THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Scrap happens, but does it have to?

On the potential of increasing machine component reuse

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Cover Picture: Scrap and "garbage" have many different faces. The object on the cover, a ball bearing, looks like others that end up in the scrap bin. Even though the bearing and its parts may still be fully functional, the risk of continuing to use it may be considered too large, at least according to the best judgment of the end-user. Remanufacturing and reusing the bearing would mean retaining its value with little additional environmental impact. Instead, such a bearing is often scrapped and recycled, which means it loses its form and function, and hence, most of its value. This is one scrap story, and a common one… Great losses, but great opportunity for improvement.

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Göteborg, Sweden 2017

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Appended papers

Paper I. Diener, D.; Tillman, A-M. 2015. Component end-of-life management: Exploring opportunities and related benefits of remanufacturing and functional recycling. *Resources, Conservation and Recycling,* 102: 80-93.

Paper II. Diener, D.; Tillman, A-M. 2016. Scrapping steel components for recycling—Isn't that good enough? Seeking improvements in automotive component end-of-life. *Resources, Conservation and Recycling***,** 110: 48-60.

Paper III. Diener, D.; Williander, M.; Tillman, A-M. 2015. Product-Service-Systems for Heavy-Duty Vehicles – An Accessible Solution to Material Efficiency Improvements? *Procedia CIRP- 7th Industrial Product-Service Systems Conference - PSS, industry transformation for sustainability and business,* 30: 269-274.

Paper IV. Diener, D., Kushnir, D. and Tillman A.M. Scrap happens— Industrial end-users and their role in product obsolescence and remanufacturing outcomes, *Submitted to a scientific journal in the field of industrial ecology*

Paper V. Diener, D., Tillman, A-M, Ljunggren-Söderman, M., Willskytt, S., André, H. Breaking down obsolescence, *Submitted to a scientific journal in the field of industrial ecology*

<u>Contributions by the Author</u>

Paper I. Derek Diener conducted the bulk of research work including data collection and analysis and drafting the manuscripts. He received assistance from the co-author in research design and analysis and in the form of multiple rounds of reviews and comments. A few other colleagues also reviewed and commented on the manuscript.

Paper II. Derek Diener conducted the bulk of research work including data collection and analysis and drafting the manuscripts. He received assistance from the co-author in research design and analysis and in the form of multiple rounds of reviews and comments. A few other colleagues also reviewed and commented on the manuscript.

Paper III. Derek Diener conducted data collection and analysis with the co-author (MW). MW focused on business model aspects while DD focused on material flows. DD drafted the manuscripts. He received assistance from the co-authors in research design and analysis and in the form of reviews and comments.

Paper IV. Derek Diener conducted data collection with assistance from sponsor company personnel and conducted analysis with the co-authors. Co-authors also assisted with research design and in the form of reviews and comments, and more substantially, with a rewrite.

Paper V. Derek Diener led the initial theoretical discussions and wrote drafts. Co-authors assisted with critical analysis in the form of discussions, draft reviews and comments and provided empirical data for a couple product examples.

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Abstract

The vision of the "circular economy" provides some guidelines for society to strive towards. In the circular economy, material resources are used and reused and recycled better, if not endlessly. Products are to require less material and deliver more function. In industry, manufacturers of all types of products and parts have started to investigate how they and their products can fit in.

The purpose of this study was to address the question – *What can a component manufacturer do to improve the resource efficiency of its products through extending product lifetime and improving end-of-use management?* To answer this question, the study focused on the key product of one component manufacturer, a *bearing,* a part that is used in many things mechanical. Mixed methods were utilized including material flow analyses to quantify downstream bearing material flows and interviews with customers of the component manufacturer to provide explanations about the fate of bearings, their obsolescence, and the possibility to remanufacture and reuse more of them and recycle them in a better way.

Results of the study reveal that there are large opportunities for the component manufacturer to remanufacture more and that there are sizable environmental benefits to doing so. Most notably, bearings in industrial use oftentimes become scrap not because they fail but because an end-user deems them to be untrustworthy. In these situations, remanufacturing offers a way to restore the bearings but often, end-users do not choose that option. End-users make obsolescence and remanufacturing decisions with consideration to risks at the system-level and their ability to make a thorough assessment is limited by lack of time and information. These and other lessons learned from this study demonstrate the kind of low-hanging fruit that component manufacturers may have but indicate that picking it may require changes to the way they do business.

Key words: reuse, remanufacturing, circular economy, component, obsolescence

1 Introduction

The “circular economy” vision can be seen as a necessary response to alarms signaling that our current way of life is not sustainable and leads to potentially irreversible environmental change. Earlier warnings about our “way of life” sounded in publications like Osborn’s *Our Plundered Planet* (1948), Boulder’s *Spaceship earth* (1967), and the Club of Rome’s *Limits to growth* (Meadows et. al 1972). More recently, Rockström and colleagues (2009) and Steffen and colleagues (2015) have reemphasized the physical limits of our planet through the concept of planetary boundaries and what they mean for our society’s continued ability to sustain life on Earth. The 1967 book *Silent Spring* (Carson 1967) and the 2002 movie *Inconvenient Truth,* among others, have made the public more aware of the specific environmental problems that may arise when pollution from society exceeds the Earth’s capacity to handle it. Common to each of these communications is the idea that *we are on a bad path and something has to change*.

The vision builds on and bundles ideas of industrial ecology (e.g. Ayers & Ayers 2002; Graedel & Allenby 2003) design, and economy, such as those of the waste hierarchy (EC 2008), cradle to cradle design (McDonough & Braungart 2002), sustainable consumption and production (Jackson & Michaelis 2003), the performance economy (Stahel & Clift 2016), and absolute decoupling (Jackson 2009). It provides a vision for *how things could be,* a conceptual alternative to the linear or *take-make-dispose* economy (EMF 2017).

The circular economy vision may just be a reframing of old concepts (Blomsma 2016), but it provides, at the very least, a common name and normative guidelines for industry, and society at large, to strive towards. The circular economy should produce (almost) no pollution or waste. In it, material resources are used and reused and recycled better, if not endlessly (EMF 2017). Products are to require less material and deliver more function. Product flows are to be reduced with resource efficiency, closed with recycling, and slowed with product life extension and reuse (Bocken et al. 2017).

The guidelines insinuate no exceptions; all products, their parts, and the infrastructure around them are to be included. Manufacturers of big and small, complex and simple, tech and bio, and products and parts alike have started to investigate how they and their products can fit in.

Naturally, a manufacturer’s most immediate control lays in its own operations, while a product normally lives and dies outside the manufacturer’s immediate control. Specifically, a product is used, deemed obsolete, discarded, and reused, recycled or disposed of downstream from the manufacturer. As such, management of a product’s life downstream is inherently challenging.

This project took interest in the challenges associated with a component manufacturer’s relative distance from its products’ life downstream and was jumpstarted by two driving forces: (1) a research interest to document challenges and opportunities that a manufacturer may have with actually making a component fit the circular economy vision and (2) a real company interested in improving the end-of-use management of its product, with specific interest in increasing reuse and improving recycling.

2 Purpose and scope

The purpose of this study is to address the question – *What can a component manufacturer do to improve the resource efficiency of its products through extending product lifetime and improving end-of-use management?* In order to do this, the investigations involved *exploring* the current state of the product's life downstream, specifically its use, obsolescence, reuse, and recycling, <u>and</u> *evaluating* possible opportunities to reuse more and recycle better. As such, the project pursues both exploratory and evaluative research questions.

The exploratory questions are as follows:

> *RQ1: Why do industrial end-users scrap otherwise remanufacturable components? (Paper 4)*

> *RQ2: Where in the life cycle of products do components become obsolete <u>and</u> where do they and their materials go? This question was posed specifically to identify opportunities to improve component end-of-use management (Papers 1 and 2).*

The evaluation questions are as follows:

> *RQ3: What are the environmental benefits of functional recycling and remanufacturing? (Papers 1 and 2)*

> *RQ4: Can a function sales model for a higher-level product result in better material efficiency for a component? (Paper 3)*

In the attempt to answer these questions, I found it helpful to *derive more stringent definitions for obsolescence and product lifetime.* This resulted in a theoretical question:

> *RQ5: How can obsolescence be defined in a way that is conducive to identifying opportunities for product life extension and use intensification? (Paper 5)*

As a whole, the study's scope covered both (1) the view of a component's downstream product chain and (2) the component manufacturer's perspective from its position early in the product chain. The project departed from an applied life cycle management and company perspective, and ended with a product-centric and somewhat theoretical view of a product's obsolescence and lifetime. It provides lessons learned about how a company might better manage its product's life downstream, practical recommendations for the company investigated, insights about how a component becomes obsolete and opportunities and challenges of reusing and recycling it.

The project was done following the downstream flow of products from the company and documenting real opportunities and challenges with four separate investigations of the component, two focused in heavy industry (PI, PIV) and two focused in the automotive industry (PII, PIII) (Table 1).

Table 1: Objectives, papers, and sectors in focus

Primary objectives	**Heavy industry**	**Automotive**
Identify opportunities by exploring and describing the current state	Papers I, IV	Paper II
Evaluate opportunities	Paper I	Papers II, III
Define obsolescence and lifetime	Paper V (no sector)	

The studies focused product use, obsolescence, remanufacturing, and recycling. Papers I and II follow and quantify the flows of components after use, and calculate material and emissions related benefits of recycling and remanufacturing. Paper III assesses the potential for material efficiency gains were the component to be made part of a product offered as a service rather than as a product (function sales of a truck). Papers IV and V focus on use and obsolescence. Paper IV addresses the use phase in heavy industry and the role of end-users in determining obsolescence and remanufacturing outcome. Paper V utilizes examples of a variety of products (including *bearings*) to suggest definitions for obsolescence and product lifetime.

