THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Resource efficient products in a circular economy – The case of consumables

From environmental and resource assessment to design guidelines

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Cover:
The cover image of this thesis is based on a painting of Sonia Delaunay (1886-1979) named "*rythme couleur 1076*". The original painting explores through colors, the idea of rhythm, a pattern essentially made by sound and silence, in other words, a dance between two different entities.

The painting was mirrored to give the impression of the earth orbiting the Sun, in which also four seasons can be perceived. The central message of this thesis is related the urgent need to follow earth´s rhythm, to dance with her, to engineer a pattern that can be beneficial for both dancers, our species and the earth itself.

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ABSTRACT

The circular economy (CE) is a concept to challenge the unsustainable production, consumption, and waste management of products, through the recirculation of resources and products through various means while reducing environmental impact. Within this concept, many measures are recommended for reducing environmental impact and resource use. However, to ensure and verify whether a measure is leading to its intended outcome, environmental and resource assessment is necessary.

This thesis aims to investigate which measures are resource efficient and identify for which products different measures are suitable and under what circumstances they lead to their intended outcomes. Based on this, design methods are developed to enable the design of more resource-efficient products. Finally, this thesis aims to investigate more specifically the measures that are suitable for consumable products, as these products have not been examined thoroughly in the circular economy literature as durable products.

The aims of this research were met by investigating which resource-efficiency measures exist and are applicable to products with different characteristics. This was done through life cycle assessment studies of specific consumable products. Further, a synthesis study was carried out in which lifecycle-based assessment studies of different products and measures were analysed. This research concludes that depending on a product's characteristics, some measures are more relevant than others. In addition, the analysis shows that many measures lead to trade-offs between different types of environmental impacts and resources uses, as well as between different life cycle phases. For these findings to be practically useful, they were subsequently translated into design guidelines expressed as a design tool.

Finally, a literature review was conducted of general product design guidelines in the CE and ecodesign literature to compile and analyse to what extent the design guidelines are applicable to different types of consumables. Among other factors, this review shows that, on average, less than half of the recommendations found in the general product design guidelines are possible to apply to consumables. Further, the CE literature was found to provide fewer relevant design considerations than the ecodesign literature. This work also identifies what aspects make product-types specific design guidelines transferable to other consumables.

Key words: LCA, resource efficiency, circular economy, consumable products, product characteristics, design guidelines, ecodesign, circular product design

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List of appended papers

The thesis is based on the following appended papers, referred to by roman numerals in the summarizing essay.

I. Böckin, D., Willskytt, S., André, Hampus, A., Ljunggren Söderman, M., Tillman, A-M. (2020) How product characteristics can guide measures for resource efficiency – A synthesis of assessment studies. *Resources, Conservation and Recycling*. Vol. 154C, 104582.

II. Willskytt, S., Brambila- Macias, S. (2020) Design guidelines developed from environmental assessments: A design tool for resource-efficient products. *Sustainability,* Vol. 12, 4953.

III. Willskytt, S. (2020) Design of consumables in a resource efficient economy – A literature review (Manuscript)

IV. Willskytt, S., Tillman, A-M. (2019) Resource efficiency of consumables – Life cycle assessment of incontinence products. *Resources, Conservation and Recycling.* Vol. 144, p. 13-23

V. Neramballi, A., Sakao, T., Willskytt, S., Tillman, A-M. (2020) A design navigator to guide the transition towards environmentally benign Product/Service Systems based on LCA results. *Journal of Cleaner Production*. Vol. 277, 124074.

Other publications

Work related to the thesis has also been presented in the following papers:

A. Tillman, A.-M., Ljunggren Söderman, M., André, H., Böckin, D. and Willskytt S., 2020. Circular economy and its impact on use of natural resources and the environment - Chapter from the upcoming book Resource-Efficient and Effective Solutions – A handbook on how to develop and provide them. Report no. 2020:1. Chalmers University of Technology: Gothenburg, Sweden.

B. Tillman, A.-M., Willskytt, S., Böckin, D., Andre, H., & Ljunggren Söderman, M. (2020). What circular economy measures fit what kind of product? In M. Brandão, D. Lazaveric, & G. Finnveden (Eds.), Draft chapter in Handbook on the Circular Economy, Edward Elgar Publishing Ltd, Cheltenham, UK.

C. Willskytt, S., D. Böckin, H. André, M. Ljunggren Söderman and A. M. Tillman (2016). Framework for analysing resource-efficient solutions. EcoBalance 2016, October 3-6. Kyoto, Japan.

D. Böckin, D., S. Willskytt, A.-M. Tillman and M. Ljunggren Söderman (2016). What makes solutions within the manufacturing industry resource efficient? EcoBalance 2016, October 3-6. Kyoto, Japan.

Contribution report

The author of this thesis has made the following contributions to the papers:

I. AMT and MLS developed the idea and research design. SW, DB and HA performed the data collection and investigation, formal analysis of synthesizing data, documented metadata, and wrote the initial draft of the manuscript, in which HA wrote the introduction and aim, SW the method, and DB the analysis, results and discussion and conclusions. All authors developed the methodology and the analytical framework, critically reviewed and edited the manuscript. DB and AMT lead the revision of the manuscript to which SW, HA and MLS contributed with critical review and editing.

II. SW and SBM developed the idea and methodology. Both authors collected data, and were responsible for validation, SW by means of LCA and SBM by means of a questionnaire. SW performed the formal analysis, investigation, documented metadata and wrote the original draft. Both authors critically reviewed and edited the manuscript. SW revised the manuscript following the peer-review comments.

III. SW developed the idea, research design and methodology. SW performed the data collection, investigation, formal analysis and wrote the manuscript.

IV. SW and AMT developed the idea and research design. SW performed the data collection, documented the metadata, performed the formal analysis, and wrote the initial draft of the manuscript, supervised by AMT. Both authors developed the methodology and critically reviewed and edited the manuscript. SW revised the manuscript following the peer-review comments, supervised by AMT.

V. AN and TS developed the core idea and research design. All authors made contributions to the methodology, formal analysis and validation. AN and TS developed the method for deriving the customer requirements and the service characteristics. SW and AMT developed the method for deriving the environmental requirements and SW conducted the comparative LCA as validation. In addition to developing the visualizations, AN wrote the original draft with contributions on specific parts from SW and TS. All authors critically reviewed and edited the manuscript.

Figures and tables

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Abbreviations

CE	Circular Economy
DfSB	Design for Sustainable Behaviour
DRM	Design Research Methodology
EMF	Ellen MacArthur Foundation
EO	Existing offerings
EU	European Union
FMCG	Fast-Moving Consumer Goods
LCA	Life Cycle Assessment
LFD	Lifecycle-Oriented Function Deployment
MFA	Material Flow Analysis
PLA	Polylactic Acid
PSS	Product Service System
QFD	Quality function deployment
RE	Resource Efficiency
REDIG	Resource Efficient DesIgn Guidelines
RO	Redesigned offering

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1 Introduction

We are currently experiencing a growing global population together with an ever-increasing consumption of products. As a result, by 2050, annual global material extraction is expected to more than double from current levels to reach 183 billion tonnes (UNEP, 2017). This has put sustainability (Brundtland, 1987), resource efficiency (UNEP, 2017), and now the circular economy on the political agenda as a response in, e.g., Europe (EC, 2015, 2020) and China (Pesce et al., 2020; The Standing Committee of the National People's Congress, 2008). Within the frameworks of these concepts, a number of measures[1] have been presented as solutions to the unsustainable production and consumption of products. Initially, the focus was on so-called end-of pipe solutions (e.g., Frondel et al. (2007)), later on the cleaner production (e.g., Matos et al. (2018)) and ecodesign of products (e.g., Brezet & van Hemel (1997)), and now more recently on circular product systems and business models (e.g., Bocken et al. (2016)).

The circular economy (CE) is believed to involve a radical transformation of industry, the market, and society and is understood by many as a "an industrial economy that is restorative or regenerative by intention and design" (EMF, 2013a). Within the CE concept, there are many hierarchies of measures that determine which solutions are most important to focus on (Reike et al., 2018). Such rankings of measures are advocated, for example, by the Netherlands Environmental Assessment Agency, which provides a framework of resource efficiency strategies to underpin political and administrative decision making and includes nine measures (from refuse, to reuse, remanufacturing and recycling) (Potting et al., 2017). This ranking is also promoted by the Ellen MacArthur Foundation, which is one of the leading proponents of CE (EMF, 2013a), as well as by the European Commission's waste hierarchy (EC, 2008). Similarly, Kirchherr et al. (2017), who reviewed 114 definitions of CE, emphasized the need for clear prioritization between measures to provide ample guidance and avoid greenwashing. However, research has shown that these hierarchies are not always valid. For instance, Ljunggren Söderman & André (2019) advocated that the ranking of measures rests on idealized descriptions of those measures, without accounting for real-world conditions like insufficiently exploited life-times, low collection rates, and losses in remanufacturing, repair, and recycling. The benefits from such measures can, therefore, be considerable smaller in reality, and following such ranking recommendations risks shifting the burden between environmental impacts and life cycle phases, leading to other and potentially greater environmental problems. Also, as suggested by Blomsma & Brennan (2017), several measures can work together, in

[1] Measures can, for instance, be policy or business model-based; however, in this work, a measure is considered to be physical or design-based action or an activity to improve the environmental performance and resource uses of product systems.

sequence, or in parallel. It is, therefore, important to investigate the environmental and resource consequences of different individual measures and combinations thereof (Blomsma & Brennan, 2017). For such purposes, life cycle assessment (LCA) is a useful tool and can aid in the investigation of potential environment and resource outcomes from various measures, scenarios, and product systems (Baumann & Tillman, 2004; Kjaer et al., 2018). In recent years, many LCAs have investigated the outcomes of different measures for various products (see e.g., André et al. (2019), Böckin & Tillman (2019) and Castellani et al. (2015)). Some synthetizing review papers have taken a sector perspective (e.g., the construction sector (Ghisellini et al., 2018) and the textile industry (Kjaer et al., 2018)). However, there are few attempts to systematically analyse the outcomes from environmental assessment studies of products in different sectors. Against this background, the following knowledge gap has been identified.

Gap 1. *Knowledge is missing about when and under what circumstances CE measures lead to their intended outcomes for different products—e.g., less environmental impact and resource use—and when and in which cases they do not*.

Consumable products are a group of many products that are short-lived by nature. These products are either literally consumed or disposed of after a short lifetime. Consumables can be defined in a number of ways: goods that are capable of being consumed; those that may be destroyed, dissipated, wasted or spent (Locke, 1913); products that need to be replaced after they have been used for a period of time (Webster, 2018); goods that people buy regularly because they are quickly used and need to be replaced often (Cambridge, 2011); or commodities that are intended to be used up relatively quickly (Oxford, 2010). In this thesis, consumables are considered to include three distinct product groups (Paper II): *Dissipative products* are consumed during use and are, therefore, not intact after use. Instead, they are transformed, perhaps dissolved, and become intangible post-use. Examples include food, fuels, and cleaning agents. *Disposable products* are those that are typically used once and thereafter disposed of. These products still exist as a distinct object after use. However, they usually become contaminated and, in some cases, unhygienic after use. Examples include packaging, single-use articles, and hygiene products. *Short-lived components in durable products* have a relatively short lifespan compared to the entire product and must be replaced several times during the product's lifetime. The function of these products deteriorates at a faster pace than the rest of the durable product. Examples include filters in vehicles, single-use batteries, and ink cartridges.

Consumables generally have a quick turnover in society, which means that they constitute a large share of the products that end up as waste from households, industry, and the public sector. Some of product materials are recycled, but an increasing proportion is incinerated or landfilled

(EMF, 2013a). In Europe, in 2018, municipal waste amounted to 489 kg per person, of which only 47% was either recycled or composted (Eurostat, 2019). In addition, disposable products contribute to litter, which ends up in the environment and eventually in the seas, where this litter lead to further environmental problems such as the accumulation of microplastics (UNEP, 2018). However, not all consumables end up as solid waste. Some find their way into the sewage systems, such as cleaning and personal-care products that are flushed or rinsed off during use, and require treatments to be broken down and diluted before being released in nature. Other products, such as fuels, are instead released directly into the air when consumed and thus lead to numerous environmental concerns, such as global warming and acidification.

Several authors have, therefore, pointed to the improvement potential of the design and delivery of consumables, especially for a circular economy (Charnley et al., 2015; EMF, 2013b; Kuzmina et al., 2019). However, much of the focus within the CE has been on long-lived products that can be made even more long-lived or recirculated through, e.g., reuse and remanufacturing (Bakker et al., 2014; Bocken et al., 2016; den Hollander et al., 2017; Pozo Arcos et al., 2018). Less focus has been placed on how consumables and short-lived products can be improved (Böckin et al., 2020; Park, 2015). Based on this, the following gap was identified.

Gap 2: Knowledge is limited about what measures can be applied to consumables to improve their resource efficiency.

Product design is considered to be important for enabling environmental and resource efficient product solutions (Bocken et al., 2016; De los Rios & Charnley, 2017). In product design, there is a great possibility to influence the product's life cycle (Bhamra et al., 1999) through one’s choice of materials, lifetime design, possibilities for repair, and design for use and end-of-life. Design to reduce environmental impact over the product’s entire life cycle is usually called ecodesign (Pigosso et al., 2015; Rossi et al., 2016). However, regardless of the decisions made during product design, there is no guarantee that the product will actually be used as intended (e.g., for its full technical lifetime), receive the treatment it needs, or be properly handled once it has been worn-out (Selvefors et al., 2016). Nevertheless, through the planning of sustainable product systems, the opportunity is greater for the proper use of such products.

In ecodesign, there is often limited focus on the user (Ceschin & Gaziulusoy, 2016; Shu et al., 2017). It has been found that the inclusion of a design aspect that influences user behaviour is important for the circular economy (Wastling et al., 2018). Two such methods are Emotionally Durable Design, which focuses on the emotional connection between products and users, and Design for Sustainable Behaviour, which aims to influence user behaviour into more benign patterns (Ceschin & Gaziulusoy, 2016).

There are many types of methods for product design, such as guidelines, checklists, software tools, and matrixes (Rossi et al., 2016) . The term “guideline” is generally used to indicate a procedure or method for orienting a decision-making process towards given goals (Vezzoli & Sciama, 2006). General guidelines, i.e., those that aim to be applicable to all types of products, can be useful at a conceptual level and for educational purposes but work less well for specific product design applications according to Vezzoli & Sciama (2006). To be effective in such a context, design guidelines need to be specific to certain product groups or adaptable to certain product groups (Luttropp & Lagerstedt, 2006; Vezzoli & Sciama, 2006). Design guidelines for specific product groups instruct on specific considerations related to the products and the contexts that they are used in and thereby filter irrelevant concerns and enrich context-specific information. In design for CE, however, design guidelines tend to be general and are often based on general rankings of measures, without reflecting the characteristics of specific product groups (Bakker et al., 2014; Bocken et al., 2016; den Hollander et al., 2017; Moreno et al., 2016). Based on these findings, the following knowledge gap was identified.

Gap 3: *Product-group specific design guidelines for creating more resource-efficient products in a circular economy are lacking, especially for consumable products and those that consider design that influences user behaviour*.

1.1 Thesis objectives and research questions

In response to the three identified knowledge gaps, this thesis aims to investigate which measures are resource efficient and identify for which products different measures are suitable and when they lead to their intended outcome. In addition, design methods are accordingly developed to enable the design of more resource-efficient products. Finally, this thesis aims to investigate more specifically what measures are suitable for consumable products.

The research objectives were further specified into research questions:

1. What product characteristics are relevant for the outcome of resource efficiency measures?

2. How can the suitability of RE measures for product with different characteristics be used to formulate guidelines for the design of resource-efficient products?

3. Which guidelines exist for the design of resource-efficient consumables?

4. What resource efficiency measures can be applied to consumables, and what are their outcomes in terms of environmental impacts and resource use?

The research questions were answered in the appended papers according to the method shown in Table 1.

Moreover, this research was conducted as part of the Swedish research programme Mistra REES, Resource Efficient and Effective Solutions, based on circular economy thinking (www.mistrarees.se). The programme has had the overall aim to accelerate the transition of the Swedish manufacturing industry toward a resource-efficient and circular economy. Participation in Mistra REES has enabled research to be conducted with real industrial cases and facilitated interdisciplinary collaboration with design researchers.

Table 1. Overview of the appended papers and their contributions to answering the research questions.

Title of paper		**Addressed research question**
I.	How product characteristics can guide measures for resource efficiency—A synthesis of assessment studies	1, 4
II.	Design guidelines developed from environmental assessments: A design tool for resource-efficient products	1, 2, 4
III.	Design of consumables in a resource efficient economy—A literature review	1, 3
IV.	Resource efficiency of consumables—Life cycle assessment of incontinence products	1, 4
V.	A design navigator to guide the transition towards environmentally benign Product/Service Systems based on LCA results	4

1.2 Thesis structure

The research conducted for this project resulted in five papers included in this thesis (see the list of appended publications, p.V). This introductory essay synthesises the results presented in the papers by answering the research questions (Chapter 4). This is followed by a discussion of the implications and limitations of the results (Chapter 5). To provide a relevant background to the synthesis and discussion, the issue at stake is introduced in Chapter 1, and the underlying theory and methods are presented in Chapter 2 and Chapter 3, respectively. Finally, Chapter 6 presents the conclusions and the contributions of the thesis and provides an outlook based on the identified future research needs.

