	2	1	2	2	4	3	4	2	2	3	2	2	2	3	3	3	4	3
Standard Deviation	0.6	0.5	0.9	0.5	1.0	0.8	1.3	0.6	0.8	0.9	0.6	0.8	0.7	0.8	0.9	1.1	1.2	1.2

Appendix E. Results of market analysis for small WEEE

	Current status of PfR	Quality of goods	Mobility of goods	Infrastructure	Strategic investment costs	Technical feasibility	Expertise	Regulations and laws	Existence of sales platforms	Customers' willingness to pay	Demand	Technological life cycles	Conflicts of interest with OEMs	Product design	Awareness level	Existence of cooperation	Reuse alternatives	Competitive situation
Expert 1	1	2	5	4	2	2	1	3	3	3	3	2	2	1	2	1	2	4
Expert 2	1	2	4	4	2	1	1	1	3	3	3	1	3	1	2	2	2	4
Expert 3	1	2	5	4	2	1	1	2	2	3	3	1	3	2	4	2	2	1
Expert 4	1	2	5	4	2	2	1	1	3	3	3	1	3	1	1	1	2	3
Expert 5	2	2	3	4	2	2	4	2	2	3	3	3	1	2	2	2	2	2
Expert 6	1	3	4	4	2	2	2	2	1	4	3	3	2	2	2	1	4	4
Expert 7	2	3	4	4	2	2	2	1	2	3	3	3	2	2	3	4	2	1
Expert 8	1	3	5	4	5	4	2	2	1	2	1	1	1	1	2	2	5	3
Expert 9	2			3	1	2	2	2	3	4	4	3	2	3	2	4	1	2
Expert 10	1	2	4	3	1	2	1	1	1	2	2	2	2	2	2		2	3
Mean	1.3	2.3	4.3	3.8	2.1	2.0	1.7	1.7	2.1	3.0	2.8	2.0	2.1	1.7	2.2	2.1	2.4	2.7
Minimum	1	2	3	3	1	1	1	1	1	2	1	1	1	1	1	1	1	1
Maximum	2	3	5	4	5	4	4	3	3	4	4	3	3	3	4	4	5	4
max. Difference	1	1	2	1	4	3	3	2	2	2	3	2	2	2	3	3	4	3
Standard Deviation	0.5	0.5	0.7	0.4	1.0	0.8	0.9	0.6	0.8	0.6	0.7	0.9	0.7	0.6	0.7	1.1	1.1	1.1

3

Conclusion and research outlook

3.1 Added value and findings

This doctoral dissertation contributes to the data basis concerning the amounts of products viable for PfR as well as its potential to reduce environmental impacts. Additionally, action recommendations for its practical implementation are presented. In the following section, the most important added value and findings are presented.

Messmann et al. (C1) address the aforementioned lack of data needed to enforce the waste management hierarchy. With the empirical collection of primary data at Bavarian collection points, a unique database is compiled. Based on this data, a theoretical potential for the preparation for the reuse of WEEE, used furniture, and used leisure goods is derived. This knowledge provides aid for the formulation of a PfR quota by politics. Additionally, literature addresses a variety of challenges that currently hinder the realization of these potentials. Causal analysis of damage allows identification of the most pressing issues for preparation for reuse at collection points. The findings thereby support the selection of effective actions to increase the processed amounts of waste.

Boldoczki et al. (C2) analyze the environmental impacts of PfR for WEEE and thereby explores potential benefits of PfR compared to other waste management options for a representative selection of WEEE (four white goods and small electric devices each). To determine the environmental saving potential of reuse in Germany, comparable LCA data for all eight analyzed products is required. No publication assesses all of the required products. Furthermore, LCA studies currently available on the level of individual products vary too widely in terms of system boundaries and modeling assumptions to compare results among them. Boldoczki et al. (C2) therefore add to literature on comparative LCAs by following a consistent approach for eight representative products of WEEE. The LCA results allow deriving generalizable recommendations about waste management options for WEEE in the German scope. Furthermore, product-specific recommendations for reuse are delineated that support environmentally-conscious consumer decisions about acquiring new versus second-hand products.