3 Literature background

In general terms, this thesis is written about a company and its main product's possibility of being compatible with the so-called *circular economy (CE)*. *Industrial ecology (IE)* provides some of the principles and tools for evaluating such possibilities. The project further departed from a normative position provided by *life cycle management (LCM*) that companies have responsibility for the entire life cycle of their products including the *management of the product's end-of-use (EoU*[1]*)*. Addressing a product's end-of-use or extending its *lifetime* brings into question the nature of its *obsolescence*. Together, these principles provide one view of the prospects and challenges for components in the circular economy.

3.1 Circular economy and Industrial ecology

The alarm associated with our society's consumption and associated consequences is not new. Concerns about the absolute limits of our consumption and "growth" were more extensively popularized by the Club of Rome in 1972 (Meadows et al 1972). But even before then, the extensive resource use of our society was lamented by Osborn in the books *Our Plundered Planet* (1948) and *Limits of the Earth* (1953). Packard described the foundation of the consumer, throughput-based society already with *Waste Makers* in 1960. Boulding (1966) described ecological limits of the world as a closed system and contrasted what he called the throughput-based cowboy economy with the spaceman economy, a model in which throughput is minimized and stock management is the main effort. Unfortunately, in 2017, it would appear economic growth is still coupled to material throughput and while efficiencies reduce resource use per unit of product, associated savings are invested in more production resulting, in the end, in increased resource use (Jackson 2009).

Nonetheless, Boulding's description is said by some to be the seed that grew into the circular economy movement, and this age's and society's hope. The "circular economy" is an alternative vision and movement towards a better future, in which we will use renewable energy and we will have near-perfect material loops. The continued popularization of this concept is accompanied with great hopes and energy. However, when speaking more than superficially about it, there is uncertainty as to what it is and what it will become.

Importantly, the circular economy vision is not exclusionary. Nowhere does it proclaim some products or materials to be exempt. All products, big and small, currently recycled well or not, are supposed to become more "circular".

Now, institutions and individuals are collectively forming a vision of what this "circular" economy may look like and how it can be realized from the economy level, right down to

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[1] While downstream phenomena obsolescence, reuse and recycling are sometimes referred to as end-of-life (EoL), the term end-of-use (EoU) is favored here. This choice is made to match the view that a product lifetime only ends when a product is destroyed (Paper V).

individual products and services. Research and policy over the last many decades provides some of the building blocks, from prioritizing how to handle waste with the waste hierarchy, applying more biological models to perhaps non-biological artefacts (e.g. cradle-to-cradle, biomimicry), documenting macro-level opportunities and challenges surrounding resource efficiency (UNEP 2013), proving benefits of remanufacturing (Lund 1985), as well as suggesting alternative ways of conducting business via function or performance-based economic models (Stahel 2007).

The field of Industrial Ecology (IE), as well as being key to the CE vision's origins, provides some key principles and tools. Whereas CE is the vision and the movement for resource stewardship, IE provides some clear guidance and tools for evaluation. IE has provided some of the key principles; circularity itself (as well as linearity) refers to physical flows, which is the focus of industrial ecology.

IE also provides some of the tools to define, conceptualize and evaluate the current and circular economies. For example, Stahel (2007) (and later, Stahel & Clift 2016) advance Boulder's discussion of the spaceman economy with the so-called "lake economy", in which stocks are managed but products are still the main mode of delivering value, and the ultimate, the "functional service or performance economy", in which value is measured solely by customer satisfaction. Managing product stocks via extending product life and by intensifying product use takes center stage here. These measures are suggested as preferable to common "loop-economy" resource efficiency efforts, such as increasing proportion of products remanufactured and reducing inputs required for manufacturing. While there may be some debate as to what should be in focus – the stocks or the flows – when talking about transforming the economy, the common agreed-upon message is that an all-in-one, prevent-reduce-reuse-recycle approach is needed, whether by implementing alternative business models (Stahel 2007; Bocken et al. 2014; Bocken et al. 2017; Halme et al. 2007; Boons & Lüdeke-Freund 2013) or alternative closed-loop production strategies (Rashid et al. 2013; Lieder & Rashid 2016; Asif et al. 2012; Tukker 2015; Barquet et al. 2011). In the end, the literature provides suggestions for reducing material intensity and suggests a need for industry to decouple economic growth from material production (Jackson 2009).

All in all, according to the CE vision, individual companies are supposed to take action and do what they can with their product flows and their operations. This idea of company responsibility is evident in the principles of life cycle management (LCM). LCM often takes a dual company-product perspective, a company's perspective on the life cycle of specific products, *what can a company do to better manage the life cycle of its products.* One thing a company can do is improve end-of-use management by minimizing product disposal by initiating improved recycling and/or reuse.

Product end-of-use management can be said to be a cornerstone of the CE vision. Products become obsolete, they are disposed or recycled or depending on how they are handled or processed, they can be used. One can reduce material flows by preventing obsolescence, or better handling products when they become obsolete, repairing, remanufacturing and reusing more often, or by recycling their materials better.

3.2 LCM and IE tools

Industrial ecology provides the tools and principles for a company to improve its product's life cycle. Life cycle management (LCM) is a concept that implies that companies should take responsibility for the entire lifecycle of their products and services or that multiple organizations should cooperate to do the same (Westkämper et. al 2000; Tsoulfas and Pappis 2006). Traditional standards for management systems, such as ISO 9001 for quality, and ISO 14001 for environment and OHSAS 18001 for occupational health place focus on individual organizations (Jörgensen 2008), and such internal focus may result in the mere shifting of environmental impact from one lifecycle phase to another (Jackson & Clift 1998; Welford 2003). In response, LCM encourages "interaction of life cycle partners" (Westkämper et. al 2000) or on "expanding the value chain" (Steger 1996).

Regardless of how big its willingness may be to take responsibility for product lifecycle, an individual company cannot start everywhere. There are a wide range of LCM approaches, from transformational to those focusing on the details. For example, a company can assess its very foundations and change the very way it does business to maximize life cycle resource efficiency (Rashid et al 2013; Tan et al 2010; Williams 2007; Mont 2002). It is also possible to make smaller changes to the existing business or organizational structure by integrating life cycle thinking into existing business processes and training (UNEP/SETAC 2007) as well as already-used management systems, such as those for product design, sourcing, health and environmental risk management, and even product labelling (Jörgensen 2008; UNEP/SETAC 2007; Remmen & Thrane 2005). Finally, a company can focus on the lifecycle of an individual product or on different phases of the life cycle, from its design (Bhander et al 2003) to supply chain and logistics (Tsoulfas & Pappis 2006), production (Löfgren et. al. 2011), and customer use (Steger 1996; Price & Coy 2001; UNEP/SETAC 2007) to product end-of-use (Rose 2000) and remanufacturing (Kerr & Ryan 2001).

In addition to the more managerial side of LCM, there is a wide range of tools in the IE toolbox: life cycle assessment (LCA) (ISO 14040-2006; Baumann & Tillman 2004); social LCA (Jörgensen et. al. 2008; UNEP/SETAC 2009), life cycle costing (LCC) (Rebitzer & Hunkeler 2003; Steen 2005), material flow analysis (MFA), and guidelines for eco-design (UNEP/SETAC 2009; Evans et al 1999), to name a few.

MFA is a tool used commonly in industrial ecology (Ayres & Ayres 2002). Harper et. al. (2006a) group MFA with other *systemic* industrial ecology *(IE) tools*, which involve taking a systems approach and hence, have "the benefit of illuminating behavior that emerges within a system, behavior that may not be predicted by only studying the system's individual actors." Since the late 1960s (but mostly in the last couple decades), it and its more-focused cousin, substance flow analysis (SFA), have been used primarily to follow flows of materials globally, amongst economies and regions (Bouman et. al. 2000) or industrial sectors (Sendra et. al 2011) and not to a small degree in support of policy development (Femia & Moll 2005; Moll et. al. 2003).

Obsolete products, recyclable material and waste and have been the focus in a number of MFAs (Terazono et. al. 2004; Moriguchi 1999; Mathieux & Brissaud 2010; Nakamura and Kondo 2002; van Beukering & van den Bergh 2006) to include one of the foundational works (Leontief 1970).

MFA is commonly used to map the flows (or cycles) of metals. For example, Dahlström et. al. (2004) and Davis et. al. (2007) estimate flows of iron and steel in the UK, Nakajima et. al. (2008) presents a substance flow analysis of Manganese (Mn) through iron and steel in Japan, and Gyllenram et. al. (2008) focuses on steel flows in Sweden. Elsewhere, the Stocks and Flows (STAF, Yale) program has led to a number of published metals MFA studies (STAF 2014). For example, Reck et. al. (2008) estimates global nickel flows, Harper et. al. (2006b) tracks zinc flows and stocks in the Caribbean, and Graedel et. al. (2002) addresses copper flows in Europe. While these analyses may be primarily valuable for policy design, such studies can be valuable for manufacturers of metal products as they provide knowledge of the background system for studies focused on the use and end-of-life processes of metal products.

Product flows or common product-material combinations are sometimes assessed with MFA, however rarely (Mathieux & Brissaud 2010). For example, Oguchi et. al. (2008) quantifies the flow of 94 consumer durables in Japan, Mathieux and Brissaud (2010) conduct a product-specific material flow analysis on aluminum in commercial vehicles in the EU, and Daigo et. al. (2010) follows chromium and nickel flows in stainless steel in Japan. None of these studies are conducted at the company-level.