In the following section, the included papers are described to outline how they relate to each other in the overall research process, which is also depicted in Figure 1.

In **Paper I,** a framework for analysing comparative life-cycle-based assessment studies was developed and used to analyse when and under which circumstances resource efficient measures lead to the intended outcomes for different products. To perform such an analysis, numerous assessment studies were collected (in which Paper IV was one of the subsets), which were then further synthesised. The analysis and synthesis were carried out using an analytical framework that included a typology of RE measures. The study identifies which product characteristics are decisive for the suitability of different RE measures as well as the relevant environmental and resource trade-offs.

In **Paper II,** the results from Paper I were translated into design guidelines in a design guideline tool. The tool was thereafter evaluated in a design case, in which a designer used the tool to redesign an air filter. To evaluate the usefulness and usability of the tool, a questionnaire and comparative LCA were carried out.

In **Paper III,** a literature review of design guidelines for resource-efficient consumables was carried out. The work in both Paper II and Paper IV identified that there is limited research on environmentally benign product design of consumables, which motivated this review. The purpose of this study was to analyse what general product design guidelines are applicable to consumables and what design guidelines for certain product groups are transferable to other types of consumables. This was done to investigate if the guidelines suggested in the general product design guideline literature is sufficient for the design of consumables and what could be potentially missing. This was also done to determine to what extent ecodesign and CE literature contribute to relevant design guidelines.

In **Paper IV,** an LCA study investigated different four different resource efficient measures applied to consumable products (incontinence products). The typology of RE measures in Paper

I was used to identify possible measures to apply at different lifecycle stages. This LCA study was carried out early in the research process; the results were analysed in Paper I and used as input in Paper V.

Paper V describes a design navigator developed to help product development teams develop more environmentally benign product service systems. The design navigator builds on quality function deployment (QFD) and makes use of the results from existing LCA studies. The paper describes how the method was tested on the case of a product service system for incontinence products. The LCA in Paper IV was used as the input study. To evaluate the developed method, its utility was assessed by means of an additional LCA.

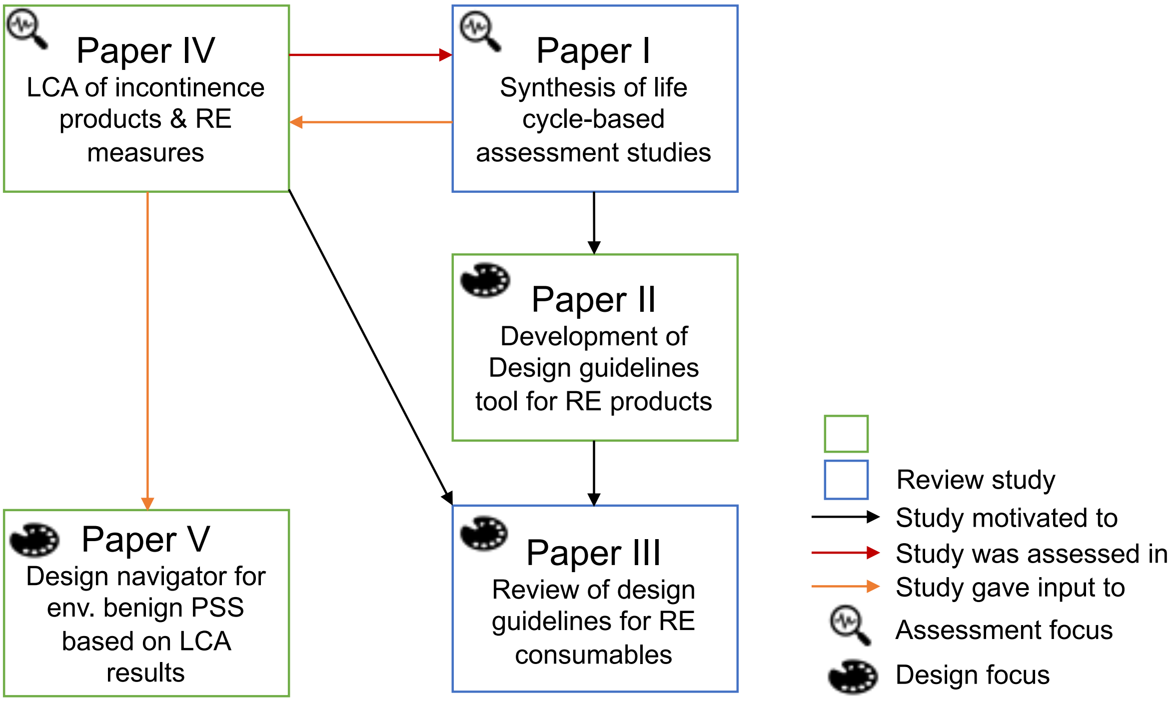

Figure 1. Overview of papers and the research process.

2 State-of-the-art

This chapter presents the conceptual and theoretical framing of this thesis and is divided into four topics: (1) circular economy, (2) resource efficiency, (3) product design for resource efficiency, and (4) consumables.

2.1 Circular economy

The concept of the Circular Economy (CE) was introduced as a response to the limitations of the linear economy (i.e., the take-make-use-dispose of products in society) as a means to harmonize the ambitions of economic growth with the needs for environmental protection (Lieder & Rashid, 2016). This concept is commonly understood as a way to recirculate products, components, and the materials they contain in different circular loops denoting different measures, such as reducing, reusing, remanufacturing and recycling (Reike et al., 2018). However, the idea of product circularity is not a novel or recent concept. Before the industrial revolution, craftmanship and hand-made production were the conventional practices, and any type of scrap or waste was used for other purposes, i.e., there was no unusable waste ((Strasser, 2000), referred to in (Lieder & Rashid, 2016)). Instead, products were maintained and repaired to as large an extent as possible. Similarly, Blomsma & Brennan (2017) categorized CE as a “new framing around prolonging resource productivity”. The concept of a CE is not only about the protection of longer-lasting products, it is an idea of how the economy can be sustained through changes in companies’ business models and how the industry and society is designed (EMF, 2013a). These ideas build on concepts such as the spaceship economy (Boulding, 1966), industrial ecology (Frosch & Gallopoulos, 1989), the performance economy (Stahel, 2010), the cradle-to-cradle design approach (McDonough & Braungart, 2002), and the European Commission’s (EC) waste hierarchy (EC, 2008).

The CE is intended to operate at multiple levels: the micro-level (products, companies, and customers) (Bocken et al., 2016; Stewart & Niero, 2018; Wastling et al., 2018), the meso-level (eco-industrial parks and economic sectors)(Domenech et al., 2019; Gunnartz, 2016), and macro-level (the region, the nation, and beyond) (EC, 2020). On a micro level, re-thinking business models for a CE is connected to product design and forward and reverse supply chains to reach and maintain operational efficiency (Lieder & Rashid, 2016). Clearly, there are many definitions of CE. For instance, Kirchherr et al. (2017) reviewed 114 definitions and concluded that there is yet no consensus. However, one of the most commonly adapted definitions is from the Ellen MacArthur foundation (EMF) (Kirchherr et al., 2017). EMF is one of the leading proponents of CE and describe a circular economy as “an industrial system that is restorative or regenerative by intention and design. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models"(EMF, 2013a).

Central to the EMF description of CE, as well as other relevant frameworks in academic literature and policies, is presenting a hierarchy of measures or strategies for CE. In declining order of priority, EMF advocates to maintain, reuse/redistribute, refurbish/remanufacture, and recycle products and their materials (EMF, 2013a). The European Waste Framework Directive describes a waste hierarchy (EC, 2008). This framework details the priority order for managing waste, from the prevention of waste; to its reuse, recycling, and other recovery; and, lastly, to disposal. Similarly, Ghisellini et al. (2016) described a ranking order of the strategies of reducing, reusing, and recycling in their review of the CE concept. Likewise, Potting et al. (2017) presented a 9R framework of measures for CE (ranking order: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover). Moreover, Reike et al. (2018) reviewed 69 peer-reviewed contributions on different R-frameworks. They found that 59% of the contributions featured a clear ranking of the measures. Moreover, the authors supported the 9R framework and stated that "*the retention of resource value means conservation of resources closest to their original state, and in the case of finished goods retaining their state or reusing them with a minimum of entropy as to be able to give them constructive lives*" (Reike et al., 2018). A similar idea of retained value is found in Walter Stahel's Inertia Principle (Stahel, 2010), which is used as the guiding principles for the design of circular products in den Hollander et al. (2017): "*the intention of the Inertia Principle is to keep the product in this (original) state, or in a state as close as possible to the original product, for as long as possible, thus minimizing and ideally eliminating environmental costs when performing interventions to preserve or restore the product's added economic value over time*". The reasons for advocating the ranking of measures vary among the authors. Kirchherr et al. (2017) stated that a clear prioritization between measures is needed to provide ample guidance and avoid greenwashing. The work presented by den Hollander et al. (2017), on the other hand, builds on the idea that there is (or at least could be) an ideal state of CE and that their work strives for such an ideal state. Similarly, the ranking of measures in EMF (2013a) can be viewed as an idealization of how a CE should be. Potting et al. (2017) also views the ranking framework as an endeavour but acknowledges that CE solutions can lead to increased resource use.

2.2 Resource efficiency

Circular strategies do not necessarily lead to decreased resource use. For instance, using a refrigerator from the 1980s today would mean consuming much more energy than necessary since refrigerators have become approximately 60% more efficient in the following years (Bakker et al., 2014). With that in mind, prolonging the lifespan of products is not always the most energy-efficient option. Another example is that shared products are sometimes used less carefully and break down more easily than owned products (Tukker, 2015). A third example is when product design is used to facilitate remanufacturing through modularity, which can result in increased material use (Proske et al., 2016). Moreover, for some products, e.g., dissipative products such as food, the possibility to apply circular measures is limited. Instead, measures to reduce food waste are more central (Berlin & Sonesson, 2006) along with efforts to recirculate plant nutrients. Keeping this in mind, overall resource efficiency can be achieved in many ways, e.g., reusing, sharing, and remanufacturing, but also via measures aiming at reducing losses and resource use over the whole product lifecycle, from production and extraction to the use of the product, followed by post-use.

In this thesis, *resource efficiency* is defined as reduced use of natural resources, both in terms of resource use and environmental impact. Natural resources "*can be regarded as assets that occur in nature from which it is extracted to be used for human purposes in society*" and are "*renewable and non-renewable resources that can be extracted from the natural system to the technosphere*"; "*raw materials and energy carriers that have been transformed and from which, in turn, manufactured and agricultural goods can be generated*"; and "*ecosystem services provided by the natural system, including provisioning services, regulating services, cultural services, and underlying supporting services*" (Tillman et al., 2020a). Efficient means the *"maximum ratio of an output to the corresponding input"* (ISO/TR11065, 1992). The definition of resource efficiency in this thesis is thus broad and inclusive, in line with UNEP (2010)(p.42): "*Resource efficiency is about ensuring that natural resources are produced, processed, and consumed in a more sustainable way, reducing the environmental impact from the consumption and production of products over their full life cycles. By producing more wellbeing with less material consumption, resource efficiency enhances the means to meet human needs while respecting the ecological capacity of the earth".* Effective use of resources is also considered in this thesis. Effective means "*to produce a decided, decisive, or desired effect*" (Merriam (Merriam-Webster, 2020).

2.3 Product design for resource efficiency

Many definitions of product design exist. In this thesis, product design considers the activities that generate and develop a product from a need, product idea, or technology to the full documentation required to realize that product and to fulfil the perceived needs of the user or other stakeholders (Blessing & Charkrabarti, 2009). A design process typically consists of four stages (Ahmad et al., 2018). The first is planning and problem definition, which is followed by conceptual design. At the conceptual design stage, the product's function is identified, alternative concepts are generated, and design specifications are determined. The third stage is the preliminary design, which includes the elaboration and evaluation of alternative concepts and the selection of the best concept. The final stage is detailed design, where the chosen alternative is elaborated in detail, further evaluation and optimization is performed, requirements for manufacturing and maintenance are identified, and documentation and communication is done.

The term “product”, in this thesis, is used to denote both products and services, as well as combinations thereof, conforming to the standard for LCA of the International Organization for Standardization (ISO, 2006).

To design resource efficient products, there are several design concepts of relevance: Ecodesign, Design for Sustainable Behaviour and Emotionally Durable Design, Design of Product-Service System, and Circular Product Design, which are all described in the following.

2.3.1 Ecodesign

A design that aims to minimize environmental impacts over the whole product life cycle, i.e., from extraction of raw materials to final disposal, is often called ecodesign (Ceschin & Gaziulusoy, 2016; Pigosso et al., 2015), lifecycle design (Vezzoli, 2018), or design for environment (Hauschild et al., 2004). Ecodesign is an approach to designing products with consideration for environmental issues over the life cycle without compromising other essential criteria, such as performance, functionality, aesthetics, quality, and cost (Pigosso et al., 2015).

The life-cycle approach to ecodesign has been supported by LCA methods. Ecodesign has been one of the strongly advocated application areas of LCA, identified as early as the 1990s, i.e., the early days of LCA (Baumann & Tillman, 2004). LCA facilitates the quantification of environmental impacts, enabling a meaningful comparison between different product concepts of the same category, and, therefore, supporting design decision making (Ceschin & Gaziulusoy, 2016). Conducting an LCA study is time-consuming, and product design itself is a time intensive process, which makes it difficult to use LCA within this process. Nevertheless, there are many ways to use LCA in design. For instance, LCA can be used during the planning stage by analysing a reference product, during the generation of an idea by using the LCA results of the reference product to steer the need for redesign, during conceptual design to evaluate different design concepts, and in later stages of embodied design and detail design to evaluate and verify the developed design concept (Baumann & Tillman, 2004).

The potential to influence the design and the environmental impacts of products is suggested by many to be the greatest in the early stages of design (Bhamra et al., 1999). However, using LCA in early product development processes has some drawbacks related to the “the designers paradox”(Lindahl & Sundin, 2012), illustrated in *Figure 2*. In the early design phases, the freedom to influence the design is the greatest. However, this stage is also when there is the least information about the design. For this reason, there is also a low possibility to conduct an LCA, whereas later in the design processes, the possibility for an LCA is higher because there is more product information at hand but less possibility to influence the design (Baumann & Tillman, 2004; McAloone & Pigosso, 2018).

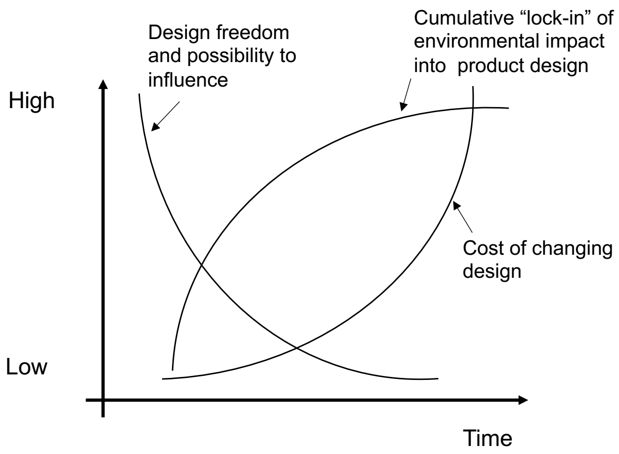

Figure 2. Illustration of the designers paradox from Baumann & Tillman (2004).

Therefore, in addition to LCA, there are many different types of more simplified ecodesign tools and methods (Rossi et al., 2016). For instance, guidelines and checklists can be used as creative tools for supporting brainstorming to generate product concept ideas. Examples include the 10 golden rules (Luttropp & Lagerstedt, 2006) and the ecodesign-strategy wheel (Brezet & van Hemel, 1997). In addition to providing suggestions on how to improve the product, guidelines can be used for a quick evaluation of the environmental profiles of products (Rossi et al., 2016). Analytical tools can be used to identify what is important to consider for a certain product type or to evaluate the environmental impacts of different design concepts (Baumann & Tillman, 2004). These types of tools can be, e.g., matrixes such as the MET matrix (Brezet & van Hemel, 1997), simplified LCA software (e.g., Sustainable Minds (Sustainable Minds, 2020)), CAD integrated tools (e.g., CAST Tool (Morbidoni et al., 2011)), design for X approaches (Benabdellah et al., 2019), artificial intelligence tools (e.g., Germani et al. (2013)), or environmental management systems adapted for product development (Rossi et al., 2016). The Design for X (DfX) concept was developed to optimize specific product requirements (Rossi et al., 2016). For the purpose of ecodesign, the following DfX concepts are relevant: Design for Disassembly, Design for Remanufacturing, Design for Recycling, and Design for Energy Efficiency (Rossi et al., 2016). In addition, there are many ecodesign methods that have been developed to balance the environmental impact of products with other factors, such as product function, performance, safety and health, cost, marketability and quality, and legal and regulatory requirements (see e.g., Bovea & Pérez-Belis (2012)).