Boldoczki et al. (C3) address the need for a long-term quantitative assessment in the evaluation of CE activities. By applying the hybrid LCA dynamic MFA approach to the case of WEEE reuse (as an example of a CE activity), this paper contributes to the research on monitoring environmental pressures of CE activities over time. The combination of these methods allows an economy-wide evaluation of a range of environmental impacts of reuse for a certain product group. Future increases in product efficiency and changes in energy mix and demand are considered as well. Therefore, the results not only picture the current situation to inform policy decisions, but also assess mid to long-term consequences of a CE incentive. So far, impacts during the use phase have rarely been included in a hybrid approach, but findings are of value for researchers and decision-makers in the field of WEEE management (De Meester et al., 2019; Islam & Huda, 2019). The findings show that even high reuse rates only have limited leverage on reducing environmental impacts. Thus, it is necessary to include detailed environmental assessments in a holistic evaluation of Circular Economy activities.

Boldoczki (C4) delivers a structured compilation of action recommendations to promote PfR. The assessment of the market attractiveness for PfR operators provides information on the characteristics, mechanisms, and interdependencies of the market. Subsequently, action recommendations are classified by actors and targeted market force and additionally prioritized based on the number of citations. This structured overview serves as a guide for decision-makers as to which recommendations for action should be given priority and implemented.

3.2 Outlook

Although presenting several steps advancing the research on PfR, this work shows some limitations that can be addressed by future research. First of all, the research majorly focuses on one dimension of sustainability, namely environmental aspects. It is believed that social and economic benefits are discussed less controversially. Nevertheless, this hypothesis should be tested in future research by applying approaches such as Life Cycle Costing or Social Life Cycle Assessment. Second, all four contributions contain case studies within the German scope. While the findings deliver valuable insights that not only apply to Germany, the approaches could be transferred to international regions or other countries to validate the conclusions.

Regarding the first contribution (Messmann et al., C1), primary data for three waste streams within the scope of Bavaria are retrieved. This study was carried out with a broad scope regarding general differences between municipalities. Whereas the approach could be transferred to different international regions, in the future, narrower research on specific collection sites or specific wastes is necessary to identify relevant action recommendations.

Boldoczki et al. (C2) find that assumptions concerning the usage behavior as well as the scope of the study and especially the energy mix have a strong influence on the outcome. The goal of the study was explicitly to generate comparative LCAs on eight products in the German context. Therefore, the adaption of country-specific usage patterns and energy sources is crucial if insights are to be delineated for other countries.

The hybrid dynamic stock model in Boldoczki et al. (C3) does not consider storage times as an immediate discard of a product is assumed. Besides analyzing impacts of a potential time-shift between replacement and disposal of a product, subsequent efforts should be focused on obtaining more comprehensive data on technological advances (such as future efficiency gains). Further applications of the methodology could analyze other product groups, different geographical scopes, or additional Circular Economy measures.

The relevance of each action recommendation for PfR (Boldoczki, C4) is evaluated based on the number of references from literature. A more distinct prioritization could be based on an evaluation of the personnel and financial effort required to implement each measure and the potential quantities of WEEE that could additionally be prepared for reuse after the implementation of each measure.

Concluding, this doctoral thesis delivers insights into the potential of the waste management option preparation for reuse to contribute to the goals of a Circular Economy in policy and academic contexts. In four scientific publications, quantitative analyses as well as assessment approaches, transferable to further areas of interest in the field of waste management and Circular Economy actions, are provided. These findings and approaches can be used by researchers and practitioners to support decision-making on practically appropriate and environmentally favorable End-of-Life pathways. That way, this work presents gradual steps within the pursuit of sustainable development in a transition towards a Circular Economy.

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