Company and product specific studies are more often addressed with life cycle assessment (LCA), which uses a similar input-output approach as its foundation, but also quantifies emissions and assesses environmental impacts related to those emissions. LCA focuses, however, on specific products and functional units, not bulk company-level flows (Baumann & Tillman 2004). Hence, LCA is often tailored to assessing one scenario or multiple defined alternatives. Examples focused on end-of-use include: life cycle inventory of mobile network components in end-of-life processes (Scharnhorst et. al. 2005), comparisons of manufacturing and remanufacturing alternatives (Kerr & Ryan 2000; Smith & Keolian 2004), comparing lightweight cars and standard cars in end-of-life processes (Schmidt et. al. 2004), assessing the waste hierarchy of waste paper (Schmidt et. al. 2007), and the environmental benefits of composting (Blengini 2008).

Beyond comparison studies, alternatives for product end-of-use are otherwise often presented in descriptive lists of options (e.g. King et. al. 2006; Cooper 2010; Pigosso et. al. 2010), looking at societal opportunities for improved resource efficiency (e.g. Yellishetty et. al. 2011; Allwood et. al 2011; UNEP 2013), or in case studies of successes in design, recycling and/or remanufacturing (e.g. Paton 1994; Sundin 2004; Östlin et. al 2008).

3.3 Product end-of-use management

Focusing on product end-of-use (EoU) is one approach that many companies and research entities have taken to identify and enact material intensity reductions. Such efforts have provided evidence of environmental and economic benefits, success stories for reuse and remanufacturing, and strategies for success as well as focusing on what companies ”should do” (Rose 2000). What actually happens and challenges faced are less well described (Rose 2000).

A company’s area of influence is limited and not all pursuits are as easy to enact as others. A manufacturing company does have control over which material flows enter and exit its facilities, where they come from (sourcing), what products and by-products come out (product and production design), and to whom and to where the resulting products are sold (sales and distribution), but it has often indirect or no control over what happens at product end-of-use (EoU), a critical point for shaping ultimate material intensity and when a product can be reused, recycled or disposed.

What are EoU products and why are they interesting? EoU (or obsolete) products are products that have reached either functional obsolescence, due to physical failure or need of repair, or fashionable obsolescence, due to cosmetic flaws or the availability of something more attractive on the market (King et. al. 2006). They are interesting to society and companies for two reasons. First, obsolete products, especially those that have minimal material value, are viewed often as unwanted “waste” or “refuse”, and as such, they present challenges and burdens to the end-user and society. These challenges, presented by waste handling and transport, landfilling and incineration, are viewed here as less relevant for the steel products studied, which are likely recycled because of their material value.

The second reason for interest in obsolete products is more relevant here – they contain invested values in the form of commodity, embodied energy, added value (Smith & Keolian 2006), and an ecological footprint (Clift & Wright 2000). These values are lost to a certain degree during EoU management dependent on what processes are used to dispose of the products or make them, or the materials they are made from, usable again (Herrmann et al 2008; Cooper 2010). Saving products and their embedded values reduces the need for more material and foregoes material extraction and at least some manufacturing steps (Bras & McIntosh 1999; Allwood et. al. 2011; Rathore et al 2011).

What opportunities are there to save these values and what are the benefits? From the waste perspective, the waste hierarchy says that prevention of something becoming waste is better than reuse, which is preferred to material recycling, which is preferred to energy recovery, which is preferred to disposal (EC 2008). The hierarchy has been widely accepted as both a rule of thumb in industry and as guidance in policy. Exceptions exist with less recyclable materials but the hierarchy is a rule of thumb which largely holds from the material perspective (Schmidt et. al 2007).

Waste prevention can be approached in many ways including product dematerialization and extending product service life. Since the amount of waste that results from a product is dependent partially on how much material is contained in a product, reducing the amount of material in a product, or dematerialization, contributes to reducing the amount of eventual waste and in essence, prevents waste and material use. Extending the service life of a product also prevents waste by reducing the amount of waste over time (Allwood et. al. 2011).

In regards to reuse, products can be directly reused either for the same function, cascaded into use that is less functionally or cosmetically demanding (Cooper & Allwood 2012), to a different market (Ijomah et. al. 2007), or to an altogether different function (Cooper & Allwood 2012). It is however common that products are not in proper condition for direct reuse and require some sort of preparation before they can be reused (Allwood et. al. 2011). Such preparation include, in order of increasing quality reached, repair, reconditioning, and remanufacturing (Ijomah et. al. 2007).

Compared to new manufacturing, remanufacturing yields benefits in resource efficiency despite that it sometimes requires replacement components and extensive processing (Sundin 2004; Ijomah et. al. 2007). For example, Lund (1985) presents a case in which remanufacturing of an engine requires only one fifth of the energy that manufacturing requires. Kerr and Ryan (2001) found that remanufacturing of a photocopier can reduce the resource consumption and waste generation required to deliver the photocopy function by two thirds. Smith and Keoleian (2008) estimated that remanufactured automobile engines can be produced with up to 83% less energy, up to 87% less carbon dioxide emissions, and up to 90% less raw material than newly manufactured engines. Allwood et. al. (2011) notes that remanufacturing (generally) of products results in material and energy uses that are 30-90% less than for manufacturing of new products. Less material and energy use often translates into environmental impact reductions as well; something a number of studies show (Kerr & Ryan 2001; Sundin & Lee 2011).

The waste hierarchy's third recommended option, material recycling, offers benefits as well. For example, according to one study, avoiding raw material acquisition and refining makes recycled steel 40% less exergy intensive than virgin steel (Michaelis et. al. 1998). Other sources show that scrap steel production requires between a third and a half as much energy as virgin steel production does (Yellishetty et. al. 2011).

There are limitations to recycling, however (Verhoef et. al. 2004, UNEP 2013). For metals, material function is dependent greatly on the specific composition. Functional recycling results when the function of a material is retained and utilized in next use, such as when alloyed steels of similar composition are used to make new alloyed steel (Guinée et al 1999). Thus, functional recycling occurs only if substances such as alloying elements end up where their unique properties are utilized again (UNEP 2013).

As an explanation, if alloyed steel scrap is used as raw material in the making of carbon steel, alloying elements such as zinc, nickel and chromium are not only not utilized, but are often considered contaminants. If carbon steel scrap is used in the making of alloyed steel, on the other hand, the alloying elements (from the alloyed steel) are diluted resulting in the need of additional alloying elements (Verhoef et. al. 2008; Yellishetty et. al. 2011; UNEP 2011; Johnson et. al. 2006; Daigo et. al. 2010).

With this in mind, Verhoef et. al. (2008) stresses the importance of taking into consideration specific metal contents and metallurgy paths when assessing what specific recycling outcomes will be. Unfortunately, scrap metals such as steel are generally collected and treated as a mix of products and most products are mixes of many materials. It is difficult to separate materials in a manner that keeps materials of different composition apart and thus retains their function. Thus, the rate of functional recycling is less than 50% for many substances (UNEP 2011).

Even with the best material sorting system, there are losses to slag in recycling metallurgy and in forming and cutting of raw steel products. In addition, the second law of thermodynamics is a barrier – 100% recycling is not technically possible (Reuter et. al. 2006, Amini et. al 2007). In addition, some obsolete products (around 20%) never make it into the recycling system (Manouchehri 2007). For example, it is estimated that around 10% of machinery metals are never recovered (UNEP 2011).

Notwithstanding this general knowledge about material recycling, the rate of functional recycling is highly dependent on specific product design, composition, and the material's monetary value (Graedel et. al. 2011). The rate of functional recycling for some metals has been assessed at the societal level but as noted by Graedel et. al. (2011), has been rarely product-specific. The importance of taking a product-specific perspective when conducting recycling analyses has been emphasized in UNEP's report, *Metal Recycling: Opportunities, Limits, Infrastructure*, wherein the *product-centric approach* is proposed as a needed alternative to the traditional *material-centric* one (UNEP 2013). This proposition indicates that companies and sectors take a closer look at their own products to assess what specific recycling results may be.

How can a manufacturing company capitalize on these opportunities to improve product EoU management? From a business perspective, products can provide market value at no less than six occasions during their lifecycle. The most obvious two are upon the initial (1) sale or lease, and (2) service and support. Others include (3) performance-sensitive reuse (e.g. when the product is still modern or fashionable) and (4) price-sensitive reuse (when the product's a little passé), (5) component reuse, and (6) material recovery for recycling (Paton 1994). Alternative business strategies such as closed-loop business (product take-back or reverse supply chain) and product-service systems (PSS) try to capitalize on some of these values (Guide and Van Wassenhove 2009; Mont et. al. 2006). Although the two options are similar and may focus on the same resource efficiency goal, closed-loops are centered on the physical take-back of product and may involve change of product ownership (Rose 2000; Guide and Van Wassenhove 2009), whereas the principle of PSS suggests bundling products and services and shifting focus away from products and towards delivered value (Mont 2002; Baines et. al. 2007). This shift in focus is thought to be most substantial with use or results-oriented PSSs, which involve selling function or performance without change in product ownership.

In theory, when manufacturers retain ownership of products, they are more inclined to retain and manage product values throughout the product lifecycle, this since the function, not the product is the unit of sale (Baines et al 2007; Tukker 2013). Because of this, squeezing the most function out of a product is incentivized. For example, product service life can be extended for certain products by service during installation or condition monitoring throughout use (Cooper 2005; Cooper 2010; Lindkvist & Sundin 2013).

Theoretical benefits aside, PSS (and other service-focused models) do not always deliver environmental benefits. Commonly cited PSS environmental successes of Xerox (Kerr and Ryan) and Rolls Royce are hinged largely on well-established remanufacturing operations. Although such cases are shining examples of how the PSS could be, they seem to be dependent on remanufacturing. Some documented product service systems do not result in reductions in environmental impact. For example, Williams (2007) provides a qualitative analysis of various PSS types utilized in the automotive industry (such as leasing and car-sharing) and concludes that there is currently little to no effect. In light of such examples, it is necessary to point out that the idea of servitization in business has been around for a long time (e.g. Vandermerwe & Rada 1988) without always achieving (nor with the intent of achieving) environmental improvements. This may be why many definitions of PSS include language about the intent of such a business and/or the resulting reductions in environmental impact (Baines et al 2007).