Despite the vast number of ecodesign methods, researchers have reported that the use and development of ecodesign methods have mainly occurred at research institutes and universities, with fewer activities observed from companies (Baumann et al., 2002). A more recent review article by Pigosso et al. (2015) highlighted that although many ecodesign methods and tools exist, they are still not used systematically in the development of new products. Another noted limitation is that ecodesign often lacks complexity and focuses only on environmental problems but disregards problems that cannot be accounted for in life cycle assessments (Ceschin & Gaziulusoy, 2016).

2.3.2 Design for sustainable behaviour

Although ecodesign entails designing with the whole product life cycle in mind, ecodesign often fails to consider how the product design can influence the users and their behaviour during the use-phase to minimize environmental impacts (Boks et al., 2015; Ceschin & Gaziulusoy, 2016). Design for Sustainable Behaviour and Emotionally Durable Design are, therefore, two additional design concepts that aim to influence the use-phase of products. Emotionally Durable Design sets out to strengthen the relationship between user and product to increase the product's lifetime (Ceschin & Gaziulusoy, 2016). Design for Sustainable Behaviour (DfSB), on the other hand, aims to influence the user's behaviour through product design (Niedderer et al., 2014) to reduce the environmental impact (Bhamra et al., 2011).

In Emotionally Durable Design, or Design for Attachment, the idea is to develop an emotional connection between the user and the product. For instance, Mugge (2007) identified four main product meanings as determinants that affect user–product attachment: self-expression, group affiliation, memories, and pleasure (or enjoyment). Such strategies include design that enables product personalization, the design of products that age with dignity, and design that allows the user to capture memories (Ceschin & Gaziulusoy, 2016).

Niedderer et al. (2014) summarized how behaviour can be influenced in four ways that are relevant to DfSB: making it easier for people to adopt a desired behaviour, making it harder for people to perform undesired behaviours, making people want a desired behaviour, and making people not want an undesired behaviour. One way of making it more difficult for people to behave in an undesirable way is error proof design (Lockton et al., 2008), also called "poka-yoke". This involves reducing the potential for mistakes during use, thus reducing wear and tear and ultimately repair and maintenance. This can be achieved by designing in obstacles that prevent errors from occurring and by making it difficult to proceed until an error has been corrected. Also, warnings, such as lights, information displays, and reminders can inform users about errors and the desired behaviour (Lockton et al., 2008).

According to Wever et al. (2008), there are two main approaches to influencing the user to reduce their environmental impacts during the use phase: functionality matching and behaviour adaptation. Functionality matching aims at eliminating the mismatches between delivered functionalities and desired functionalities. Redundant functionalities have an unnecessary impact, while missing functionalities can trigger unwanted behaviour, with subsequent unsustainable effects. The second option is to influence behaviour through eco-feedback, scripting, and forced functionality, in line with (Lilley et al., 2005). With eco-feedback, the user is presented with specific information on the impact of his or her current behaviour; thereafter, it is up the user to relate this information to his or her own behaviour and choose to adapt it or not. With scripting, the product is designed in such a way that the design triggers sustainable usage by either creating obstacles for unsustainable use or by making sustainable behaviour so easy that it can be performed almost without thinking about it (Wever et al., 2008). Forced-functionality instead refers to either intelligent products that adapt automatically to changing circumstances or to designing-in strong obstacles to prevent unsustainable behaviour (ibid).

According to Lilley (2009), the challenge associated with the use of "forced functionality" technologies, particularly automated systems, is that they removes decision making from the user and prevent the users from learning from their behaviour via feedback. Coskun et al. (2015), on the other hand, concluded that there is little evidence that feedback can produce a sustained behavioural change since the strategy fails to engage the user during longer time periods (ibid). This indicates that there is still room for development to assess and ensure the strategy's effectiveness.

Although much research has been conducted in the DfSB field, there are still many limitations. For instance, Coskun et al. (2015) highlighted that there is a lack of a system perspective. One such example is that an LCD screen that is designed to monitor and provide feedback on energy usage may reduce the use of electricity during use, but this boon may be outweighed by the impacts of producing the extra function of the LCD screen (ibid). There are also limitations in the application and testing of existing and developed frameworks and guidelines. In addition, there is a need to investigate when different strategies are most likely to be effective in addressing sustainability depending on particular situations (Coskun et al., 2015; Wever, 2012).

2.3.3 Design for Product Service Systems

Sustainability researchers have argued that if the focus were placed on the final users' needs or the service a user wants instead of the physical product, it would be easier to design "need-fulfilment systems" with lower environmental impact (Tukker, 2015). From this perspective, the concept of product-service systems (PSS) emerged, which can be defined as "*a mix of tangible products and intangible services designed and combined so that they are jointly capable of fulfilling final customer needs*" (Tukker & Tischner, 2006). For example, instead of a car, the function of the car, i.e., mobility, can be offered as a service. With a product-oriented business model, firms have the incentives to sell as many products as possible. However, with service-oriented business models, at least in theory, this incentive shifts (Tukker, 2015). PSS entails a shift from consumption based on the ownership of products to consumption based on access to products' functions (Ceschin & Gaziulusoy, 2016).

Despite the potential for improving the environmental impact of offerings, not all PSSs result in environmentally beneficial solutions (Tukker, 2015). For instance, a shift to a PSS could generate unwanted environmental trade-offs and even rebound effects (Ceschin & Gaziulusoy, 2016). For instance, if a PSS offering entails service personnel carrying out regular service, there is a risk of increasing impacts from transportation, as described in Chun & Lee (2016). A trade-off could also be caused by people treating products that they do not own with less care, which will then lead to premature product failure and thus higher environmental impacts (Tukker, 2015).

2.3.4 Design for a circular economy

Some believe that ecodesign is not enough for a CE and instead advocate that specific design methods for CE are needed. For example, den Hollander et al. (2017) argue that there is a fundamental distinction to be made between ecodesign and circular product design and that circular product design, therefore, requires new or adapted strategies and methods. Similarly, Bocken et al. (2016) stated that "*the new paradigm of a circular economy requires new concepts and tools to describe and support this paradigm".* Moreno et al. (2016), however, argue that the framework of strategies in Bocken et al (2016) is limited since it does not consider "*the wealth of the extant and valuable literature on Design for Sustainability*". Similarly, Bovea & Perez-Belis (2018) acknowledge that design guidelines within ecodesign and Design for X (where X stands for environment, disassembly, reuse, or recycling) can be applied and integrated into frameworks for the design of products in CE.

The framework of Bocken et al. (2016) for the design of circular products builds on work by Stahel (2010) and McDonough & Braungart (2002) and introduces two fundamental and preferable strategies for cycling of materials. Slowing resource loops through the design of durable goods and product-life extensions (e.g., reuse and remanufacturing) and closing resource loops through recycling. These two strategies are distinct from narrowing resource loops (resource efficiency), which aims at using fewer resources per product. However, no concrete design strategies for how resource use can be reduced were mentioned since the paper only focused on the circulation of goods (Bocken et al., 2016). A design framework presented by Mestre & Cooper (2017) also includes strategies for slowing and closing the loops but adds two strategies for the design of bio-inspired loops (biomimetic) and bio-based loops.

Additional circular product design frameworks were recently put forward (Bovea & Perez-Belis, 2018; den Hollander et al., 2017; Moreno et al., 2016). den Hollander et al. (2017) presented a typology for circular product design that contains two main principles, design for product integrity (to avoiding obsolescence[2] of products) and design for recycling. Moreno et al. (2016) instead presented a conceptual framework that builds on Design for Sustainability approaches, resulting in a broader view of design, ranging from the product level (over the whole product life cycle) to more systems-level design, such as design for regenerative systems. Bovea & Perez-Belis (2018) identified design guidelines to meet the circular economy principles and focused on adapting different DfX guidelines. However, these design methods are limited in certain respects. Hollander et al. (2017) and Moreno et al. (2016) provide a limited user perspective beyond emotional durability, and Bovea & Perez-Belis (2018) did not include any strategy to influence the user. Also, den Hollander et al. (2017) and Bovea & Perez-Belis (2018) excluded strategies for improvements in production and upstream. Another limitation is that such design methods provide a ranking order of the design strategies of den Hollander et al. (2017), Bocken et al. (2016), and Moreno et al. (2016), in line with many CE frameworks, e.g., EMF (2013a), Potting et al. (2017) and Ghisellini et al. (2016). However, Bocken et al. (2016) noted that strategies for resource efficiency can be applied in conjunction with recirculation strategies.

Product design together with business model design is considered important when designing for a circular economy (Bocken et al., 2016; Wastling et al., 2018). For instance, when designing for product life extension (e.g., remanufacturing), it has been suggested that adjusting the offer from selling the ownership of a product to a PSS could facilitate the collection of products and the application of circular strategies (Mont & Tukker, 2006; Tukker, 2015). It is also suggested that multiple use life cycles of products can be enabled through circular business models. However, such business models are more complex than traditional ones and require different setups for multiple sets of users (Nußholz, 2017). Thus, new ways of using and owning products in circular business models also require greater emphasis on investigating the different sets of users (Lofthouse & Prendeville, 2018).

2.4 Consumables in a circular economy

This thesis begins from the realization that consumable products have not been as broadly investigated and assessed in the context of CE as durable products, as also previously reported by e.g., Park (2015) and Kuzmina et al. (2019). Few authors explicitly mention that their work neglects consumables in their scope, such as the study by den Hollander et al. (2017), which leaves out single-use consumer goods in their circular product design strategies. More commonly, this delimitation is not mentioned in the paper, and instead it is understood that such content is not valid or applicable for consumable products, e.g., Pozo Arcos et al. (2018). This is also clear from the fact that much of the attention in CE discourse is on strategies such as

[2] A product becomes obsolete if it is no longer considered useful or significant by its user (due to aesthetic, functional, or technical reasons), which leads to the product becoming unused or discharged by the user (den Hollander, 2018).

increasing products' lifetimes (increase durability) or recirculation through different measures such as reusing, repairing, and remanufacturing products (Bakker et al., 2014a; Bakker et al., 2014b; den Hollander et al., 2017; Pozo Arcos et al., 2018).

In this thesis, durable and consumable products are clearly divided into two separated product groups. A similar division was made by Ellen MacArthur Foundation (EMF, 2013a) and Vezzoli (2018); (Vezzoli & Manzini, 2008). EMF states that circularity introduces a strict differentiation between the consumable and durable components of a product (EMF, 2013a). The EMF argues that consumables need to be made of bio-based materials that can be safely returned to the biosphere. An additional strategy suggested for short-lived products is to redesign them into durables (EMF, 2013a). Vezzoli & Manzini (2008) also make a division between consumer goods (*consumables*) and durable goods (*durables*). Consumer goods are further divided into two subcategories in line with this thesis: 1. Goods that are consumed, such as food and washing powder (*dissipative products*), and 2. Throwaway goods, such as packaging, newspaper, and disposable razorblades (*disposable products*). For the former category, Vezzoli & Manzini (2008) suggest to concentrate on minimizing product resource consumption and selecting low impact materials, whereas for the latter category, they propose extending the product's lifespan by making it reusable.

The broad concept of consumables as a product group, as in this thesis[3], is uncommon in the literature. A more commonly used concept is fast moving consumer goods (FMCG), which is defined by market traits rather than the physical product characteristics. There is a certain overlap between the concepts of consumables and FMCG. Both are characterized by mass production, are inexpensive, have a short lifespan, and are bought frequently (EMF, 2013b; Haffmans et al., 2018). The concept of consumables is, however, broader in the sense of considering "non-durables" beyond retail products, e.g., products used also in public and private enterprises, whereas the FMCG concept includes semi-durables, such as fast-fashion, gifts, and gadgets (Haffmans et al., 2018).

Another way in which consumable products are treated in the literature is by studying products belonging to specific product groups or sectors, such as food, beverages, packaging, healthcare products, etc. For instance, in the EMF's report on opportunities for FMCG in CE, (EMF, 2013b), for food, the report mentions the potential for circularity in industrial food processing, where waste is mostly created as a by-product. Instead of placing such waste in landfills or biologically digesting that waste, it could instead be sold as a feed supplement. For packaging, reusable solutions are suggested, and when it is not feasible to install reuse infrastructure,

[3] See the definition on page 2.

recycling is suggested. Likewise, biodegradable packaging is suggested as a solution so that single-use packaging can facilitate the return of bio-based materials to the soil (EMF, 2013b).

There are also some recent academic studies on fast-moving consumer goods and CE (Haffmans et al., 2018; Kuzmina et al., 2019; Stewart & Niero, 2018). Kuzmina et al. (2019) investigated future scenarios for the FMCG sector in a CE and mainly focused on the role of business models and user engagement. De los Rios & Charnley (2017) investigated the new skills that designers require to design products for a CE and provided one example of the household cleaning product Splosh, which aims at minimal environmental impact and extended packaging lifecycles. Haffmans et al. (2018), on the other hand, presented an overview of circular business models and design strategies specific for FMCG with examples from real businesses. A different approach was taken by Stewart & Niero (2018), who reviewed companies' sustainability reports in the FMGC sector to see how they had incorporated the CE concept. The authors found that most companies reported activities related to end-of-life management and sourcing strategies. It was also found that companies, to a lesser extent, reported activity related to circular product design and business model strategies (ibid). Despite these recent efforts to investigate the role of short-lived products in the circular economy, there is a knowledge gap regarding the ways in which different consumable product can be designed to be resource-efficient and circular.

3 Methods

The key methods used in this thesis are presented in this chapter, as summarized in Table 2. Section 3.1 presents details related to the literature review, Section 3.2 describes the methods for developing the design methods, and Section 3.3 presents the method of lifecycle assessment and describes how the method has been used in the appended papers. Detailed information about each method can be found in each respective paper.

Table 2. Overview of the research and methodology of the five papers.

Paper	I	II	III	IV	V
Contribution	Identification of resource efficiency (RE) measures suitability depending on product characteristics and trade-offs	Development of a design guideline tool for resource-efficient products called REDIG	Review of design guidelines for consumables	Assessment of RE measures applied to incontinence products	Development of a design navigator for resource-efficient product service systems, named LFD
Main method	Literature review Development and use of analytical framework (Typology of RE measures, product characteristics and categorisation of studies)	Development of design guidelines and tool based on findings in Paper II Application in the design case of industry Validation of usefulness and usability through a questionnaire and LCA study, respectively	Literature review Analysis with framework (Typology of RE measures and product characteristics)	Comparative life cycle assessment (LCA) study Typology of RE measures to identify possible measures	Development of design navigator based on quality function deployment and LCA Application in design case Verification of design method in an LCA study
Main data source	Academic and grey literature on lifecycle-based assessment studies Reports from Mistra REES companies on lifecycle-based assessment studies	Academic literature on design considerations Case company (meetings and questionnaire) LCA database (Ecoinvent)	Academic and grey literature on design guidelines for RE of consumables	Case company (meetings and documents) LCA database (Ecoinvent)	Workshop Ecoinvent database
Data collection period	2016–2017	2019	2020	2016–2017	2018–2019

3.1 Literature review

Literature reviews are suitable to identify what has been reported previously, thereby allowing for consolidation, building on previous work, summation, avoiding duplication, and identifying omissions or gaps (Grant & Booth, 2009). In this thesis, literature reviews were used in all the papers, but with varying scopes and purposes (see Table 2). Regardless of the type of study, a literature review is needed to motivate and justify the research for both the introduction and the discussion. In Paper IV, on the LCA of incontinence products, a literature review was used for background screening and the verification of results. The latter related the assessment of other products in the healthcare sector with LCA along with their relation to the results obtained in Paper IV. In Paper V, on the design method for PSS, a literature review was carried out to identify service characteristics, i.e., different types of services elements that a PSS solution could consist of. In Paper II, on the REDIG design tool, a literature review was carried out to complement the guidelines with specific design considerations and design theories.

In Paper I, the main purpose of the study was to investigate for which products and under what circumstances different RE measures lead to their intended outcomes. To answer this broad question, a literature review with synthesizing aims (or a literature synthesis according the definition in (Sakao & Neramballi, 2020))[4] was carried out to draw some generalized conclusions. For that purpose, a library of comparative lifecycle-based assessment studies was created. The search for such studies focused on LCA, simplified LCA, or material flow assessment (MFA) for investigating products or services after potentially introducing RE measures compared to a more conventional product system. The focus was given to studies covering typical circular measures such as reuse, repairing, remanufacturing, sharing, etc. To include studies of measures taken in production and in post-use, the collection was complemented with assessment studies of cleaner production efforts and recycling options.