Regardless of what type of business model is used, a product's design has a tangible impact on the technical feasibility of product life extension, reuse, remanufacturing, and recycling. If reasons for obsolescence are identified, proper design can help extend product service life and can facilitate reuse and recycling. If fatigue or wear is the reason for product obsolescence, products can be designed to be more durable while fashionable obsolescence can be mitigated by instituting aesthetic upgrades (Cooper 2010). For remanufacturability, important design criteria include product durability as well as ease of inspection, cleaning (Kerr & Ryan 2001, Santini et. al. 2010; Sundin & Bras 2005) and dismantling (Pigosso et. al. 2010; Ijomah et. al. 2007). For recyclability, material liberation during shredding and sorting is critical (Van Schaik & Reuter 2007).

In summary, literature suggests a number of opportunities for a company to improve product end-of-use management including: *extension of product life*, *direct and cascading reuse*, *reusing of a component after parent product obsolescence*, *repair or remanufacturing*, *increasing capture for recycling*, and *increasing functional recycling*. The potential of realizing the above opportunities may be facilitated by *enacting closed-loop business models or product-service systems* and *changing product design and composition*.

3.4 Obsolescence and product lifetimes

The search for and analysis of end-of-use opportunities has forced an extensive consideration to product obsolescence. This section utilizes a portion of the literature review from Paper V to present established views on product life and obsolescence.

Obsolete is defined by Oxford as “No longer produced or used; out of date” and by Merriam Webster as “no longer in use or no longer useful”. According to these definitions, the mere status of not being used or useful renders a product obsolete.

Obsolescence is defined by the Oxford dictionary as “The process of becoming obsolete or outdated and no longer used” and by Random House, as “the state, process, or condition of being or becoming obsolete”. Rai & Terpenny (2008) offer two definitions, one as a measure of loss in value, and another, as “a state in the product’s lifecycle which occurs when a product is no longer wanted”, while Cooper (2010) defines it “to fall into disuse”. Hence, there are two general definitions for obsolescence. The first indicates a process towards something becoming obsolete and the other indicates the state of being obsolete.

Product obsolescence is still a topic mostly approached from the consumer product perspective (e.g. DeBell & Dardis 1979, Cooper 2010; Jacoby et al. 1977; Antonides 1990; Fernandez 2001) but such works provide generic insights that could be applied to non-consumer products as well.

Focus has often been on reasons *why* products become obsolete and on its drivers. Packard (1960) provided the first typology and popularized the term of *planned obsolescence*, for which characteristics of a product’s *quality*, *desirability* and *function* were known by their manufacturers and marketers to render products broken, undesirable, or outmoded in “the not so distant future” (Packard 1960). While a product’s *quality* may be affected by shoddy construction, its *desirability* can be influenced by the exciting appearance of newer products, and its *function* may be inferior to new ones (Packard 1960).

Cooper (2005) provides another typology. *Absolute obsolescence* arises when a product ceases to function while *relative obsolescence* occurs when differences in function, quality, safety, social or emotional value, design or economy of use lead to discarding (Cooper 2005; van Nes 2010).

Relative obsolescence can be *technological, psychological* and *economical*. *Technological* advancements may render an older product functionally inferior and obsolete (like Packard’s obsolescence of *function*), *parts* may be out of production (Cooper 2005; Bradley & Guerrero 2009; Singh & Sandborn 2006) or changes in the surrounding *system* may make the product incompatible (Mueller et al. 2007).

Psychological obsolescence can arise when product appearance is not *aesthetically* or *cosmetically* pleasing *(e.g.* Lilley et al. 2016; Cooper 2005), not in line with prevailing *fashion*

(King et al 2006), or when there is a *social* stigma (Mueller et al. 2007; Burns 2010). Such stigma may be induced with *notifications*, such as best-before dates, and product bans can result in *obligatory obsolescence* (Proske 2016).

Finally, maintenance and operation costs of an “older” product may make the product a cost burden and *economically* obsolete (Paton 1996) (Cooper 2005).

Table 2: Obsolescence types noted in literature, each focused on a particular cause or source.

Type	Description	Source(s)
Absolute	Not functional	Cooper 2010
Function/Technological	Outmoded by another more functional, more advanced product	Packard/Cooper 2010
Quality/material	Due to substandard construction, robustness	Packard 1960; Proske 2016
System	Product not compatible with surrounding system/infrastructure	Mueller et al. 2007
Parts	Replacement parts not available, out of production	Singh & Sandborn 2006
Psychological/Desirability	Perceived as not good enough: Aestetically	Packard/Cooper 2010
Aestetic/Cosmetic	Doesn't look good enough	Cooper/ Lilley et al. 2016
Economic	Due to high or increased maintenance and/or material cost	Cooper 2010
Social	Not socially acceptable perhaps due to stigma or ban	Burns 2010
Obligatory	Based on legal grounds, a ban	Proske 2016
Notification	Published or communicated, e.g. best-before dates or alerts	Mueller et al. 2007
Planned/accepted	Designed for obsolescence or made just "good enough" for the market	Packard 1960; Proske 2016
Relative	Functional but not good enough	Cooper 2010

Regardless of the type of obsolescence, it doesn’t just happen; a person makes a decision about whether a product is obsolete (Antonides 1990). Even *absolute obsolescence*, which may sound definitive in theory, is not as clear in reality.

End-users judge product function and value both objectively and subjectively (Cooper 2010) and their judgements are limited in their rationality (Antonides 1990; Valente 2012). Replacement decisions are known to be based on perceived differences between the actual and desired state of the product (van Nes 2010) as well as on what alternatives are available and how much they may cost (Jacoby et al 1977; Antonides 1990). End-users are also known to be influenced by physical surroundings, peer and media influences, as well as their connection to the product (Jacoby 1977; van Nes 2010). Even if a product’s usefulness remains constant, the user’s expectations can change resulting in a reduction in perceived value and ultimately, obsolescence (Rai & Terpenny 2008; Antonides 1990). As such, obsolescence decisions can be said to be made in context; they are made based on the user’s “current” circumstances and one end-user’s “broken” might still be another’s “good-enough”.

Obsolescence is part of a product’s life or lifecycle. A “product life cycle” is an analogy derived from the biology field to represent the stages of a product’s existence. How a product life cycle is specifically described and portrayed depends on the context in which the term is utilized.

From the industrial design viewpoint, product life cycle management is focused on a product meeting a particular need and includes both intellectual processes, such as definition of consumer need, and physical processes, including manufacturing and maintenance, and recycling or disposal (Ameri & Dutta 2005; Stark 2015). The product itself is defined by characteristics, among them its lifespan (Saviotti & Metcalfe 1984; Brouillat 2015).

From the marketing view, a “product life cycle” (PLC) refers to, not an individual product entity, but a concept that creates value for customers. While one individual product may live a short period, the product may live on the market much longer. As such, the physical making of individual products is not of primary importance. Instead, market phases of the product, from introduction, through growth, maturity and decline, are of primary concern (Anderson & Zeithaml 1984; Polli & Cook 1969; Day 1981; Rink & Swan 1979).

From a logistician’s point of view, it is suggested that a well-planned PLC shall include considerations to product returns and reverse logistics (Tibben-Lembke 2002). While product returns naturally lag product sales, each individual product type will have its own estimated (expected) lifetime, and hence, rate of product returns (ibid). It is these lifetime estimates along with product sales numbers that are critical to planning for reverse logistics and waste management.

Reverse logistics is part of a complete closed-loop business and focuses on getting used “cores” back to a manufacturer for remanufacturing. In cases of one-for-one exchanges (i.e. a customer exchanges used one for remanufactured one), success is greatly dependent on the in-flow of cores and planning for it (Ostlin et al. 2008; Kumar & Putnam 2008).

In waste management, disposal or end-of-life predictions are made by distributing product populations over time based on median or average product lifetimes (Wang et al. 2013; Thiébaud -Müller et al. 2017). Similar product lifetime estimates are used for generating models of macro-level material cycles (Murakami et al. 2010; Chen & Graedel 2012; Yamada et al. 2006).

At the user level, product lifetime estimations contribute to how a user perceives the value or reliability of an aging product over time (Antonides 1990). Each product has a different reliability profile and expected lifetime based on its aging and decay (Smith & Hinchcliffe 2004). Based on these principles, Reliability Centered Maintenance (RCM) formalizes system reliability assessment and involves determining what types of maintenance strategies should be assigned for each part or piece of equipment, partially by attempting to predict part failure or obsolescence (Smith & Hinchcliffe 2004; Daley 2005).

Life cycle assessment (LCA) uses product lifetime in another way. The objective of LCA is to estimate potential environmental impact that can be assigned to one unit of function (functional unit). As such, an LCA models the product life cycle, required to deliver the function in question. The product life cycle starts with the cradle, where raw materials for the product are obtained, and ends with the grave, waste disposal or recycling of materials. The product lifetime is the phase during which the product delivers its function. How function is measured is based on how the function of the product can be reasonably captured (Baumann and Tillman 2004).

It is no surprise that the exact meaning of product life varies. Product lives can be measured by the *replacement life*, the time between replacements, or the *service life,* the period in use from acquisition to final disposal (Cooper 2010), or the *economic* or *optimal life,* how long before maintenance or other ownership costs becomes more expensive than replacing it (van Hilten

1991). These lives are seldom as long as the *technical life*, the maximum duration that the product *should* last based on its durability or material construction (Jönsson 1995; Cooper 2010). Finally, one may derive an estimate of *expected life* based on both technical and social factors (Fernandez 2001).

Even with these definitions, where a product life starts and ends, whether or not phases before and after use (such as shipping) are to be included in the life, and whether a product can have multiple lives or only one, is not consistent. *Disposal/discard* is defined in many ways, from physically throwing in a container to replacement (DeBell & Dardis 1979). A product end-of-life, on the other hand, can be when one use phase ends (Guide & Van Wassenhove 2009), "at the moment a product becomes obsolete" (Den Hollander & Bakker 2016), or at the discard of the "final" owner (Bakker et al 2014). As such, a life can be measured as equivalent to one use (Iacovidou & Purnell 2016) and a product can go through multiple lifecycles (Lieder & Rashid 2016), or a product has one life (Murakami et al 2010).

A single-life view is often insinuated in discussions about product life extension. A product lifetime is often referred to as extended if the product is reused, remanufactured, or repurposed, regardless of change in ownership (Manouchehri 2007; Bocken et al. 2017; Chapman 2009).

Since most restorative actions are preceded by a product being deemed obsolete, this means that obsolescence doesn't necessarily mean end-of-life, it is potentially one of many periods of disuse. Following this view and noting the prevailing inconsistency in the meaning of product life, Murakami et al (2010) defined *service lifespan* as "the duration of period when the goods function and can be put to use, including the duration of distribution for the next use" (Murakami et al 2010). This is likened to the *total lifespan* for vehicles and other durables, which is illustrated (but not explicitly defined) as the duration between the end of production and the end-of-life treatment or recycling *(ibid.)*.

All phases, both use and non-use (disuse), are included in the product life; repair, refurbishment, storage and shipping all represent times of "hibernation" or "dead storage" (Murakami et. al 2010; Bakker et al. 2014). These phases are known to be extensive for many consumer products. For example, people store clothing and electronics and only turn them in "when they get around to it" (Thiébaud -Müller et al. 2017). It is periods of disuse that, hypothetically, could be converted to periods of use, resulting in higher use intensity.

4 Methods

While individual manuscripts include more detailed description of the "methods" employed for each study, this section focuses more broadly on explaining how the project was done. Here, the first section describes key ways of working. The subsequent sections describe what was studied and why (*the case),* and the methods used for data collection and analysis (*following and analyzing the product chain*), which are covered more extensively in each paper.

4.1 Ways of working

The project was done, in part, as a collaboration with the company, and loosely followed (in hindsight) the three main phases of transdisciplinary research: problem identification, problem analysis, and integration of lessons learned (Pohl & Hirsch Hadorn 2008). As part of the collaboration, the problem(s) were identified and defined and results were sorted and analyzed for transferable knowledge and possible solutions. Some of the suggestions are being integrated into company strategy, however researchers have been less involved in this phase and it continues. It should also be stated that the study did not depart from an action research/learning (Stokols 2006; Schein 1999) platform nor did it have an explicit goal to implement anything in the end. Collaboration, was nonetheless important to making the study work.

Collaboration with the company was especially important to the study process and the results yielded. Even before the study (and before I was involved), the company and senior researchers met to suggest and discuss possible projects. Serendipitously, both parties' first-choice of project theme matched – *Product End-of-Life*.

A specific group of company representatives – *the project support group* – was formed to support the research. In the beginning of the study, the group provided regular feedback. Most critically, the group helped find relevant and willing contacts, those employees who were expected to be helpful in finding data, whether it be via spreadsheets or interviews.

Interviews with business and technical experts at the company yielded crucial insights into the business, customers and products and identified customers for interviews and site visits. Researchers provided updates and results regularly. New results or analysis lead to discussion and identification of additional contacts or new data or insights from the company. Results were refined, communicated and discussed within the company in various formats.

Later on in the project, the researchers and a team in Latin America worked together to generate understanding about why customers don't choose remanufacturing more often (Paper IV). For this, the team helped create a questionnaire and interviewed customers. In addition, interviews of Swedish customers led to more discussions about remanufacturing between the customers and customer representatives. Thus, not only did collaboration with company representatives facilitate interview and site visit activities, it appeared to instigate action outside the study.

The nature of progress of the project over time can be best described as exploratory. It resembled the iterative "systematic combining" (abductive) process described by Dubois & Gadde (2002). Data collection and analyses were conducted not linearly, but interchangeably throughout the study. Thus, while articles are invariably (according to tribal rules) written as if questions-data collection-data analysis occurred linearly, the studies actually occurred with each of these stages occurring interchangeably.

Making something out of the data we collected – even how we drew the figures, where boxes and arrows should go and whether they should be included at all – can only be partially explained (by me at least) by the activities of sense-making (Weick et al. 2005) and theorizing (Merton 1949). These two activities were the intangibles but the things that are most difficult to explain. We took the data we received and based on the more formal knowledge around us, like literature and written theories, as well as our informal hard-to-explain knowledge, the stuff that helps us understand, our "cognition", our "language ability" and "our experiences", even our "artistic ability", to make something out of the jumble, explain and make figures to communicate what we learned. This process was critical throughout but was most pivotal for Paper IV, for which researchers used theory to make sense of and conceptualize what they had seen empirically.

A good part of the work called theorizing is taken up by the clarification of concepts, and rightfully so." (Merton 1949, p. 513)

Theorizing was more specifically used for Paper V. A group of researchers got together with all their knowledge, conceptions (and perhaps misconceptions) to talk about product life spans and obsolescence. We were not experts (at the beginning at least); we were having a hard time using those terms in our own work. We realized that defining them might help us and others, and might even be fun. While the definitions are not meant to be the equivalent "theory of everything" for discussions about product life and death, they provide theory that can be applied and used to explain and possibly find solutions. A theoretical aim with perhaps, an instrumentalist's outcome.

4.2 The case: What to study, where and why

What to study was determined by the project purpose and research questions as well as practical aspects. While the purpose addressed the company perspective – what a company can do – research questions addressed the product and component perspective, what can be done with a component.

What a company can do is invariably dependent on the company's products and the product systems around them. Inversely, the company could be looked at as one part of the product system of a component, part of the practical context of the component. *The component in context is considered the primary case for this project.* The company was used to add context and for practical access to places where the component is used.

The company and project sponsor is a multi-national mechanical engineering solutions provider based in Sweden. The company manufactures and sells, among other things, products for machine maintenance, lubrication, and mechatronics, and rotation. Of all these products, bearings, which allow rotation of mechanical parts, were chosen to be the case *component*.

In order to fit all types of rotational applications, from wash machines to vehicle gearboxes to paper machines, bearings are produced in many different sizes and constructions. They are the sponsor company's bread-and-butter product and they present the added benefit of being, technically speaking, a rather "simple" product. It, contrary to some of the other choices, which may include many parts and materials including electronics, they have less parts and material types. In fact, the standard type, while made up of many parts, is made almost exclusively of steel and only three main part types. As such, some of the challenges associated with separating and handling parts and material types for reuse and recycling are less extensive. In addition, the technology on which the bearing's based evolves slowly relative to other products; a bearing produced one year can be relevant technology-wise for many years. Hence, challenges associated with technological obsolescence are less relevant. Since these types of challenges are less extensive for the bearing, it arguably provides a cleaner study object for which to study other challenges associated with product end-of-use management. If the problem can't be solved with this product, then what can we do with others?

A product is a mere part of a "product system", the things around it that make it relevant. It is dependent on that system; the quality and quantity of the product's life is based on the system around it.

The relationship between product and product system is no more apparent than with a bearing. A bearing is physical part of and moves as part of a larger product or machine, which in itself is a mere constellation of components. A bearing's life is somewhat dependent on the product but its birth and death can be independent of the machine's life and death. Once obsolete, a bearing is just like other products; the success of reuse or recycling is dependent on the reuse and recycling systems around it. Whether or not it is reused is dependent on what practices are normal in its immediate surroundings, what decisions its handlers make, and what reuse "infrastructure" exists (or is known to exist). Alternatively, the bearing will enter recycling systems where its construction and composition and the recycling infrastructure are the preconditions for how "well" it is recycled.

Finally, considering the component in context of a manufacturer is interesting for two reasons. First, from the perspective of a component manufacturer, the component *is* the product. It is the thing that represents all the function, all the value and all the (direct) environmental impact. It is what matters. Second, lack of control of what happens to a product when it becomes obsolete is no more evident than with a component manufacturer which oftentimes relinquishes control already before the final product is ready for use.

Where to study the component

Our choice of where to study the component can be described as information-oriented selection, for which samples are chosen not based on representativeness but based on variation and potential of yielding new information (Flyvbjerg 2001). Contrast in samples was considered critical for building a nuanced understanding of the bearing's use and end-of-use.

As the company has customers in many business sectors, it allowed access to the bearing in many settings. Two very different sectors were chosen, *Heavy Industry* and *Automotive* (Table 3).

Characteristic	Heavy industry	Automotive
Example applications	Rollers, engines, and moving production lines	Wheel-ends and drivetrains
End-users - business or consumer	Entirely business-to-business	Mixed
Contact with end-user	Direct business	None, only via OEMs and distributors
Use setting	Industrial use	Road use
Product size	Bigger	Smaller
Product cost	More expensive	Less expensive
Remanufacturing	Sometimes	Never

Table 3: The two sectors, Industrial and Automotive, with short description for each characteristic.