To analyse the library of lifecycle-based case studies, an analytical framework was developed. This framework consisted of three main parts: 1) A typology of physical measures for RE, which can be applied to a product system; 2) a life cycle-based list of characteristics of product systems hypothesized to be of importance for the outcome of RE measures; and 3) a way to describe the assessment studies of RE measures in a comparable and systematic manner. The typology of RE measures was divided into three main parts that distinguished where in the product life cycle the measures could be taken, i.e., *extraction and production*, *use-phase,* and *post use*. The typology draws on existing frameworks in CE (Allwood et al., 2011; EC, 2008; EMF, 2013a; Potting et al., 2017; Stahel, 2010; Stahel & Clift, 2016) and was complemented by definitions found in the literature (of remanufacturing (Sundin, 2004) and functional

[4] Literature synthesis is a process that aims to present insights in a form that can be effectively exploited by users in other disciplines or practitioners but requires more scientific development (Sakao & Neramballi, 2020).

recycling (Graedel et al., 2011; Guinée et al., 1999)). The typology also draws on ecodesign literature (Brezet & van Hemel, 1997; Ceschin & Gaziulusoy, 2016; Luttropp & Brohammer, 2014; Sundin, 2009).

In Paper III, the literature review comprises the central core of the study. This study aimed to identify to what extent general ecodesign and CE design guidelines in the literature apply to consumables. The main criteria for selecting that literature was that the study covered design guidelines or presented design recommendations, design proposals, etc. to improve the product's RE. Improvements in RE were considered to include both the use of natural resources and environmental impacts. Studies that aimed to cover all products (general guidelines), consumables in general, and groups of consumable products were selected. Studies covering only durable products were excluded. The method for analysing the selected literature was characterized by mapping and categorizing. First, the design guidelines and their design recommendations were mapped against the typology of RE measures presented in Paper I (and applied in Paper II) and sorted according to where in the lifecycle the RE measure would take place. The design considerations within the guidelines were also mapped and grouped to identify common denominators. The design considerations were likewise categorized according to what type of consumable they were applicable for, i.e., dissipative, disposable, or specific product groups, such as food or packaging.

3.2 Interview and Questionnaire

Interviews are a common resource for gathering data (Blessing & Charkrabarti, 2009). There are many types of interviews: rigorous ones, such as semi-constructed interviews with open-ended questions that usually require transcription and coding, and less rigorous ones using questionnaires. In this research, the interviews in Paper II predominantly used questionnaires. A questionnaire is an instrument for collecting data that almost always involves asking a given subject to respond to a set of oral or written questions. The purpose of using a questionnaire in Paper II was to gather information about the user of the developed tool and to evaluate the usefulness and usability of that tool. The questionnaire included statements that the designer answered on a scale from "Not important/familiar" to "Extremely important/familiar", as well as open question to obtain more in-depth answers.

3.3 Document analysis

Document analysis is a systematic procedure for reviewing or evaluating documents—both printed and electronic material. Document analysis requires that the data be examined and interpreted to elicit meaning, gain understanding, and develop empirical knowledge (Bowen, 2009). In Paper IV, documents were studied to gather information about incontinence products from the case company. The data covered information and details about the production processes, energy and resource use, material composition of the products, number of manufactured items, and waste and spillage during production. These data were used as input for the life cycle assessment. The case study also involved visiting a nursing home to study how the use of incontinence products could change based on recommendations that were themselves based on measurements of the users' degree of incontinence. A nurse working for the case company provided recommendations that were not processed or analysed but taken as reliable suggestions.

3.4 Methods for developing product design support

In this section, the methods for developing the product design supports in Paper II and V are presented, as these papers focused on the development of new product design supports (Table 2).

Design research is considered to involve the development of understanding (the formulation and validation of models and theories about the phenomenon of design from the perspective of all factors, including people, products, knowledge/methods/tools, and organisation) and the development of support (support based on these models and theories to improve design practice and its outcomes) (Blessing & Charkrabarti, 2009). DRM, which stands for Design Research Methodology, can be used as a systematic method for developing product development methods (Blessing & Charkrabarti, 2009). Developing a design support is carried out through a prescriptive study in line with DRM (ibid). A support can take many different forms (guidelines, checklists, methods, procedures, reorganisation proposal, etc.) and use various media (e.g., paper, software, models, and workshop). A prescriptive study involves the development of a prescriptive support for design based on the insights derived from a background study (to understand a certain design need and provide a sound basis for the support) and identified knowledge gaps and motivations for developing a support. A prescriptive study also entails a plan for the evaluation of the support, i.e., to evaluate whether the developed tool meets the aims and fulfils its purposes, which is usually carried out through a prescriptive study II, according the DRM framework (Blessing & Charkrabarti, 2009).

In Paper II, a design tool named REDIG (Resource Efficient DesIgn Guidelines) was developed. In this paper, the results from Paper I were transformed into a useful and usable tool for design purposes. The process of moving from results of Paper I towards a design guideline tool consisted of several steps. The first step was to develop the results (i.e., what key product characteristics were decisive to the outcomes of which RE measures and what trade-offs connected to those measures exist under what circumstances) into the general guidelines presented in Tillman et al. (2020b). The second step focused on the general guidelines for design aspects. This was done by adding design considerations from design guidelines mainly found in the design for X literature (see Table A5 in Appendix A in Paper II) to the recommended measures. This was conducted to add concrete examples of how these measures could be achieved through different design considerations. The third step was to operationalize the guidelines into a useful tool. This was done by involving an industrial designer from a company in the transport sector. From that collaboration, it was determined what type of design support would be of interest to the designer. This was used together with general user requirements on design tools, derived from a requirement list by Brambila-Macias et al. (2018), to develop a useful and usable tool. The designer was also involved in the test and evaluation of the developed tool to redesign a certain component.

Another design method was developed and presented in Paper V—a generic design navigator named Lifecycle-oriented Function Deployment (LFD) to help companies design PSS with comparatively less of an environmental impact than an existing industrial offering. This design builds upon earlier works with a combination of Quality Function Deployment (QFD) for a product and LCA (Sakao, 2007), as well as QFD for PSS (Sakao et al., 2009). In short, QFD is a method for integrating customers' requirements into product design by translating their demands into design targets and quality assurance points (Akao, 1990). QFD was adopted because it enables the translation of various requirements into design characteristics and components in a systematic manner (Fargnoli and Sakao, 2017) and because it is one of the most widely used methods in industry (Booker, 2012). Design requirements in this research refer to certain aspects of the offering that need to be addressed during redesign from the perspective of the customer and the environment. The customer requirements are taken from market research where customers' and users' needs and expectations are collected. The requirements are thereafter rated according to their importance and market research. The environmental requirements, on the other hand, are taken from an LCA study conducted on the product system to be redesigned into a PSS offering. The environmental requirements and their relative importance were derived from the results of the LCA-study, filtered using different weighting methods. A weighting method can aid in identifying the environmental impacts (and thus environmental requirements) of most importance to the product system by weighting all the scores of all the impact categories into a single score. By using several weighting methods, different principles for valuing the environment are considered for the environmental impact categories. The developed support was also evaluated through the application of the LFD together with the staff at the collaborating company.

3.5 Life cycle assessment

This section highlights the main method for the analysis and validation of the studies included in this thesis, namely, life cycle assessment (LCA), (Table 2). LCA is a structured, comprehensive, and internationally standardised method that quantifies all flows, i.e., resources consumed, and emissions generated in association with a product's life cycle (ILCD, 2010). As shown in Figure 3, LCA includes all phases (processes) of the product's life cycle, from the extraction of raw material, to production and use, to the recycling and disposal of the remaining waste. All processes require inputs such as materials and energy. When these inputs are processed into products, the process also generates output such as solid wastes and emissions into the atmosphere and water.

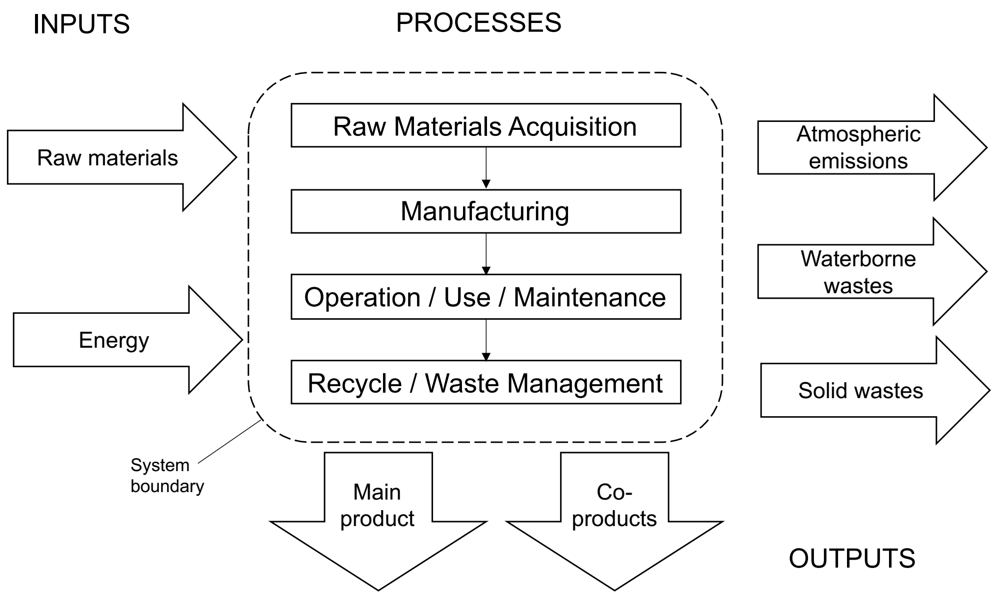

Figure 3. Model of the inputs and the outputs of the processes for a product's lifecycle; from raw materials acquisition to waste management, from (Fedkin, 2020).

An LCA study consists of four main stages: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation (see Figure 4 (ISO 14040, 1997)). The methodology for conducting an LCA will only be briefly described here; for further explanations, please see Baumann & Tillman (2004) and ISO 14040. As Figure 4 indicates, LCA is an iterative process, and some of the earlier decisions for the study may be changed later in the process.

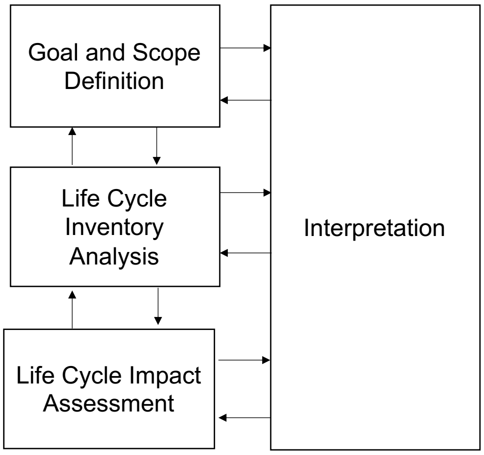

Figure 4. Phases of an life cycle assessment according to ISO 14140 (ISO 14040, 1997).

The *goal and scope* define the goal of the study, the intended application, the reason for carrying out the study, and to whom the results will be communicated. In this step, defining the functional unit is central. The functional unit is the reference unit to which all flows are related. It also service as the basis for comparison, e.g., by comparing different scenarios in the same study. Another important decision is the system boundaries, which decide the processes to be included in the study related to the boundaries between the technological system and nature, geographical boundaries, time perspective, and the boundaries between the life cycle of the product studied and related life cycles (Tillman et al., 1994). The data requirements, allocation (i.e., partition of environmental impact between multiple process inputs or outputs), and impact categories to be considered in the study are also decided upon in the goal and scope (Baumann & Tillman, 2004). Depending on the purpose for conducting the LCA, studies are generally divided into two types: attributional and consequential. Attributional studies are broadly used to create awareness and produce information on the potential environmental impacts from a product system. According to Curran et al. (2005), attributional LCA attempts to answer "how are things (pollutants, resources, and exchanges among processes) flowing within the chosen temporal window?'', whereas consequential attempt to answer ''how will flows change in response to decisions?". Consequential LCAs are thus change-oriented and investigate the implications of initiating a change in the product system.

Inventory analysis is the second stage in the LCA. Here, the studied system data are modelled according to the defined scope. The inventory model can be seen as an incomplete mass and energy balance over the system that only includes flows relevant to the environment. This section includes setting up a flow chart according to the system boundaries, data collection for all activities with input and output flows, and calculation of the environmental loads of the system in relation to the functional unit (Baumann & Tillman, 2004).

The third main stage in the LCA is the impact assessment, which is intended to describe the environmental consequences of the environmental loads quantified in the inventory analysis.

This is done via a two-step procedure. The first step (classification) involves assigning all flows of the inventory, such as resource consumption and emissions into air or water, to their relevant impact categories according to their ability to contribute to different environmental problems. In the second step (characterization), the amount of each flow assigned to an impact category is multiplied with a so called characterization factor (Hauschild & Huijbregts, 2015), which is an quantitative representation of a flow's importance for a specific impact category. In this way, a total score of how much the product's life cycle contributes to an environmental problem is obtained, such as the effects on global warming, acidification, and eutrophication.

Another possible, and optional, step in impact assessment is weighting. To do so, the result is aggregated using weighing methods. This enables one to aggregate various environmental impacts to facilitate the interpretation of environmental information and the impact assessment results (Itsubo et al., 2015). Different weighting methods are built on different principles for valuing the environment and thus give different weights to different environmental impact categories. For example, the EPS method (Steen, 1999) is based on a willingness to pay, whereas the ReCiPe (Goedkoop et al., 2009) weighting factors derive from the judgment of an expert panel. An additional principle is the distance to politically set targets, which are operationalised, for example, in the EDIP method (Hauschild and Potting, 2015).

The last stage involves interpreting and presenting the results. In ISO 14040, the stage is defined "the phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are combined consistent with the defined goal and scope to reach conclusions and recommendations" (ISO 14040, 1997).

In this thesis, LCA is used in four out of five studies. In the synthesis of lifecycle-based assessment studies in Paper I, no LCA study was carried out. Instead, the data upon which the study was based consisted of LCA studies and other lifecycle-based assessment studies. In the study presenting the REDIG tool (Paper II), the LCA was used to evaluate the developed design guideline tool by conducting a comparative LCA study. This process involved investigating the impact assessment results of the initial product system and the results from the new product system after using the developed design support. Information about the current and redesigned product concepts was gathered from the company that carried out the design case.

In the study on incontinence products (Paper IV), LCA was used to assess the implications of different RE measures applied to incontinence products from a current time perspective. The LCA was performed with data and knowledge support from an incontinence product manufacturing company, and product-specific data was used when possible. This collaboration enabled the development of relevant and realistic scenarios, resulting in the investigation of four different possible ways of improving the RE of incontinence products with current technology. Two different weighting methods were used as a means for filtration, to identify what the most relevant impact categories were for the product system.

In Paper V (on the LFD design navigator), an LCA study was used as both input data to the developed PSS design support and as a method to evaluate the developed design support in a case study for incontinence products via a comparative LCA study. This study was conducted in collaboration with the manufacturing company. To do this study, the LCA from Paper IV was used in two ways. First, the original study was used to provide input data about what environmental impacts dominated the product system and where in the product life cycle those impacts occurred. The inventory data from Paper IV were also used when evaluating the redesigned offering.

4 Results

This chapter presents the key findings of the research. In line with the research questions, this chapter begins by identifying which product characteristics are relevant for the suitability and outcomes of the RE measures. Next, the identified product characteristics and RE measures are further developed into a product design guideline tool. Lastly, the findings from a review of design guidelines for consumables are presented, followed by identifying which RE measures are suitable for the different types of consumables.

4.1 What product characteristics are relevant for the outcome of the resource efficiency measures?

A list of product characteristics hypothesized to be of relevance for RE was developed in Paper I. As shown in Table 3, these product characteristics cover use aspects, product complexity, possibility to disassemble, content of concern, and system perspectives.

Table 3. List of product system characteristics believed to be relevant for RE, adapted from Paper I.

Type of characteristic	Product characteristic

Use aspects	Consumable
	  Disposable
	  Dissipative
	Durable
	  Technical lifetime
	  Intensity of use
	  Frequency of use
	  Requires auxiliary material or energy during use phase
	  Maintenance needs of product/service
	  Need for auxiliary components during maintenance
	Environmental relevance of user behaviour

Complexity	Number of components in product Number of materials in product
Possibility to disassemble	for remanufacturing/repair/upgrading for recycling
Content of concern	Scarce materials Hazardous substances
System characteristics	Dominant life cycle phase Industry Development pace in terms of efficiency, functionality, and appearance

* Active products use energy and/or auxiliary materials in the use phase, whereas passive products do not.

In addition to the list of product characteristics, a typology of physical RE measures was developed (see Table 4). These cover all physical measures that were considered to influence the RE of a product during extraction and production, during the use of the product, while extending the use of the product, and, finally, in the post-use phase.

Table 4. Description of RE measures adapted from (Paper I).

Life cycle phase	Resource efficiency measures	Description
Extraction and production	Reduce losses in production	Reducing losses in production involves reducing losses of both material and energy in production, e.g., by re-introducing scrap and energy flows into the production process.
	Reduce material quantity in product	Reducing material quantity in a product means reducing the material in the product without material substitution.
	Change material in product	Changing materials in a product can be done by, e.g., substituting fossil-based material and hazardous, scarce or critical, or primary materials for less environmentally burdensome materials.
Use	Use effectively	Using a product effectively means ensuring that the appropriate function is provided for the user's needs, as well as reducing losses during use.
	Reduce use of auxiliary materials and energy	This means reducing the resource consumption of either the energy or auxiliary materials in the use-phase.
	Share	Sharing a product means that a product is used by several users regularly through, e.g., a product-pool, a library, or a renting service.
	Use more of the technical lifetime	Using more of the technical lifetime means using more of an existing product either by the same user or a new one (denoted as reuse).
	Increase technical lifetime (by design)	Increasing the technical lifetime by design means redesigning a product to last longer.
	Shift to multiple use	Shifting to a multiple use product means that a single-use product is redesigned as a multiple-use (reusable) product.
	Maintain	Maintenance involves activities where products are inspected, maintained, and protected before breakdown or other problems occur.
	Repair	Repair takes place after the wear, malfunction, or failure of a product.
	Remanufacture	This is the process of restoring a non-functional product to a functional state (as good as new or better) through disassembly, repair/ exchange of components, re-assembly, and quality assurance.
	Repurpose	Repurposing means reusing a product with a different function than the original design.
Post-use	Recycle material	Recycling restores materials and returns them to use.
	Digest anaerobically/ Compost	Digesting anaerobically means digesting biodegradable materials without oxygen to generate biogas and digesting material that can be used as fertilizers. Compost is an aerobic digestion process that digests organic materials and generates a soil enhancer.
	Recover energy	Recovering energy involves the combustion of materials (incineration) with energy recovery (electricity and heat).
	Treat wastewater	Wastewater treatment handles waste collected via sewers and sometimes recovers energy and plant nutrients
	Landfill with control	Landfilling of discarded products with gas collection for energy recovery

Based on the synthesis of the assessment studies of many RE measures applied to diverse products, it was possible to distinguish which product characteristics were significant for the application and outcome of different RE measures. A main distinction made was between durable and consumable products (Figure 5). For *consumable products*, the suitability of RE measures can further distinguish between whether the product is used in a dissipative manner (e.g., food) or is a disposable product (e.g., a diaper). Durable products, on the other hand, can be further distinguished based on five characteristics. The first type of durables is *active products*, which means that such products use energy or other auxiliary materials during their use phase, such as a car or a fridge. The second type is products that are *typically used for their full technical lifetime*, such as furniture. The third type are products that are *typically discarded before being worn out*, such as clothes. The fourth category includes products that are *used infrequently and discarded before being worn out,* such as consumer tools. The last product characteristics of importance for the suitability of RE measures includes products whose *functionality remains after end of use*, such as a worn-out electrical car battery. It is worth noting that a durable product can, and usually does, have more than one relevant product characteristic, e.g., an *active product* can also be *used infrequently and discarded before being worn out.*

Typology of RE measures	**Key product characteristics**	**Consumable**		**Durable**					**Potential trade-offs**
		Used in dissipative manner	Disposable	Active	Typically used for full technical life-time, active and passive	Typically discarded before being worn out, active and passive	Infrequently used and typi-cally discarded before worn out, active and passive	Part of function remains at end of use, active and passive	
Extraction and production	*Reduce losses in production*	All products can be produced more efficiently							a)
	Reduce material quantity in product without material substitution								b)
	Change material in product								c)
Use phase - use effectively and efficiently	*Use effectively*								d) + e)
	Reduce use of auxiliary materials and energy (use efficiently)								f)
	Share								g)
Use phase - extend use	*Use more of technical lifetime (incl reuse)*								h) + i)
	Increase technical lifetime by design								h) + i) + j)
	Shift to multiple use								h) + i) + k)
	Maintain								h) + i) + l) + m)
	Repair								h) + i) + l) + m)
	Remanufacture								h) + i) + l) + m)
	Repurpose								h) + i)
Post use	*Recycle material*								i) + n)
	Digest anaerobically or compost	Not analysed in present study							
	Recover energy								
	Treat waste water								
	Landfill and control								

a) Reduced production losses <=> energy use for avoiding losses
b) Risk for losing function, e.g. durability
c) Risk for burden shifting when substituting materials
d) No identified trade-offs, except: chemicals with higher functionality vs risk of more hazardous constituents
e) No identified trade-offs, except: reduced use phase impact <=> production of sensors (when required)
f) Reduced use-phase impacts <=> Increased production impacts
g) Sharing can increase car transportation for users accessing the shared stock
h) Use-phase efficiency <=> benefits of use extension (for active products with technological development towards use-phase efficiency)
i) Risk for keeping hazardous substances in circulation
j) Durability <=> Amount (or impact) of materials
k) Benefits of multiple use <=> increased impact from production and
l) Maintenance can increase transportation
m) Design for disassembly can increase material use
n) Impacts from recycling need to be smaller than impacts from primary

Figure 5. The product characteristics for which each measure in the typology is suitable (coloured tiles in the centre of the figure), as well as the potential associated trade-offs (indexed alphabetically to the right).

4.2 How can the suitability of RE measures to products with different characteristics be used to formulate guidelines for the design of resource efficient products?

In Paper II, the suitability of RE measures for products with different characteristics was developed into design guidelines. To operationalize these guidelines into a usable tool, the identified product characteristics were structured as a question tree to help the user identify the characteristics relevant to their product and thus guide them toward suitable design recommendations (Figure 6). In addition to the product characteristics which were identified in Paper I to determine which measures are suitable, measures in the production and post-use phase were not dependent on the product characteristics and were, therefore, treated separately (Figure 7). However, solely describing the relevant measures for RE (activities aimed at improving RE) was not considered sufficient for product design purposes. To be useful in a product development process, concrete design considerations (how the measure can be practically implemented during design) were needed. In ecodesign (and especially within the different designs for X design guidelines), there are many concrete examples of how different RE measures can be achieved through design, e.g., by using few or uniform materials (locating the same materials together) to enable recycling. Such considerations where added and customized in the developed design guideline tool named REDIG.

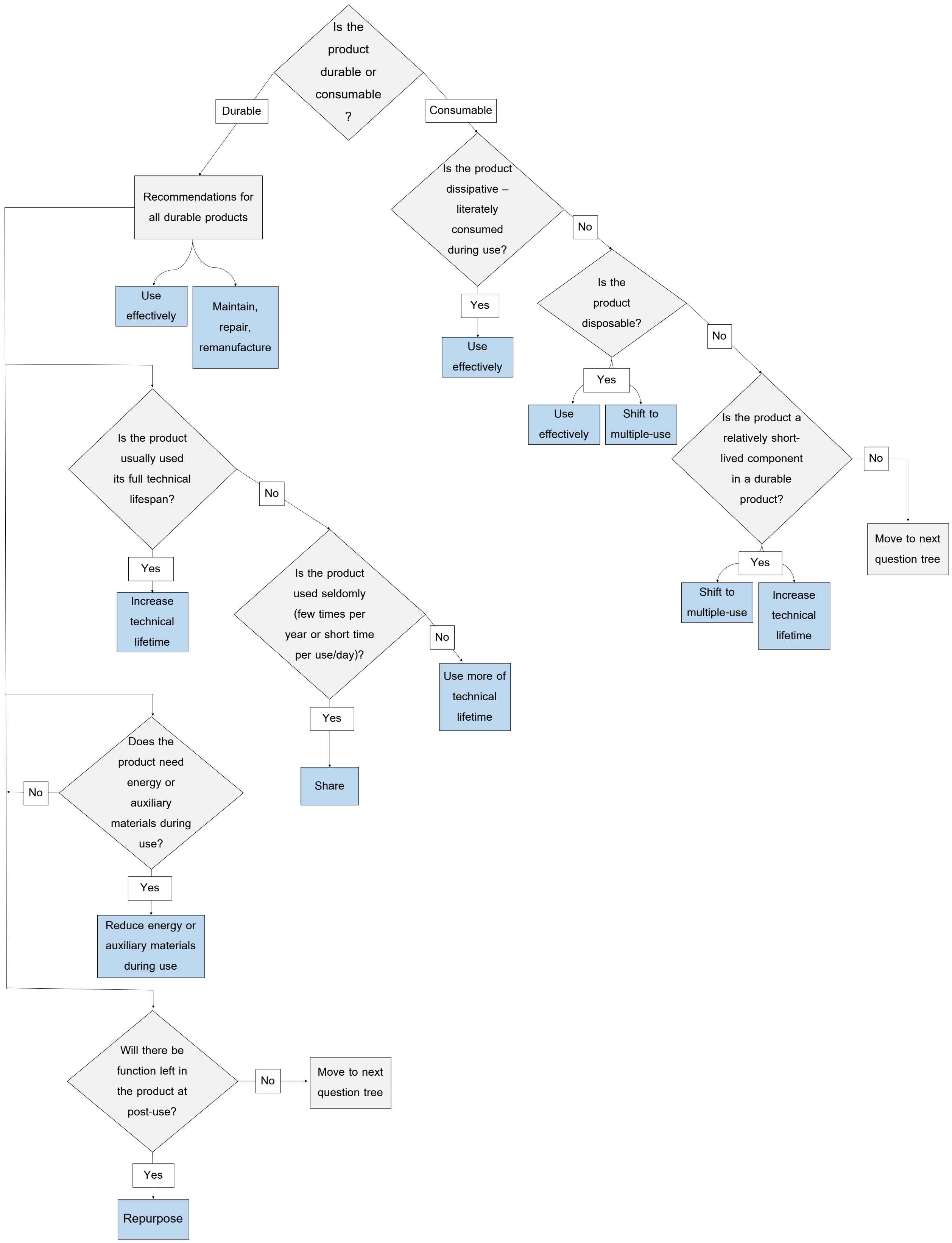

Figure 6. Guideline question tree for product specific guidelines. Note that several product characteristics can be relevant for a durable product; hence, the entire question tree must be viewed (Paper II).

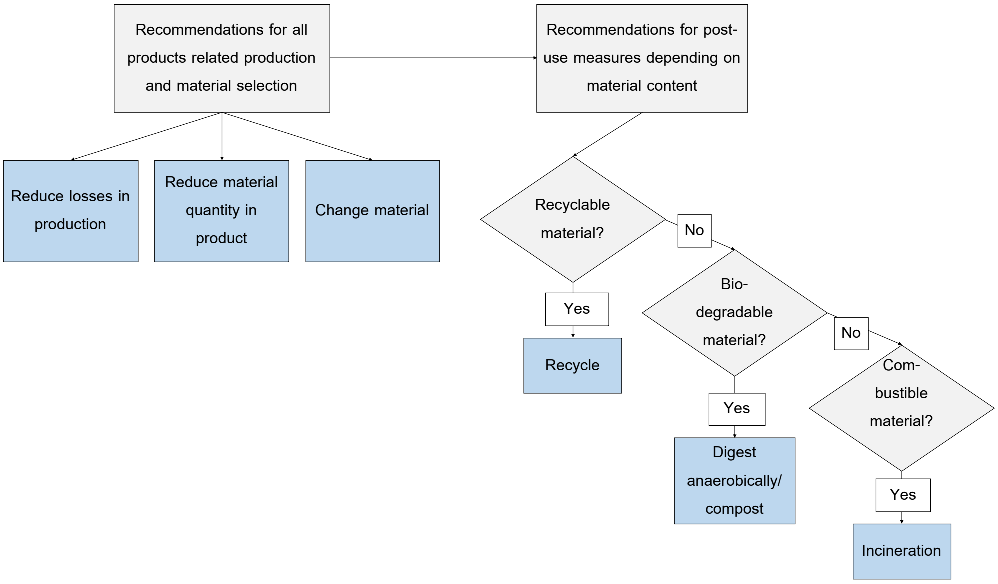

Figure 7. Guideline question tree for all products (Paper II).

The two guideline question trees (Figure 7 & 8) enable the designer to identify relevant product characteristics by clinking on the blue boxes, which then direct them to the appropriate design guidelines. Note that the designer may need to go back to both trees additional times to identify several relevant design guidelines. These design guidelines can be found in the Appendix A of Paper II and are structured as follows: product characteristics, example of a product, the recommended design/RE measure, and an example of a recommended measure of relevance for the product's characteristics. Thereafter, environmental trade-offs are presented in relation to the measure, and then relevant design considerations are described in relation to the measure. These considerations are both preconditions for and enablers of the measure. The guidelines are divided into four parts: Guidelines for durable products (these include general guidelines for the use phase of both durable products and products with specific characteristics), guidelines for consumable products (these include design recommendation related the use-phase for each specific product characteristic), guidelines for all products (design recommendations that are relevant to all products in terms of material selection and production), and, lastly, guidelines for post-use measures, which present design recommendation on how the product should be treated in post-use, regardless of the product type and instead depending on the material content in the product.

4.3 What guidelines exist for the design of resource efficient consumables?

In Paper III, a literature review was conducted to identify to what extent existing general product design guidelines are applicable to consumables. The identified literature was structured according to where in the life cycle the design guidelines applied according to the typology of the RE measures in Paper I. In addition, it was identified whether the literature stems from the ecodesign field or the CE field.

To outline to what extent the reviewed literature contributed design recommendations for different types of consumables, Table 5 was created. The percentage design considerations of relevance for each type of product were calculated in relation to the total number of design considerations under each reviewed guideline. These percentages can only be seen as a proxy indicator on how well covered the different consumable product types were in a particular guideline. As expected, the percentage of relevant design considerations was the lowest for dissipative consumables and the highest for disposable products turned into reusable ones. It is also clear from Table 5 that, on average, fewer design considerations applicable to the different types of consumables can be found in the CE literature.

Table 5. List of reviewed general product design guidelines together with their percentage design considerations relevant to each consumable type (Paper III).

Source	Percentage relevant for dissipative consumables	Percentage relevant for disposable consumables	Percentage relevant for disposables made reusable
Ecodesign			
Brezet & van Hemel (1997)	33%	64%	73%
Lewis et al. (2001)	33%	75%	87%
Wimmer et al. (2004)	50%	54%	71%
Telenko et al. (2016)	32%	51%	66%
Luttropp & Brohammer (2014)	46%	71%	77%
Vezzoli (2018)	36%	50%	64%
Average	38%	61%	73%
Circular product design			
Van Den Berg & Bakker (2015)	0 %	7 %	31%
Moreno et al (2016)	50%	62%	80%
Bocken et al. (2016)	27%	36%	64%
Haffmans et al. (2018)	32%	44%	52%
Bovea & Perez-Belis (2018)	0%	19%	47%
Willskytt & Brambila-Macias (2020)	41%	50%	59%
Shahbazi & Jönbrink (2020)	40%	40%	74%
Average	27%	37%	58%
Total average	33 %	49 %	66%

As expected based on the work in Paper II, the design considerations related to the production, material selection, and reduction of material quantity in products, the applicability to dissipative versus disposable products were similar (Table 4 in Paper III). However, structural product changes are mainly applicable to disposables, while only dissipative products can be made into concentrates. Moreover, it was also clear that the literature from the ecodesign field provides more detailed insights into how design can improve production and reduce the amount of material in products. For material selection, the avoidance of hazardous materials was mentioned to a greater extent in the literature from the ecodesign field, whereas the use of biodegradable materials was more common in the CE literature. Further, while all ecodesign literature provided design suggestions related to production to some degree, there was less of a contribution from the CE literature. For instance, van den Berg & Bakker (2015) and Bovea & Perez-Belis (2018) each only provided one design suggestion for this lifecycle part.

Among the design considerations for the use-phase (Table 5 in Paper III), there were fewer design considerations for improving resource efficiency than at the production stage. The design considerations were also found to be similarly appreciable to those of dissipative and disposable products. There were also few concrete design considerations mentioned in the CE literature (except for those in Paper II) in comparison with ecodesign, where Brezet & van Hemel (1997) and Telenko et al. (2016) contributed the largest number of relevant design considerations. Moreover, even though design considerations to reduce impacts during use largely involve design for sustainable behavior (DfSB) strategies, few of the guidelines mention DfSB as a design concept. In the CE literature, DfSB is addressed only in Paper II, and in the ecodesign literature, it is mentioned as a design concept by Vezzoli (2018).

There are several considerations during design that can reduce the impacts of transportation (Table 7 in Paper III). These design suggestions were applicable to the same degree for dissipative and disposable products. However, the review revealed that transport-related design considerations are omitted in most of the CE literature but are included to a greater extent in the ecodesign literature.

Of the design guidelines applicable for post-use, significantly fewer design considerations are suitable for dissipative products than for disposable ones (Table 8 in Paper III). This is unsurprising, since dissipative products are not intact after use. Many, if not most, dissipative products end up in wastewater treatment. The packaging of dissipative products, as well as other disposables, on the other hand, still exists as a distinct object after use, which makes such products possible to be treated in more ways. Moreover, there is a similar coverage of design considerations for post-use treatments in the CE and ecodesign literature. However, more material-specific recycling considerations seem to be provided in the ecodesign literature.

Design considerations of relevance when redesigning disposable products into reusable and durable ones were also identified among the design guidelines (Table 6 in Paper III). Reusable product designs are generally advocated over disposable ones in CE literature. Nevertheless, the CE literature did not provide more concrete recommendations for the design of reusable product systems. However, the CE literature provided more insights into emotionally durable design, whereas the ecodesign literature provided more examples on how to design maintenance systems.

4.3.1 Transferability of design guidelines

The literature review of design guidelines in Paper III also includes an analysis of product-type specific design guidelines for different types of consumables. This was done to explore which design considerations are suggested for different consumables and to determine if any considerations are transferable to other design guidelines for other consumable groups. From this analysis, it was found that several aspects determine the transferability of design considerations to other consumables.