While the *Heavy Industry* setting involves products used in stationary factories in such applications as motors and moving production lines, the *Automotive* setting involved products used in (by nature, mobile) vehicles in such applications as wheels and the drivetrain. Whereas the *Industrial* business involved businesses as end-users, the *Automotive* business involved many consumers as end-users. The company sometimes has a direct relationship with end-users in *Heavy Industry*, but not with those in *Automotive*. The bearings are generally larger and more expensive for use in *Heavy Industry* and smaller and less expensive for use in *Automotive* applications. Products of interest for the study are sometimes remanufactured for *Heavy Industry,* but never for *Automotive.*

The bearing was studied with snapshots from *Heavy Industry*, with samples and analysis of the bearing in sectors including metals, marine, cement and paper (PI, PIV) and from *Automotive*, in wheel-ends and drivetrains for both passenger vehicles and trucks (PII, PIII). How the samples were taken and analyzed is discussed in the next section.

4.3 Mixed methods of data collection and analysis

This section covers main methods: mapping material flows with ***MFA*** and ***LCA***, gaining explanations of what happens to the bearings with ***interviews*** focused on bearing obsolescence, recycling and remanufacturing outcome. The study started with a quantitative material analysis the downstream product chain (Papers I & II) and moved towards a more "populated" and qualitative view of the product chain (Baumann 2011) where actors in it have choices and determine final end-of-use outcomes (Paper IV)

Mapping material flows

Deliverables for Papers I, II, and III were material flows in the form of Sankey diagrams showing the flows and highlighting potential opportunities for improving material efficiency, most specifically with improved end-of-use management (such as remanufacturing or better recycling).

MFA as described by Brunner & Rechberger (2004) was used to estimate the material flows. Although LCA is a good method for assessment of specific products, functional units and the inventory or comparison of alternatives, it was not considered to be as suitable as MFA for use in an exploratory study of bulk company product flows.

For Papers I and II, mapping *product-material flows* and *fates* with MFA gave an overall picture of *where* materials go, *what processes* they go through, *who* controls those processes and what the *circumstances* of bearing obsolescence are. The MFA was paired with an analysis of raw bearing sales data augmented with product mass. This analysis provided information about how much product mass different product types, customers or regions represented, generating insights into which “targets” of product mass could be the most fruitful or feasible to capture and remanufacture or recycle.

The main steps of the MFA for Papers I-III were: 1) determining relevant flows and processes, 2) system definition, 3) data collection and determination of transfer coefficients, 4) producing example flow diagrams and 5) making comparisons and analysis. Especially the first two steps were iterative. A conceptual diagram of the *bearing EoU system* was drawn and redrawn (Figure 1).

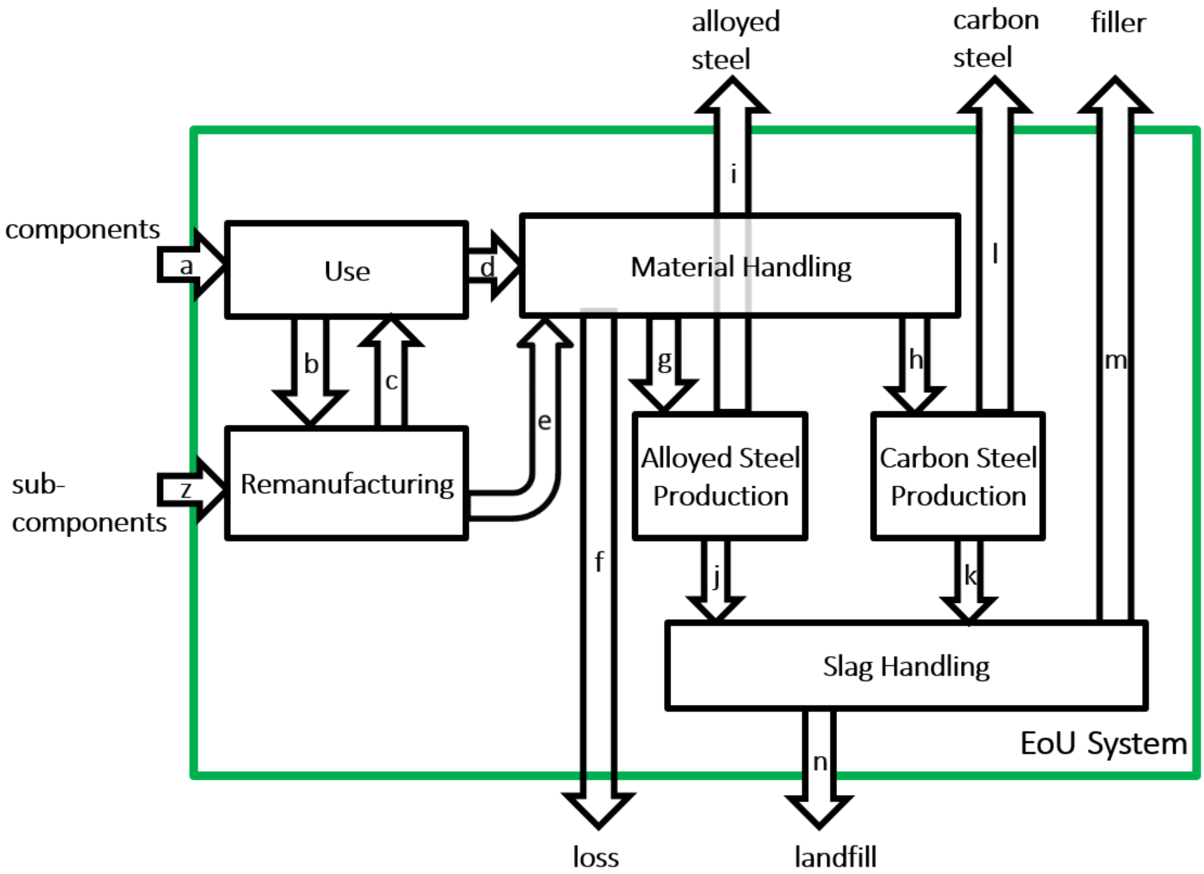

Figure 1: Conceptual diagram of the bearing *End-of-Use System*. Processes are shown in boxes, and material flows are shown as arrows.

The data collection included gaining data about 1) product composition, design and sales, 2) user activities, 3) product remanufacturing, 4) material (scrap) handling, 5) scrap steel production, and 6) resulting secondary material use. With these data, product flow and throughput for each process was estimated. Transfer coefficients were determined for each process with assistance from the company, customers, subject matter experts from respective fields, and publically available studies. Based on the data collected and calculations, example material flows were generated. Examples of customers or types of products were chosen to compare and communicate outcomes.

As a complement to the MFA for Paper I, LCA was used in order to compare the environmental impacts of remanufacturing to those of recycling and functional recycling as well as to estimate environmental impacts related to losses of substances in material recycling.

Interviews and site visits

Throughout the study, interviews of company experts provided information about the basic business strategies, the company's products and services as well as how they are delivered, basic product designs, and related trends. These interviews also yielded a general description of the product chains in question including: customer types, other actors in the product chain (and relationships between them), product types as well as preconceptions about product fate.

For Papers I and II (*Heavy Industry, Automotive),* interviews and site visits provided transfer coefficient estimates for some parts of the MFA as well as some depth and actor insights to the remainder of the study. They also provided a possibility to compare theory and preconceptions from within the company with real-life examples and others' conceptions, and to identify other points of interest or "unanticipated yet related issues" that can be investigated further (Dubois & Gadde 2002). For Paper I, *Use, Maintenance* and the point of product *obsolescence* was explored with end-user customer questionnaires and follow-up questions, some follow-up interviews, and one site visit. For Paper II, interviews and site visits were conducted at maintenance garages, remanufacturers and vehicle dismantlers.

Interviews of company *Remanufacturing* experts and a visit to one of the company's remanufacturing sites were conducted with focus on the process, challenges and the company's product preferences.

Interviews with material handlers (metal scrap brokers) and visits to sorting and shredding facilities were conducted to better describe *Material handling,* material fate and challenges related with the process.

Only one steel production site was visited but transfer coefficients and most information about *Steel Production* was taken from literature and publically available studies.

Interviews were most important for Paper III (*Function sales heavy vehicles*) and Paper IV (*Scrap happens*). Paper III's investigation included conducting interviews with 16 professionals at two companies, *the component company* and one of its customers, *the truck company,* and determining what changes could be made if a function sales model were to be enacted for the trucks. Interviews were semi-structured and explorative. The professionals interviewed had not thought about the implications of a function sales model before, so their answers and discussions around them were a learning process in themselves. In the process of answering, experts identified key capabilities (including design possibilities) and practices that already exist within the companies that could impact a possible function sales model as well as noted key data sources for material flow analysis.

Importantly, interviews for Paper IV took place as part of site visits to cement, steel, and paper mills. Site walks and specifically, seeing the machines and seeing the mechanics work allowed the researcher to see things the mechanics themselves take for granted. These site walks results in many new questions. These questions led to key explanations that helped make the end-user system model that resulted.

In addition, site walks led to situations in which new trails of thought were blazed for both the researcher and end-user. *Never thought of that before* OR *Why do we do it like that? I don't know.* Importantly for this study (Paper IV), interviews conducted by the author were augmented with interviews by company representatives with customers in other regions. The data received from these interviews was more superficial, but provided breadth in the study that wouldn't have otherwise been feasible.

5 Results

This section summarizes the results, structured according to the research questions.

5.1 End-user determination of obsolescence and choice of remanufacturing

RQ1: Why do industrial end-users scrap otherwise remanufacturable components? (Paper IV)

Interviews with ten customers of the component company provided some answers about how end-users determine that components are obsolete and why otherwise remanufacturable components are scrapped. Obsolescence of the components occurs when they break or, more often, when the maintenance crew determines that they are no longer serviceable or trustworthy. Both determinations of obsolescence and whether to send products for remanufacturing are made considering the possible implications the choice may have on the system in which the component operates.