The first aspect that seems to be relevant is the *product characteristics,* i.e., whether the product is *dissipative* or *disposable*. At a general level, design considerations for products with the same product characteristic are possible to transfer between guidelines for different product groups. However, there are some additional aspects that inhibit or enable transferability.

For dissipative products, the *shelf life* and the *use time* (the time from the product is opened until it deteriorates) of the product can differ. For instance, products can be perishable (milk), persistent (soap) or something in-between (facial sunscreen). This means that while some products may have a long shelf life they need to be consumed quickly once opened while others can last longer in an opened packaging. Design considerations are possible to transfer between products with a similar degree of required packaging protection and shelf life, for instance, preserved food and cosmetics products. Also, dissipative products with similar *rheological properties* can share design consideration. For example, viscosity determine what type of packaging shape is suitable.

The second aspect is connected to the type of *function* that the product delivers. This can be especially important for disposable products and serve as a limiting aspect. For instance, whether the function is to protect and provide hygienical care (e.g., a diaper) or to protect and avoid damage to other products (e.g., a packaging), there could be very different design considerations of relevance. For products with similar functions, design considerations could be transferable.

The third aspect of relevance is *who handles* the product, as the actor who handles the product can also differ (e.g., the user, service personnel, or caregiver). For products used by similar actors, design considerations related to how the handling should be designed can be assumed to be transferable.

The last aspect of relevance that may function as a limiting aspect on what design considerations are possible is the *legal requirements* of the product. For instance, whether the product comes into contact with food (EC, 2004), whether it is a medical device (EC, 2017), and/or how the product should be treated at end of life according to the waste directive (EC, 2008). Therefore, seemingly different products, such as food, and medical products, could provide more insight into how they can be designed since they have high hygiene requirements that limit their possibilities for reuse and recycling. For instance, Gaasbeek (2018) suggests that similar to the EU regulations for recycled plastic for food contact (EC, 2014), the possibility to set-up strict legislation for using recycled paper in absorbing hygiene products could be investigated.

4.4 What RE measures can be applied to consumables?

In Section 4.1, Figure 5 showed the RE measures suitability to the identified key product characteristics in Paper I. In this section, the RE measures especially applicable to the three different types of consumables, i.e., dissipative, disposable, or a short-lived component in durable products (Paper II), are presented.

For dissipative products (i.e., those that are literarily consumed during use), all measures in the production phase (*reducing losses in production, reducing material quantity in product,* and *changing material in product)* are deemed applicable. The only measures in the use-phase that is suitable is *use effectively.* For dissipative products, this measure can involve delivering/acquiring only the needed functions, avoiding losses during use (e.g., smart dispensing), using the products for their intended purpose, and increasing functionality to improve system efficiency (e.g., detergents that allow for a lower washing temperature and fuel additives that increase engine efficiency). Due to the nature of dissipative products, their constituent materials are not intact after use. For this reason, material recycling is not possible, although, e.g., nutrients can be recycled, and energy can be recovered. *Digesting anaerobically or composting* is possible for food products that have not been consumed. Many of the dissipative products end up in the sewage system after being used. For this reason, *treating wastewater* is a suitable measure, which often includes anaerobic digestion. Moreover, many dissipative products do not consist entirely of dissipative products, as they often come in disposable packaging to which other measure apply.

For disposable products, all measures in the production phase are deemed applicable. In addition to the measure *use effectively* in the use-phase*, shifting to multiple-uses* is possible. Moreover, the shift to multiple-use measure allows the product to be made more durable, which also requires measures of relevance for durable products, such as *maintaining* (design of maintenance system) and *reducing the use of auxiliary materials and energy,* for reducing the impacts from maintenance. All post-use measures can be considered applicable and of relevance depending on the material content, i.e., *recycling material, digesting anaerobically or composting, recovering energy, treating wastewater,* and *landfilling and control*.

For short-lived components in durables (such as different filters and disposable batteries), all measures in the production phase are possible. For measures in the use-phase, there are two possibilities. Firstly, *shifting to multiple-use* and maintaining the resulting reusable product and reducing its use of auxiliary materials are of relevance. Secondly, *increasing the technical lifespan* can, in some cases, be possible. In post-use, essentially all measures except for *treat wastewater* are suitable.

4.4.1 Environmental assessment of RE measures applied to consumables

In this research, the potential environmental improvements of two different consumables were assessed via LCA. In Paper II, the developed design tool REDIG was used to redesign an air filter, which is classified as a short-lived component in a durable. Two design changes were suggested based on the use of the tool: changing from fossil-based to bio-based materials (polylactic acid (PLA)) and prolonging the lifespan of the product, which was assessed by LCA. The result from the impact assessment[5] showed a decrease in most of the environmental impact categories (Figure 8) under both design changes. It was also clear that combining design changes led to the greatest improvement. Among the impact categories, ozone depletion followed by fossil depletion and climate change had the most significant improvements. This was mainly due to the shift to bio-based plastic.

[5] The 2008 version of the ReCiPe midpoint with a hierarchist perspective was used for the impact assessment (Goedkoop et al., 2009).

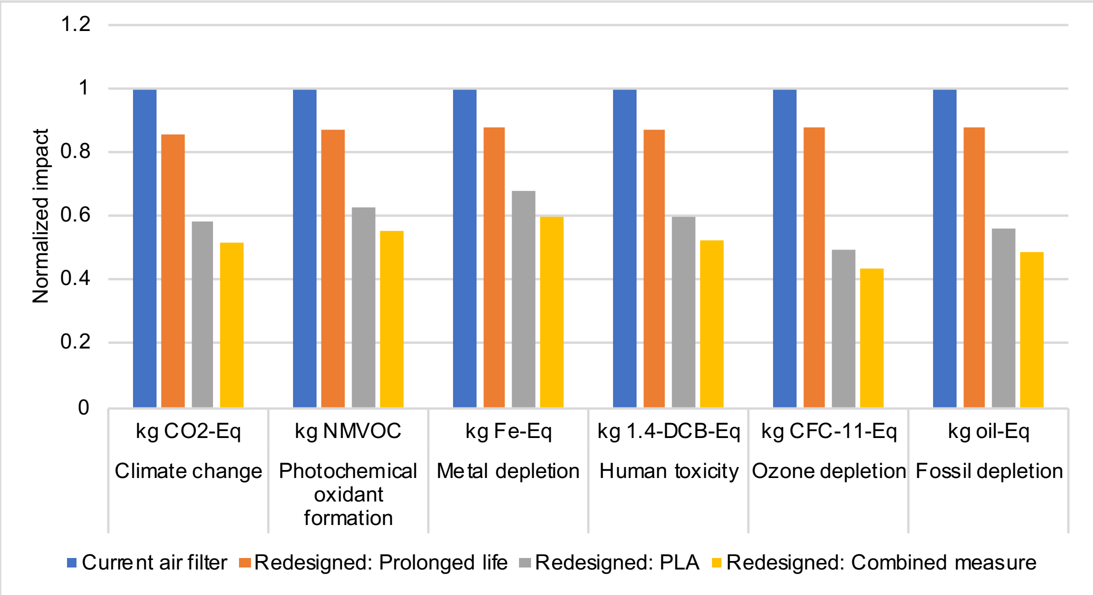

Figure 8. Impact assessment results for the current air filter compared to the redesigned air filter with combinations of measures that lead to a lower impact (Paper II).

When changing the material content in a product, the impact increased for some other impact categories, i.e., water depletion and terrestrial toxicity, as shown in Figure 9. The agricultural activities related to the production of corn for the bio-based material PLA were the cause of the increased impact of these categories.

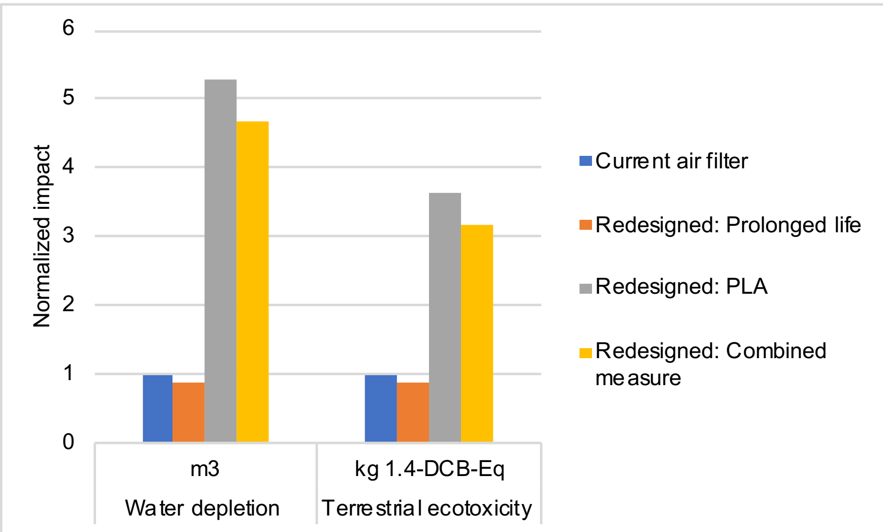

Figure 9. Impact assessment results for the current air filter compared to the redesigned air filter with combinations of measures that lead to a greater impact (Paper II).

In Paper IV, the potential of improving the resource efficiency of incontinence products (*disposable*) through four RE measures was assessed: *Reducing losses in production*, which entailed the internal recycling of production waste instead of incineration; *Changing material*, which meant reducing the share of fossil-based materials and increasing the share of bio-based materials in the product; *Shifting to a multiple-use product*, involving a partly reusable product system compared to a disposable product that provides the same product function; and *Effective use*, which was achieved by measuring the urinary leakage among one ward of patients in an elderly home to provide recommendations on what products to use, customized to each patient. This was compared to the products initially used before measurements were conducted.

Figure 10 shows the LCA results, expressed as ReCiPe single scores for the four different measures. This method ranked the "effective use" measure as the most promising, decreasing the impact by 20%. The measure to reuse part of the product was found to be the next most promising, with an improvement potential of 17%. The improvement potential from the recycling of production waste was 6%, while the improvement potential from changing to a larger fraction of bio-based material was smaller at only 4%. This can be explained by the fact that ReCiPe weighs land-use impacts as worse than fossil-related impacts.

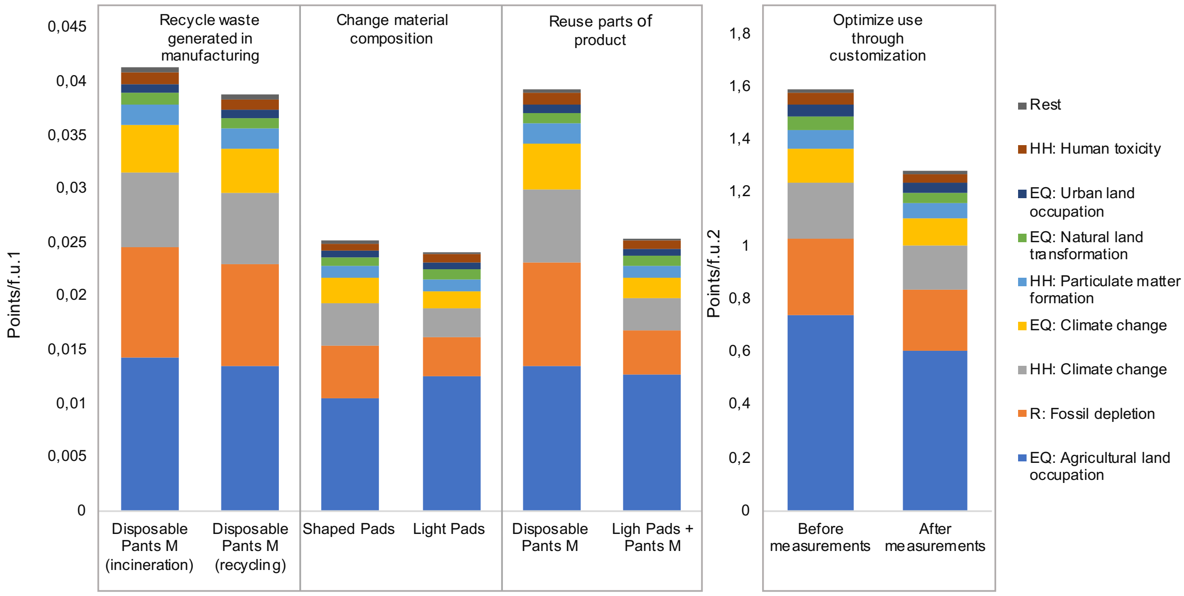

Figure 10. ReCiPe single score results for the products used in the first three investigated measures to the left (with the functional unit "hygiene function of one absorbent product") and products used in the fourth measure (effective use through customization) to the right (with the functional unit "hygiene function for one day at the studied ward in an elderly home"). EQ is Ecosystem quality, R is Resources, and HH is Human Health (Paper IV).

In Paper V, the design navigator LFD was developed to redesign products into PSS, used, and assessed with an LCA study. The use of the design navigator suggested changing the material content by reducing the share of fossil-based material and increasing the share of bio-based material. In addition, the design change "use effectively" was suggested, which entailed a measurement service that aimed at matching users with the appropriate products (products with the right size and the right absorption capacity). Figure 11 shows the LCA result for the redesigned offering (RO) compared to the existing offering (EO). For global warming potential (GWP) and fossil resource depletion (FRD), the impacts seem to have decreased by almost 20% for the redesigned offering. The impact on land use, however, was unchanged. This can be explained by the measurement service resulting in the use of less functional products, which reduced the material usage and entailed a higher proportion of bio-based materials in the product redesign. Consequently, the combinations meant that the overall use of renewable material (which is a major contributor to the land use impact category) was ultimately unchanged between the two offerings.

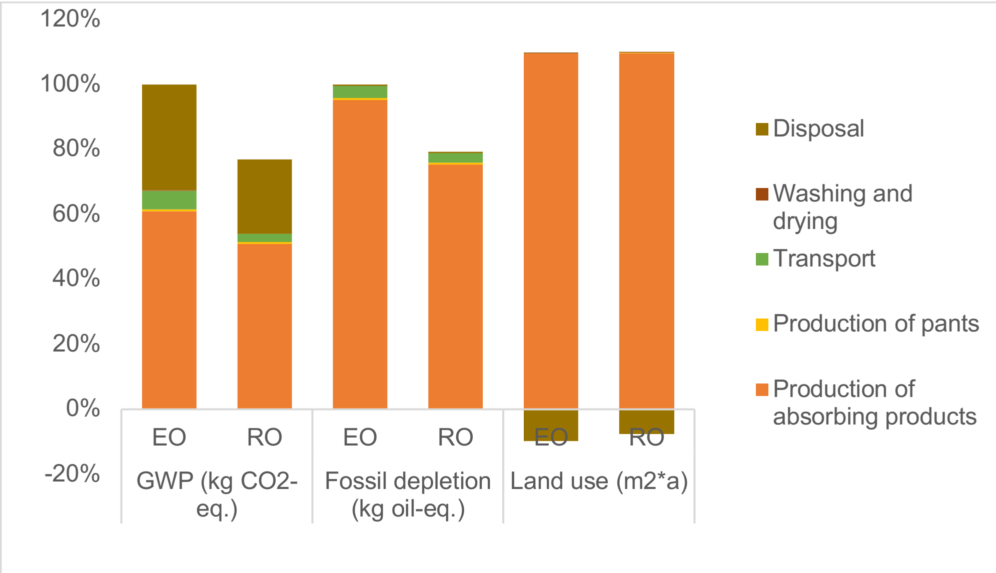

Figure 11. Normalized impact assessment result for the selected impact categories of global warming potential, fossil depletion, and land use for RO (redesigned offering) compared with EO (existing offering) (Paper V).

4.4.2 Environmental and resource use trade-offs for different RE measures of consumables

In this thesis, trade-offs, meaning when a sacrifice is made in one area to obtain benefits in another (Byggeth & Hochschorner, 2006), involves environmental and resource use in relation to different design considerations and RE measures. This phenomenon is also called “burden-shifting” or “problem shifting” in the literature (McAloone & Pigosso, 2018). One general example is that a measure aimed at improving the use phase of a product could lead to increased environmental impacts in the production phase or post-use phase. Another example is when substituting a material to a more environmentally benign one, the new material could lead to another environmental impact. It is thus important to be aware of these potential trade-offs when designing products and also during business model development and policies if new or even more severe environmental problems arise. Trade-off situations were identified in Paper I, Paper II, Paper IV, and Paper V. Such situations related to consumables are summarized in the following (see Table 6 for an overview).

In the *use-phase of consumables*, there could be a trade-off between introducing a sensor or a monitoring screen as a design approach for the effective use of both dissipative and disposable products. In this case, the impacts from producing a sensor or screen could potentially outweigh the benefits in resource savings from introducing such elements. Effective use can also be achieved through packaging design that ensures all its content can be fully utilized. This could, for instance, be accomplished with packaging that squeezes a liquid product to the exit point of the packaging. For such designs, there could be a trade-off between the benefits of fully utilizing the product and the increased material content that the packaging requires. The effective use of a dissipative product can also be achieved by means of increasing the functionality of the product to improve system efficiency (e.g., detergents that allow one to use a lower washing temperature and fuel additives that increase engine efficiency). For such product improvements, there could potentially be a trade-off with a risk of more hazardous constituents in the dissipative product.

Some disposable products can be redesigned into reusable multiple-use products. Potential trade-offs connected to shifting to a multiple-use product are linked to that product's production and maintenance. Indeed, producing a multiple-use product usually requires more resources and produces more of an environmental impact per item than producing a disposable option. The multiple-use product must, therefore, be sufficiently used to limit these impacts. The maintenance of reusable products can also lead to increased environmental impacts and outweigh the benefits of reuse. Therefore, it is also important to design an energy-efficient maintenance system and use energy from renewable energy sources.

In the *production phase*, the only identified potential trade-off is when the production requires energy (or other resources) to reduce material losses or recover scrap and by-product streams. Moreover, there are two potential trade-offs when reducing materials in products. The first concern is the risk of losing a function, such as durability. This can be an issue when designing, for example, packaging that wastes product due to the reduced durability of the protective packaging. Design that considers the whole product system is, therefore, important to avoid this potential trade-off. Reducing the material content in dissipative products can, in some cases, be achieved by creating a concentrate by removing the water from the product. The second trade-off, therefore, concerns the benefits of removing water (producing both less packaging material and less of an impact from transport) and the impact of removing water for the concentrate design option. During material substitution, there is always a risk of trade-offs between the types of environmental impacts from the different materials. For example, there is a trade-off between climate impact and the impact from land-use when fossil-based materials are substituted with bio-based ones (as shown in Paper I). An additional potential trade-off emerges when the material in the product is changed as a precondition for other measures, such as when designing a disposable or durable product. In such cases, the potential trade-off is between the benefits of the enabling measure and the impact of the new material.

Finally, in *post-use,* there are some identified trade-offs. Recycling risks keep hazardous substances in circulation. Hence, hazardous substances should be avoided. There could also be trade-offs between recycling and other measures. For example, a recyclable product (e.g., a plastic single-use cup) can be difficult to use long-term, whereas a durable product can be difficult to recycle (e.g., a ceramic mug). Designing a biodegradable plastic product can also lead to unwanted environmental impacts since such materials are seldom completely degradable under natural conditions and instead risk degrading into microplastics.

Table 6. Overview of potential environmental and resource trade-offs for consumables.

Type of product	Recommended RE measure	Potential environmental trade-offs
Dissipative products	Use effectively	– Reduced use-phase impact vs. production of sensors in cases when required – Reduced use-phase impact vs. production of smart packaging – Chemicals with higher functionality vs. risk of more hazardous constituents
Disposable products	Use effectively	– Reduced use-phase impact vs. production of sensors in cases when required – Reduced use-phase impact vs. production of smart packaging
Disposable products	Shift to multiple-use product	– Benefits from multiple use vs. increased impact from production and maintenance/cleaning, including transportation
All types	Reduce losses in production	– Reduced losses of material in production vs. energy use for avoiding losses
All types	Reduce material quantity in product without material substitution	– Risk for losing function, e.g., durability – Benefit of removing water vs. impact of removing water for the concentrate
All types	Change materials in product	– Risk burden-shifting when substituting material – Changing material is often a precondition for other measures, e.g., use-phase efficiency or increased lifetime. Potential trade-off between the benefits of the enabled measure and impact of the new material
All products, except dissipative consumables	Recycle material	– Impacts from recycling need to be smaller than impacts from alternative material production – Risk of keeping hazardous substances in circulation
All types	Biodegradable material	– Risk of creating microplastic in nature

5 Discussion

This chapter discusses the key findings of the research and their implications. The chapter is structured around the four research questions and ends with a discussion of the quality of the research and its limitations.

5.1 Measures for resource efficiency

One output from this research is the typology of physical RE measures presented in Table 4. This study has several similarities and differences with other circular economy frameworks. Therefore, this section aims to discuss these differences in relation to the RE measures (Paper I). The goal of our framework was to include all physical measures that could improve resource efficiency (i.e., both reduce the material flows and environmental impacts) of a product system and to enable analysis of the measure. For this reason, a detailed list of nineteen measures was created. The established list of RE measures was divided into three main categories, each distinguished by where in the life cycle the measure can be undertaken: extraction and production, use-phase, and post-use.

Two widely used CE strategy frameworks are the Ellen MacArthur Foundation, where the CE is portrayed as a butterfly diagram (EMF, 2013a), and the 9R strategies by Potting et al. (2017), where R stands for different re-imperative (see Table 7). Potting's framework was further adapted by, e.g., Blomsma et al. (2019) and Gaasbeek (2018). Another recent CE framework is the one from Reike et al. (2018), which instead reviews and synthesizes the most common perspectives on CE-strategies into a single systemic typology of 10 strategies.

Comparing these frameworks on an overall level, all except Paper I advocate a highly prioritized hierarchy where refusing, reducing, and reusing are the main strategies (see Table 7). However, the ranking order of the strategies in the frameworks differs slightly. All of the frameworks also have a clear life cycle perspective and consider measures over the whole lifecycle. However, EMF (2013a) does not consider reducing resources in production and extraction. Further, since the frameworks have a product focus, strategies explicitly aimed at transport are missing or intentionally left out in all of the frameworks except for that of Blomsma et al. (2019). Moreover, EMF highlights what can be done with biological materials by dividing the framework into the biological sphere (where strategies such as "cascade" and "digest anaerobically" are considered) and the technical sphere (where strategies such as "reuse", "remanufacturing", and "recycling" are included). This clear division between biological and technical materials is not applied in Paper I, although the measures explicitly aimed at bio-based materials are highlighted. Conversely, the Potting and Blomsma frameworks make biomass less visible and instead consider bio-based strategies as part of the recycling concept.

Furthermore, it is possible distinguish certain measures that are found in all frameworks, namely reusing, repairing, remanufacturing, recycling, and recover (energy). Other strategies exist only in some of the work, such as refusing/reinventing and rethinking (Blomsma et al., 2019; Potting et al., 2017; Reike et al., 2018). Potting et al. (2017) considered refuse to involve making a product redundant by abandoning its function or offering the same function with a radically different product. Examples include designing out unnecessary components or packaging. Blomsma et al. (2019) further state that refusing, or reinventing, is a strategy that strives for full decoupling. The authors mention examples such as "bringing your own" take-away mug to reduce the need for disposable ones, using music streaming instead of physical CDs, and employing multifunctional devices such as smartphones that include several functions in one product. Multifunctionality, however, corresponds to Potting's strategy of rethinking. Multifunctionality is not considered in Paper I, which is a limitation. Refusing as a concept can also be understood as not providing and/or producing a product. This is clearly the most resource efficient option since the avoidance of consuming a product in principle results in no resource use or environmental impacts. However, as a strategy for manufacturing companies, this is not a viable option. From the user perspective, however, refusing can also mean not buying a product or, for instance, choosing to dry washed clothes outside instead of in a tumble dryer. Similarly, Reike et al. (2018) considered refusing, from a consumer perspective, to involve buying or using fewer products, whereas from a producer perspective, they interpreted refusing to mean refusing specific hazardous materials and designing the production process to avoid waste.

The measure reducing also varies in its meaning between the frameworks. According to Potting et al. (2017) and Blomsma et al. (2019), reducing broadly means to increase the efficiency of resources in product manufacturing and during use. Reike et al. (2018) argued that reducing can be applied in three ways: consumer oriented, producer oriented, or as a generic term. Generically, the term means eliminating the production of waste rather than the disposal of waste itself after the product has been created. The more common use of the term is the producer view, which involves less material per unit of production or 'dematerialization' in product design. The consumer or user view was less notable in the review by Reike et al. (2018) and indicated that this view could entail desirable consumer behaviour such as using purchased products less frequently and using them with more care and for a longer time. Some also consider the sharing of goods as a way to reduce. In the typology for RE measures, reducing is central in several measures. These measures include "reducing losses in production and extraction", "reducing material quantity in products (without material substitutions)", "using effectively" (i.e., reducing losses during use), and "reducing the use of energy and auxiliary materials during use", i.e., using efficiently. In this way, we highlight that reducing is important over the whole product life cycle. Using effectively is also a measure that is not considered in the other frameworks. This measure is considered to include improvements in user behaviour in several ways to reduce losses, such as making sure that all of the products are able to be consumed, designing the product's structure to reduce losses, and avoiding the use of products that do not match the user's needs. This can be seen as corresponding to the "refuse" measure by refusing to use products that are not in line with a user's actual needs.

Both sharing and shifting to multiple-use products are two other measures explicitly mentioned in our typology. In other frameworks, sharing is treated as an example of the strategy of rethinking (Potting et al., 2017) or regarded as a business model example (EMF, 2013a). The possibility to turn disposable products into reusable ones is not explicitly highlighted as a strategy in other framework but can be considered embedded in the strategy of reusing (EMF, 2013a; Potting et al., 2017). Re-mining is a strategy that is only mentioned by Reike et al. (2018), who describe re-mining as a strategy that is mostly forgotten and involves the retrieval of materials after the landfilling phase, i.e., mining valuable resources stored in landfills.

Finally, the largest difference between the CE frameworks and the typology of RE measures is that instead of advocating a general ranking of measures, the work in this thesis advocates that the appropriateness of a measure depends on the characteristics of the product that it will be applied to.

Table 7. Overview of RE measures (Paper I) and CE strategies in the literature: EMF (2013a), Potting et al. (2017), and Reike et al. (2018). Note that the RE measures are not presented in a ranked order, whereas the other CE frameworks are presented according their ranking order.

Paper I	**EMF (2013a)**	**Potting et al. (2017)**	**Blomsma et al. (2019)**	**Reike et al. (2018)**
RE measures according to life cycle phase	**Strategy and overall priority**	**Strategy and overall priority**	**Strategy and overall priority**	**Strategy and overall priority**
Reduce losses in production	Reuse of goods	R0 Refuse	Reinvent/refuse	Refuse
Reduce material quantity in product	Product refurbishment	R1 Rethink	Rethink & reconfigure (multi-flow offering)	Reduce
Change material in product	Component remanufacturing	R2 Reduce	Rethink & reconfigure (long life products)	Resell/ Reuse
Use effectively	Cascading of components and materials	R3 Reuse	Rethink & reconfigure (access or availability of product)	Repair
Reduce use of auxiliary and energy	Functional recycling	R4 Repair	Rethink & reconfigure (result & performance - service)	Refurbish
Share	Upcycling	R5 Refurbish	Restore, reduce, & avoid (raw materials & sourcing)	Remanufacture
Use more of the technical lifetime (reuse)	Downcycling	R6 Remanufacture	Restore, reduce, & avoid (manufacturing)	Repurpose
Increase technical lifetime	Biochemical extraction	R7 Repurpose	Restore, reduce, & avoid (product use & operation)	Recycle materials
Shift to multiple use	Composting	R8 Recycle	Restore, reduce, & avoid (logistics)	Recover
Maintain	Anaerobic digestion	R9 Recover	Recirculate (upgrade)	Re-mine
Repair	Energy recovery		Recirculate (repair & maintenance)	
Remanufacture	Landfilling		Recirculate (reuse)	
Repurpose			Recirculate (refurbish)	
Recycle material			Recirculate (remanufacture)	
Digest anaerobically			Recirculate (repurpose)	
Compost			Recirculate (material recycle)	
Recover energy			Recirculate (cascade material)	
Treat wastewater			Recirculate (recover)	
Landfill with control				

5.2 Why do product characteristics matter?

This research has identified a number of product characteristics of relevance for the suitability of resource efficiency measures and their potential outcome.

First, it matters whether a product is *consumable* or *durable*. Consumable products can be further divided into *dissipative* and *disposable* products. Durable products can also be distinguished based on five different characteristics, although a durable product can, and usually does, inhabit more than one characteristic. These groups are *active* (as opposed to passive), products *typically used for their full technical lifetime,* products *typically discarded before being worn out*, products *typically discarded before being worn out and infrequently used*, and products whose *functions remain at end-of-life*.

In product design, there are others who also acknowledge that product characteristics determine what measures can be applied. For instance, Bovea & Perez-Belis (2018) presented a method for circular product design that helps to identify which design guidelines to consider by taking into account the specific characteristics of the product category that a product belongs to. To assess the guideline's relevance to different product categories, the authors provide a checklist of questions. Although this method is theoretically appliable to any product category, its focus is on traditional CE strategies, which means that very few questions are applicable to consumables. Rose et al. (2002), on the other hand, identified six product characteristics that can be used to classify products into end-of-life strategies (reuse, service, remanufacturing, recycle, and disposal) with high accuracy. These characteristics are *wear-out life* (the length of time from product purchase until the product no longer fulfills its original functions), *technology circle* (the length of time that the product will be on the leading edge of technology before new technology makes the original product obsolete or less desirable), *level of integration* (a high level means that a product has a component with many functions), *number of parts* (parts in the product), *design cycle* (the frequency with which companies design new products or redesign their existing products), and *reason for redesign* (ibid). Comparing these characteristics with our key product characteristics, it is clear that there are many similarities; however, the characteristics mentioned by Rose et al. (2002) are mostly relevant to durable products.

A similar division between durable and consumable goods is made by Vezzoli & Manzini (2008). Similar to our product characteristics, Vezzoli and Manzini further distinguish between additional product categories that are of relevance to determining the application of design strategies. The "consumer goods" are categorized into subcategories of goods that are consumed, such as food and washing powder (i.e., dissipative products), and throwaway goods, such as packaging, newspaper, and throwaway razorblades (i.e., disposable products). Vezzoli and Manzini argue that making dissipative products durable is a futile effort and instead suggest minimizing their resource consumption and selecting low impact resources. For disposable goods, the authors suggest increasing their lifespan by making them reusable (ibid). These recommendations are in line our work, except that they do not consider how losses can be reduced in the use of products.

Durable goods are also divided into more categories (Vezzoli & Manzini, 2008): 1) goods that consume little or no resources while in usage (i.e., passive products) and 2) goods that consume resources and energy during use and maintenance (i.e., active products). A passive product impact occurs mainly during the extraction and production, distribution, and disposal stages. Thus, the authors consider it very important to minimise the resource impact and consumption of production and distribution activities. The impact of disposal can be minimised by material recycling and also by extending the product's lifespan, especially in cases of cultural obsolescence (ibid). These recommendations are thus also similar to the recommendations in this work.

Similar to Paper I, for active products, Vezzoli & Manzini (2008) consider an extension of lifespan to be questionable due to trade-offs between improvements in the resource consumption of new products and the longer lifespan of the old product. Instead, a reduction in resource consumption during use is seen as a more important design strategy (ibid). For products that are disposed of before wearing out, Vezzoli & Manzini (2008) suggest that some of their parts could be substituted to upgrade their efficiency, or the activities of production and disposal could be downscaled only to the elements needed for the substituted parts. This suggestion does not take into consideration the use-patterns of the products, as done in Paper I and Paper II, which influence whether it makes sense to share a product between users or encourage the user to continue using it through various upgrade design considerations.

The key product characteristics identified in Section 4.1 (Paper I) emanates from a longer list of product characterises (Table 3). These characteristics will be discussed hereon since several of these were found to influence the appropriateness of RE measures. The first characteristic concerns the *technical lifespan of the product.* This is generally considered the maximum duration that the product should last based on its durability or material construction (Cooper, 2010). Simply put, a product with a short technical lifespan can be classified as a consumable, while if the product has a long technical lifespan, it is a durable. The second characteristic is *use time*, which can be defined as the service time of the product. That is the period in use from acquisition to final disposal according to Cooper (2010). This means that a product can be discarded by the user before its technical lifetime is reached (in line with two of the identified product characteristics). To dispose of a product before it is fully utilized (i.e., before it has delivered its total function) is usually called obsolescence and depends on several factors. Several authors noted aesthetic reasons, i.e., that the product does not look good enough

(Cooper, 2010; Lilley et al., 2016; Packard, 1960). A product that belongs to a sector characterized by fast development in appearance and sensitivity to new aesthetic trends, such as clothes or interior design, risks being disposed of for such reasons. Obsolescence can also be due to functional or technical reasons, which means that a product becomes outmoded by another more functional or more advanced product (Packard, 1960). Such products can, for instance, contain more functions (e.g., a better camera and memory in a smartphone) or improved technology that makes the product more energy efficient (e.g., a fridge). Functional obsolescence is also closely linked to systemic obsolescence, which means that a system change has made the product obsolete (Mueller et al., 2007), such as introducing a new operating system to the market, thereby creating difficulties in current hardware systems. These types of obsolescence are thus linked to the aspect of *development pace*. Obsolescence is thus often about a user who experiences a new need, which influence the user to discard the product.

The third characteristic is the *frequency* and *intensity of use*, which concerns how often and for how long a product is used each time by a user. Products that are infrequently used are considered more suitable for sharing in contrast to products that one uses every day. Fourthly, whether the *product requires energy or auxiliary materials during use* decides if a durable product can be classified as active or passive. The fifth characteristic relates to the retention of function in the product's components at disposal (i.e., that there is a possibility to reuse that component in a new or other product). Lastly, which *phase of the life cycle dominates* resource use and environmental impact is of key importance for what RE measure will be effective. This relates to active products, for which use phase efficiency is important. For products dominated by the extraction and production of raw materials, avoiding losses throughout the life cycle is important.