Customers indicated that there are critical phases during the use of the component that have an impact on the obsolescence and remanufacturing outcomes (Figure 2, below). Namely, component damage, possibly rendering the component to be not reparable, occurs at three main stages, installation, utilization and maintenance, and removal. There are complexities during each stage that contribute to component damage. For example, a couple end-users indicated that *components* are damaged during installation, often due to mistakes made by less experienced personnel (*operator error*) and indicated that it is just plain difficult to install them. Damage during utilization and maintenance occurs due to a number of *complicating factors* including, but not limited to, those related to the operator, such as the difficulty of changing out a part in a tight position, related to the environment, such as contamination of dirt and moisture, and related to the uniqueness of each machine and situation.

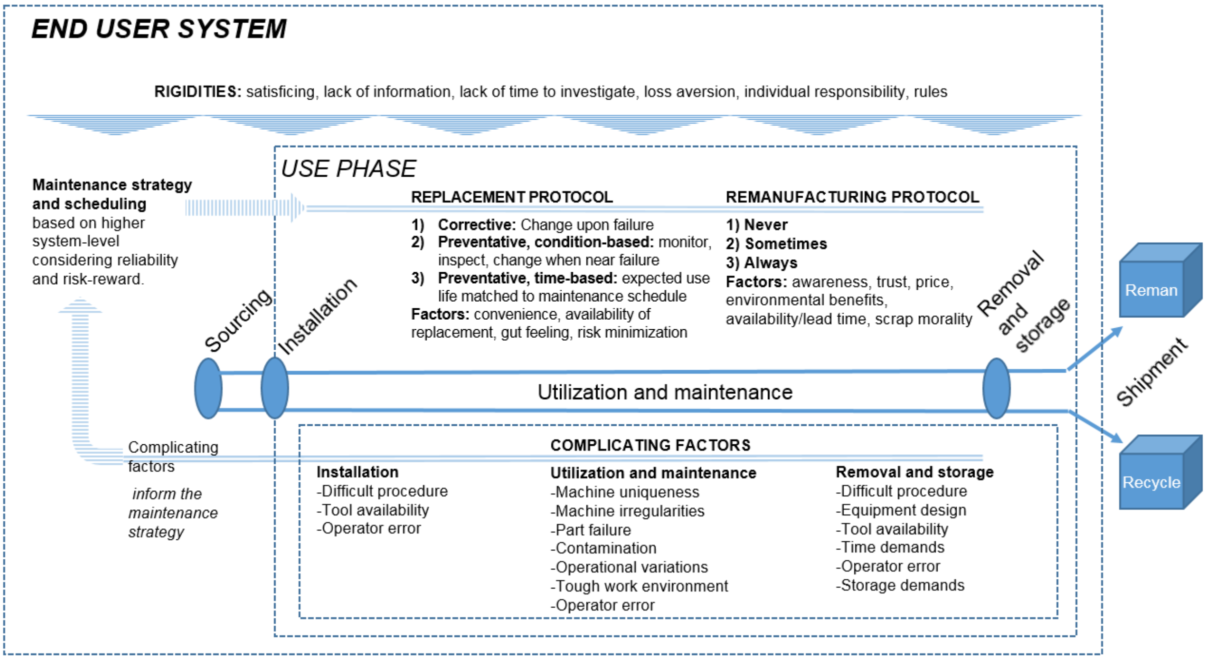

Figure 2: End-user system determining component remanufacturing outcome. Remanufacturable components go in. Used components go out as remanufacturables to *Reman* or scrap to *Recycle*. Complicating factors are addressed to a certain degree by protocols. Rigidities may act as stabilizing factors, making the system resistant to change.

To manage *complicating factors*, maintenance crews observe a maintenance strategy and derive replacement and possibly, remanufacturing protocols based on it. As maintenance theory suggests, end-users make maintenance decisions with consideration to the system as a whole.

For the study at hand, the *system-perspective* was observed to affect a few types of decisions related to individual components including: whether to maintain it, how (and when) to maintain and monitor it, and whether a component in a given condition provides enough benefit to outweigh eventual costs (or risks) at the *system-level* (Smith & Hinchcliffe 2004); Daley 2005). End-users emphasized that decisions about components were made with the system in mind and that their main goal was to minimize downtime. End-users emphasized that the cost of downtime would far outweighs any savings from reusing a part.

Three main component replacement protocols were noted amongst end-users: *corrective, condition-based* and *time-based*. While *condition-based* and *time-based* protocols involve assessing condition of components or changing components based on a schedule and aim to change components before they fail, the *corrective* protocol generally means waiting for a problem to occur and often results in components being damaged beyond repair. The corrective protocol was noted by end-users primarily for smaller components that are less attractive for remanufacturing or for non-critical applications, in which a failure does not stop the operation. Because the other protocols are, by nature, preventative, they result in more components being reparable and suitable for remanufacturing.

Three main remanufacturing protocols were noted, including never, sometimes (circumstance based), or always send components for remanufacturing and a number of end-users observe more than one of these protocols based on the application at hand. For those that have never actually considered remanufacturing, the *never* remanufacture protocol is the default. The *always* remanufacture protocol was observed to be used by one steel customer that sends all components to remanufacturing as a part of its maintenance cycle. The *sometimes* remanufacture protocol can be based on a combination of *trust* and the relative *availability or lead time of new* components.

Other factors also influence which protocol is followed. Maintenance personnel at one paper mill and one cement mill mentioned feeling bad about scrapping components that appeared to be in good condition, a phenomenon called *replacement morality* (Van Nes 2010). *Environmental benefits* of remanufacturing were also mentioned as important by many customers. Naturally, *price* is also a consideration.

With an understanding of *complicating factors* and *protocols* used to manage them, one could attempt to increase remanufacturing outcome by remediating *complicating factors* and considering ways to fit the remanufacturing offering into the existing maintenance *protocols*. However, the study also revealed some *rigidities* related to end-user decisions that could make change more difficult.

According to the theory of limited (or bounded) rationality, decision makers are limited by a number of factors including attention (time to attend to a given decision), memory (remembering lessons learned), comprehension (organizing and understanding available information) and communication (being able to understand or share information with other individuals) (Simon 1978; March 1994). End-users revealed a few of these factors when discussing their practices.

Personnel at one steel mill and one paper mill indicated that while they may seek continuous improvement, investigating more remanufacturing of components is not a priority given the *lack of time*. Other end-users mentioned that they do not have the *information* necessary (from the remanufacturer) to make a good decision and would like assistance in doing a proper analysis. As such, they may not make a choice at all, which results in a continuation of their protocol to never choose remanufacturing for components. Also, if an end-user is satisfied with the current state, he or she may not look for or assess available alternatives. One user explained that if a way of working doesn't cause problems, it can continue for a long time until someone asks "why".

In addition, if the failure of a *component* will result in a large problem, such as a costly stoppage in production, end-users may be overly cautious about using a *component* for too long or in using a remanufactured component. Even if an end-user may save 50% on remanufactured *component*s, that 50% may be miniscule in comparison to costs at the system level. A maintenance team may need to prove that the remanufacturing alternative *will* yield the benefits claimed without a risk that would offset the benefit. Here, the burden of proof lays with the alternative, remanufacturing. Moreover, the manager signing off on an alternative may feel a burden of *individual responsibility* that results in that person choosing to keep the less beneficial (but personally safer) alternative. Each of these phenomena can serve to stabilize the current protocol.

5.2 Component end-of-use: current state and opportunities

RQ2: Where in the life cycle of products do components become obsolete and where do they and their materials go? This question was posed specifically to identify opportunities to improve end-of-use management (Papers I and II).

RQ3: What are the environmental benefits of functionally recycling and remanufacturing? (Paper I and II)

Components used in an industrial setting are taken out of machines and scrapped at factories or rarely, scrapped as part of a machine. Components used in the automotive sector are scrapped at garages or scrapped with a subsystem (such as a gearbox) or with the entire vehicle.

In both Industrial and Automotive settings, there seems to be a well-established waste and recycling regimen and components are generally recycled. This means that most of the iron and alloying elements of the scrapped component are recycled. However, in steel recycling, a few percent of iron and chromium, as well as a higher percentage of manganese goes to slag, which is commonly used as road-filler. This means that some of these metals end up in waste or in a less functional use.

Moreover, since old secondary scrap steel (as opposed to new scrap from production) is commonly sorted into fractions that do not necessarily account for the presence of valuable alloying elements, it is mostly recycled into carbon steel products, such as construction beams. For these products, alloying elements remaining in the steel, such as those from the component (Ni, Mo, Mn, Cr), are not only not valued but are considered a contaminant. All in all, this means that while these elements are “recycled” they end up in a place where they are not wanted. This means that more alloying elements have to be dug up and processed to make new alloyed steel. Besides the many other environmental impacts that this mining may have, it was shown in Paper I that the process of replacing these alloying elements can result in a tangible portion of the component's carbon footprint. Thus, there is a good reason to recycle in a way that alloying elements fulfill function in their next use, functional recycling.

Functional recycling can be facilitated by sorting pieces with like-composition in the same scrap pile. Since different parts in machines and vehicles may have very different material compositions, it is beneficial to have parts separated from one another prior to recycling. Otherwise, based on the current recycling infrastructure, steels of many alloys and compositions end up being recycled together. Positively, it was estimated that almost all the components studied for the *Industrial study (Paper I)* and almost half of the mass of the wheel component (*Paper II*) studied for the *Automotive study* are liberated from the parent product when they are scrapped. These components could be sorted with like compositions for functional recycling.