The above-mentioned characteristics along with content of concern and product complexity (i.e., the remaining characteristics assumed to be relevant for what RE measures should be applied to a product in Paper I; see Table 3) are all relevant to consider when designing products (as shown in the REDIG tool, Paper II, and the design guidelines review (Paper III)). Product complexity is relevant since the number of components and materials of products are generally recommended to be kept as low as possible to enable the recycling of their materials (Lewis et al., 2001). The number of its components and the complexity of the product's structure influences the possibility to disassemble and subsequently determines whether or not products can be remanufactured/repaired/upgraded (Bovea & Perez-Belis, 2018) or recycled (Vezzoli, 2018). Content of concern indicates whether the product contains scarce materials or hazardous substances, which is suggested to guide how such products should be designed to more easily handle such materials (Brezet & van Hemel, 1997).

5.3 Can consumables be designed out?

This section discusses to what extent consumables can be designed out (i.e., made into durable products) alongside some of the limitations of this approach for a circular economy.

Dissipative products, due to their nature, cannot be made long-lasting and durable. However, their losses can be designed out or reduced. Reducing losses during use can be achieved through different conservation and sufficiency methods. Sufficiency methods are smart designs that ensure one only consumes the required amount of the dissipative product. Conservation methods instead reduce losses by postponing the degradation of the product. This can be done either through improved shelf life (making sure that the product can be used when the user feels like it rather than while the product is fresh) or ensuring that the product can last longer after being opened. Preservation methods can include drying, pickling, firing, creating a concentrate or adding preserving additives to the product, or using a packaging design that makes sure that the product is preserved.

Durable products that use dissipative consumables can also be designed to reduce losses of the dissipative product, such as lubricants or electricity.

Disposables, instead, are designed to be discarded after one use or after a short period of use when they have fulfilled their function. Some of these products can be redesigned into reusable products. However, some cannot due to concerns of safety and convenience.

For *safety reasons* (either to humans or the environment), it could be a necessity to provide a disposable product, which is usually determined by legal requirements. For example, air filters for engines need to be incinerated when disposed of (Paper III), and needles used in healthcare need to be disposable due to the risk of spreading disease. *Convenience reasons* can make it preferable to use a disposable product instead of reusable one. For instance, at a picnic, it could more convenient to dispose of the cutlery, plates, and glass, rather than dealing with washing dishes. Also, for products that provide a hygiene function, such as diapers, many customers may prefer a disposable product over a reusable one.

The tendency to choose a disposable product over a reusable one can be somewhat influenced by DfSB or nudging. However, if no legal requirements force the user to choose the reusable option, some users will likely continue to choose the more apparently convenient option.

5.4 The role of combining measures

The synthesis of the lifecycle-based assessment studies of different RE measures and products in Paper I provided insights into the role of combining measures. The reasons for combining measures are discussed in this section.

The first reason is that measures can be *interdependent* (Blomsma & Brennan, 2017). One example is a study on the reuse of computers, which found that a commercial reuse configuration, in addition to granting benefits from extended use, also increases functional recycling since non-reusable computers are effectively collected for appropriate post-use handling (André et al., 2019).

Another reason for combining measures is that such measures can be *complementary* (Paper I). For instance, in the LCA study of incontinence products (Paper IV), the four different RE measures (improving production, increasing the share of renewable material, shifting to a partly reusable product, and matching the user's needs with a correct product) were applicable simultaneously without influencing each other negatively or positively. For this reason, it can be assumed that combining the four measures would lead to the lowest impact. Moreover, this conclusion was drawn in Amaya et al. (2014), whose assessment of public bike-sharing showed that the greatest improvement in all life cycle impact categories was achieved when combining different measures.

The third reason is to *overcome impacts from burden shifting.* In Paper V, which assessed the design navigator LFD, the new incontinence product design entailed changing the material by reducing its fossil-based content while increasing its renewable material, together with matching the user's needs with the correct product. This result showed that combining these two measures resulted in no burden shifting, which would have happened if only the material content had been changed. Similarly, in Paper II, the use of the REDIG tool resulted in a design concept that included reducing the fossil-based material and increasing the renewable-based material together with increasing the technical lifespan. In this analysis, the combination resulted in the smallest environmental impact for all environmental impact categories, which was better than just changing the materials (which led to burden shifting) or extending the product's life.

However, combining RE measures does not always lead to improved resource use and reduced environmental impacts. For instance, Schau et al. (2012) found that combining remanufacturing and a lightweight alternator (converting mechanical energy into AC) resulted in increased impacts compared to the use of no remanufacturing and a conventional weight alternator. Proske et al. (2016) showed that modular designs can allow for repair and remanufacturing, but that material use can increase—in this case, due to an increased need for connectors.

Finally, the REDIG tool can help identify the risks of trade-offs when applying different RE measures. However, combining different measures makes it more important to assess the implications under that configuration (Blomsma & Brennan, 2017). For such an evaluation, LCA can be a useful tool.

5.5 Reflection on the use of the life cycle approaches in the design of resource efficient products

The literature shows the importance of a life cycle perspective in design (see, for instance, Pigosso et al. (2015), Ceschin & Gaziulusoy (2016), and McAloone & Pigosso (2018)). Although this thesis acknowledges that abundant literature exists on this matter, this section intends to reflect on the life cycle approach used in the present work to enable the design of resource-efficient products.

LCA and life cycle thinking have been used in several ways throughout the work. The first way was to use the results of an LCA of an existing product as support in redesign. In this way, the LCA can highlight the most relevant environmental issues for the product system and where in the product lifecycle the largest impacts occur (i.e., the identification of hotspots). This was the starting point for the design navigator developed in Paper V.

In addition to making use of the LCA results to identify the most important environmental problems for the product system in Paper V, LCA was used to inform where in the product life cycle these environmental problems could arise when using the design method during the actual design process. Furthermore, life cycle thinking can help detect system changes that could potentially lead to the burden shifting of environmental problems, given that the design method aims to redesign a product system into a product-service system that introduces new services and activities, which can potentially give rise to new environmental problems, e.g., increased transportation related impacts (Chun & Lee, 2016).

Lifecycle thinking and knowledge from life cycle assessments were also prerequisites to develop the design guideline tool REDIG presented in Paper II. This guideline tool builds on the work in Paper I, which consists of a review and synthesis of lifecycle-based assessment studies (mainly LCA studies). Lifecycle thinking was used for the development of the analytical framework and typology of RE measures, which structured the measures according their lifecycle phases. Furthermore, the system thinking required by lifecycle thinking was important to identify the various environmental trade-offs that can result from these measures. This review highlighted which RE measures made different product systems resource efficient when the RE measures failed to do so and what product characteristics were decisive for each measure's outcome. These results were translated into design guidelines in Paper II. The information from

LCA, therefore, underpins the design guidelines. The added design considerations in the tool, i.e., the suggested ways of achieving the recommended RE measures, were also assessed with lifecycle thinking to determine if further environmental trade-offs could potentially arise.

One of the REDIG tool's aims was to reduce the need for an initial LCA to learn about a product to guide what one should focus on based on that product's environmental profile. However, if the company want to know how much the environmental improvement the new design resulted, additional evaluation through LCA or LCA-based methods is needed. The third way that LCA is employed in this research is as a tool for evaluation (in Papers II, IV, and V).

Therefore, to design resource-efficient products, LCA is not a necessity. However, conducting and using LCA facilitates life cycle thinking, which is crucial when designing new products, especially in a circular economy.

5.6 Quality of research

The quality of the research is critically reviewed in this section in terms of its reliability, validity, and limitations. Reliability refers to the reproducibility of the measurements and results (Blessing & Charkrabarti, 2009). Validity is the degree to which the measurements actually reflect true variation in the outcomes of interest (ibid). The identified limitations of each of the appended studies can be found in each respective paper.

5.6.1 Reliability

To ensure the reliability of the research methods and data analysis, several measures were taken. Data collection and data analysis were documented. Search strategies and the results of the literature reviews are also described in the papers of this thesis. LCA models and the rationale behind the modelling choices are appended to Paper IV (the incontinence product study). The questionnaire and feedback from the designer in Paper II (presenting the REDIG tool) are also included in the published paper. Likewise, based on the details of the developed analytical framework in Paper I, the procedures and criteria for assessing lifecycle-based case studies were also documented to ensure reproducibility. The use of several peer-review processes also assured reliability and the provision of relevant details.

A *limitation* of the reliability and reproducibility involves studying documents and interviewing people as a way to gather information, as such methods can always lead to misunderstandings and, therefore, incorrect conclusions. To reduce the risk of such misunderstandings, for all conducted LCA studies, the manufacturing companies had to verify the processes data to ensure that correct assumptions had been made.

5.6.2 Validity

Validity can be understood in this research as to what degree the findings from the different studies can be generalized. The individual LCA studies are specific in their details and can, therefore, not be considered generalizable. To assure the robustness of the results in the LCA study of incontinence products, a sensitivity analysis was carried out for a sensitive parameter that was found to be conclusive in similar studies (washing and drying activities). Moreover, by analysing many LCA studies under the framework in Paper I, including the LCA of incontinence products, it was possible to generalize the results from the LCA studies.

A *limitation* of the validity concerns the evaluation of the developed design methods in this research. In both of the studies both studies (Paper III and Paper IV), the design methods were only tested in one case study with one designer and one product, respectively each. This is not enough; instead, more testes with several products and designers is needed to truly validate the usefulness and usability utility of the design methods. This is especially relevant since both methods aim to be applicable to all types of products. Assessing a developed method with only one case study is, however, not a unique limitation to these two studies; instead, this is a limitation that permeates design research in general (Baumann et al., 2002; Coskun et al., 2015; Rossi et al., 2016).

6 Conclusions

This chapter summarizes the key conclusions of this thesis in relation to the research questions.

1. What product characteristics are relevant for the outcome of the resource efficiency measure?

This thesis has identified the product characteristics that determine whether a certain measure is possible and whether that measure leads to increased resource efficiency. Products can first be divided into *consumable* products (short lifespan) and *durable* products (long lifespan). Consumable products can be furthered distinguished into *dissipatives* and *disposables*. Durable products can also be distinguished based on five different characteristics, although a durable product can, and usually does, inhabit more than one characteristic. These include *active* products, which are products *typically used for their full technical lifetime,* products *typically discarded before being worn out*, products *typically discarded before being worn out and infrequently used*, and products whose *function remains at end-of-use*.

2. How can the suitability of RE measures for products with different characteristics be used to formulate guidelines for the design of resource-efficient products?

The suitability of RE measures for products with different characteristics was able to be developed into the design guidelines. However, to do this these measures needed to be supplemented with design considerations from the Design for X literature. Moreover, it was not a straightforward process to construct the guidelines since durable products can have several product characteristics, which means that it was not possible to construct a clear hierarchy. For this reason, a question tree was constructed, which also enabled this study to operationalize the guidelines into a tool—REDIG. The product characteristics and the design guideline trees thus enable the designer to identify suitable design guidelines for different products. Furthermore, the tool was tested on a real product with a designer. To evaluate whether the use of the tool enabled the designer to develop a product concept with improved resource-efficiency, the new product was assessed with an LCA study. The results showed that the new product concept featured improved resource use and environmental performance.

3. Which guidelines exist for design of resource-efficient consumables?

This thesis has shown that among general design guidelines, i.e., those that are considered to be applicable to all products (both durable and consumable products), on average, less than half of the design considerations are applicable to consumables. These are not exclusively applicable to consumables but are generally applicable in many cases to more products. It can be further noted that the fewest design considerations were applicable to dissipative products (a third), whereas for disposables, around half of the considerations were applicable. For disposable products made reusable, a larger share of the design considerations was deemed applicable, since these considerations were also relevant for passive durable products and maintenance (two thirds). It was also found that design guidelines in ecodesign literature contributed more relevant design considerations for the different consumable types compared to the design guidelines from the circular economy field.

4. What resource efficiency measures can be applied to consumables and what are their outcomes in terms of environmental impact and resource use?

This thesis has shown that the following resource efficiency measure can be applied to consumables. All measures in the production phase (*reducing losses in production, reducing material quantity in a product,* and *changing the material in a product)* are applicable to all consumables.

Among the measures in the use and post-use phase, the applicability of measures differed between the different types of consumables. For dissipative products, *using effectively* (of the use-phase measures) and *treating wastewater* and *digesting anaerobically or composting* (of the post-use measures) were deemed applicable.

For disposable products, both *using effectively* and *shifting to multiple use* are applicable among the use-phase measures. The "shift to multiple-use" measure entails making the product durable, which also makes other measures of relevance for durable products significant, such as *maintaining* (the design of a maintenance system) and *reducing the use of auxiliary materials and energy* to reduce impacts from maintenance. All post-use measures can be considered applicable and relevant depending on the material content, i.e., *recycling the material, digesting anaerobically or composting, recovering energy, treating wastewater,* and *landfill and control*.

For the short-lived components in durables, there are two possible measures in the use phase. These measures are s*hifting to multiple-use* (including *maintaining* and *using auxiliary materials and energy*) and *increasing the technical lifespan*. In post-use, essentially all measures except for *treat wastewater* are suitable.

The LCA studies conducted in this research were used to analyse the outcomes from five of these measures. All lead to improved RE to varying extents. The conducted LCA studies also showed that combining RE measures led to greater RE improvements.

6.1 Research contributions

First, this thesis contributed a *typology of resource efficiency measures* and a framework for analysing lifecycle-based assessment studies. This enabled the analysis and identification of *product characteristics* decisive for determining what RE measures are suitable and the outcomes of the measures. This represents the *second* contribution: This work has shown that it is *not sufficient to have a ranking of measures* but instead showed that *product characteristics* are more important to determine which RE measures should be applied to a product. This finding is an outcome from using lifecycle thinking and assessing several lifecycle-based assessment studies of different products and RE measures. The *third* contribution concerns the development of the design guideline tool REDIG, which builds on the information from numerous LCAs and the findings about the product characteristics decisive for the outcomes of RE measures.

The *fourth* contribution to this research is its focus on *consumables*, which have not received much attention in the CE context. This contribution was provided through the LCA studies assessing specific consumable products and through the literature review, especially for investigating to what extent general product design guidelines apply to consumables. Another concrete contribution is this study's insights into *disposable versus multiple-use product* discussions. This work has identified which aspects determine when each option is preferable (Paper II and Paper IV).

6.2 Contributions for practice

The research has contributed by providing knowledge and tools that are relevant to both industry practitioners and policymakers.

First, this research has made contributions that are primarily of relevance to *designers*. This work considers two hands-on design methods for designing resource efficient products. The tool *REDIG* helps the designer identify suitable design guidelines and design considerations for improved resource efficiency depending on the product characteristics of the product. This tool is especially useful for companies where few or no LCA studies have been carried out, since the tool guides the user toward what is relevant to consider depending on the specific product and the materials it contains. Also, since this tool builds on the information from numerous life cycle assessments, its recommendations are well-grounded. This tool also informs the user about what potential trade-offs different RE measures could lead to, as well how some of these trade-offs could be avoided. Additionally, this tool was conceived to enable learning about life cycle thinking through an exercise for this purpose.

The second design method, *LFD,* is relevant for companies and designers who would like to move from a product centred offering to a product service–system offering. The method builds on QFD and uses the LCA studies of the product to be redesigned to identify environmental requirements, which are weighted against functional requirements, and help navigate which product areas are important to redesign, as well as provide suggestions on which service characteristics should be considered in the final offering.

The work in this thesis also highlights the importance of considering the *use-phase of products*. Moreover, the REDIG tool and the literature review in Paper III provides insight into what such design considerations can look like.

Research contributions that are relevant to *industry practitioners* beyond designers and also to *policymakers* firstly involve research about which RE measures are suitable for what product types as a nuanced comprehensive alternative to a simple ranking of measures, as well as informing about the potential trade-offs associated with such measures. The work in this thesis has also made contributions by highlighting the limitations and possibilities for resource-efficient consumables.

6.3 Future research

There is still more work to be done in the field of consumables and the design of resource efficient products. Based on the conclusions and limitations of this research, this section presents suggestions for further research.

Firstly, several additional tests and applications of the two developed design methods of REDIG and LFD are needed (Paper II and Paper IV) with different designers, companies, and products with different product characteristics. This is necessary to perform a more comprehensive evaluation and test of the usefulness and usability of the developed methods. *Secondly,* research is needed to evaluate and test to what extent the product-type specific design guidelines that were found to be transferable to other specific consumables are truly suitable. *Thirdly,* research should be done to determine how to decrease the resource use of consumable products during use through LCA studies where different sustainable user behaviour design considerations are applied to consumables. Currently, many research efforts have focused on reductions in electricity and water usage in the field of design for sustainable behaviour, but fewer have focused on other consumable products.

Lastly, this research has, to a large degree, left out the business models aspects of creating resource-efficient consumable solutions. Research is needed to study combined design and business model measures for improving the RE of consumable products and evaluating these measures from a resource and environmental perspective.

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