Despite the benefits of functional recycling, remanufacturing and reuse would provide much greater reductions in material intensity and carbon emissions. For the *Industrial* settings *(Paper*

I), remanufacturing appears to be a big opportunity. Many components are scrapped not because they are no longer functional but because they are no longer trusted (*Paper IV*) and there appears to be many components that are of a preferred size for remanufacturing but that are not sent to be remanufactured (*Paper I*). In fact, it was estimated that components of a size that is more often profitably remanufactured represent over half of the mass sold to customers in the company's metals industry sales segment. Other sales segments in heavy industry are known to have similar component make-up, meaning that a sizable portion of the product mass sold to these segments could potentially be remanufactured and reused, greatly improving the material efficiency of the components to those segments. Notably, these same components represent only a few percent of the total number of components sold, so handling only a "few" of the components could yield great improvements in material efficiency (Figure 3, below).

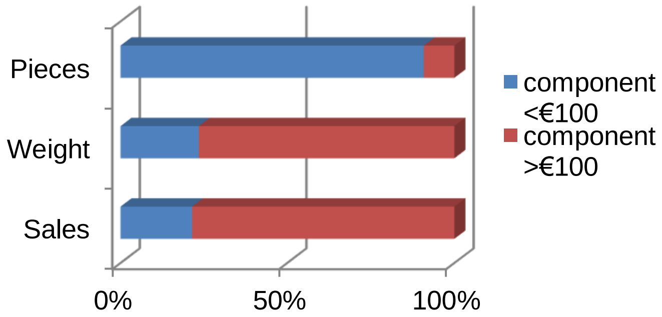

Figure 3: Components segregated at €100 sales price reflecting the share (%) of product count (pieces), material weight, and sales revenue.

Additionally, only a handful of customers purchase most of the product mass, hinting that cooperation or remanufacturing contracts with a few customers could make a big difference in material efficiency.

Benefits in material efficiency are revealed when comparing material flows of one example customer that sends a lot of components to remanufacturing and whose components are more often functionally recycled and another customer that uses the products in a similar manner but does not send its components for remanufacturing (Figure 4, below).

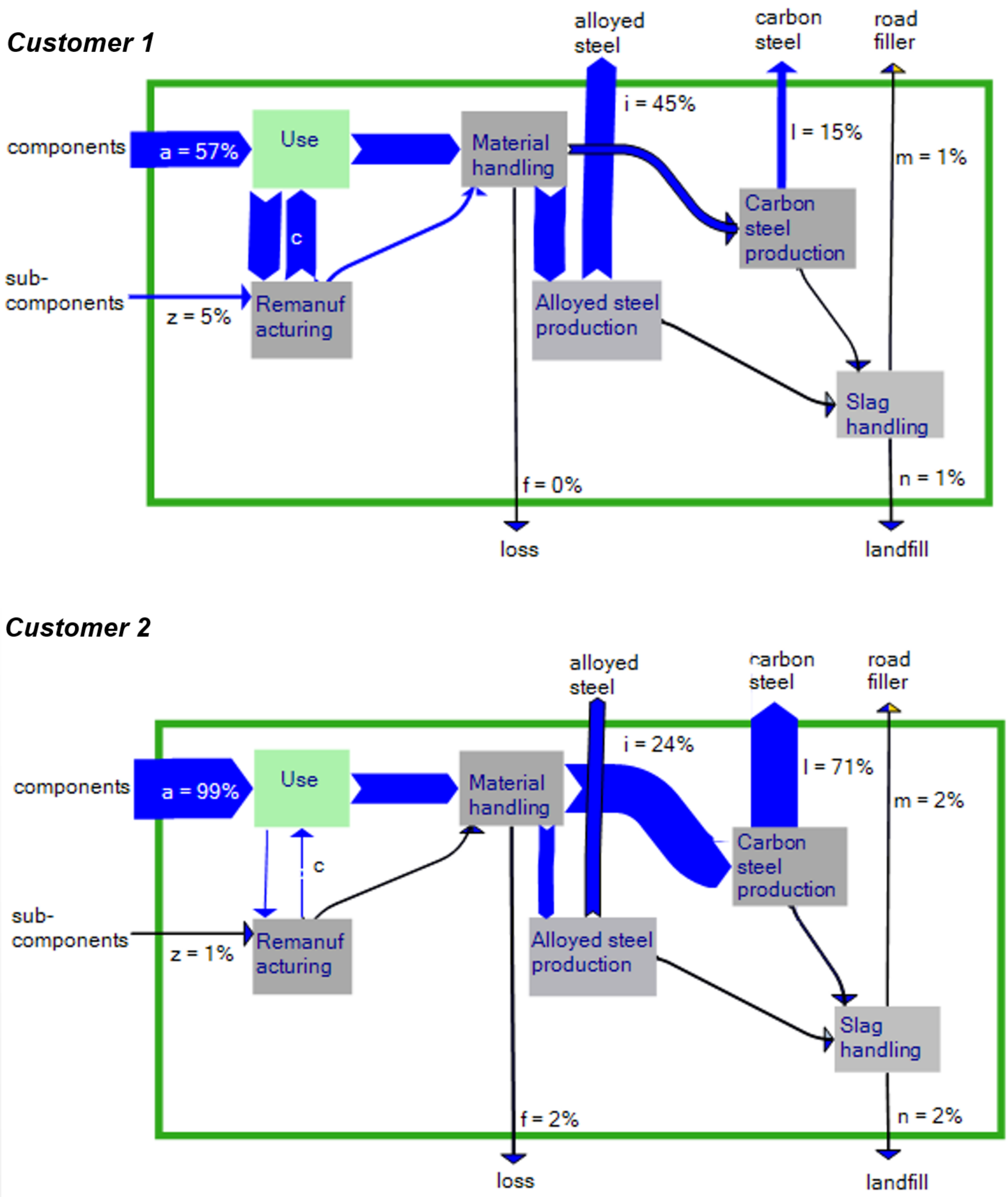

Figure 4: Comparing the material efficiency of components for two customers. Percentages (rounded to nearest percent) are normalized to functional component flow (a + c = 100%). Customer 1 sends most components for remanufacturing and that has many components going to functional recycling. Customer 2 rarely sends components for remanufacturing and has most components going to normal steel (non-functional) recycling.

The non-remanufacturing-inclined customer's material flow results in approximately three times as much material loss as does the remanufacturing-inclined customer. Said in another way, the remanufacturing-inclined customer fulfills the same function with approximately a third less material input as the other customer requires. Less material input means less material going through recycling processes, and less material lost. Losses of some of the substances is naturally more substantial. Most notably, it was estimated that around half of manganese (Mn) is lost to slag. If one assumes that Mn and other material has to be "replaced", one can say that these losses of alloying elements represent a tangible amount of the total carbon footprint of the component.

Besides the benefits associated with less material inputs, remanufacturing can result in a fraction of the carbon emissions resulting from end-of-use outcomes recycling or replacing (starting from scratch) (Figure 5).

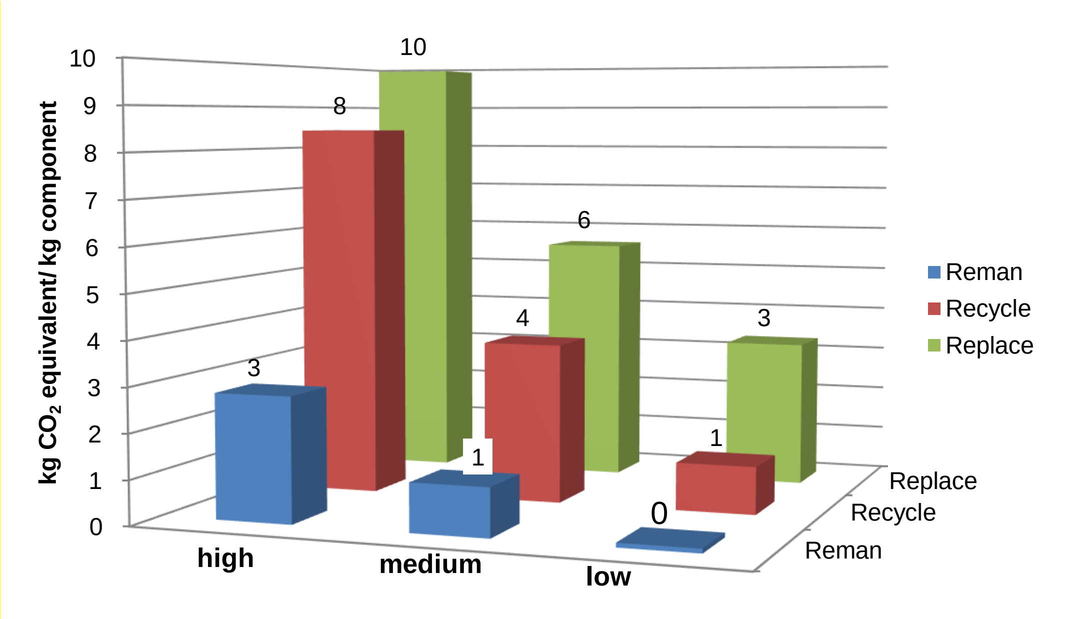

Figure 5: CO_2-eq (kg per kg component) for three possible component end-of-life outcomes, remanufacturing (Reman), recycle, and replace. Showing three estimates based on high, medium and low estimates of CO_2-eq resulting from the processes required for each outcome.

5.3 Possibilities to reduce material intensity with function sales

RQ4: Can a function sales model for a higher-level product result in better material efficiency for a component? (Paper III)

The study considered the possibility of a truck manufacturer (OEM) selling truck function instead of selling trucks and whether this change could result in higher material efficiency. Based on interviews with practitioners from a truck OEM and the *component company* exploring this possibility, it was concluded that implementation of a function sales model could result in greater material efficiency at the component and truck level.

Currently, while uptime is a primary concern for the truck OEM, focus is on the first and second owners, and the OEM sources not the components with the longest possible lifetimes but the ones that have a reasonable life length for the price and according to *normal* expectations. As a result, some parts are changed out several times during the truck lifetime.

Interviewees from the truck OEM indicated that, under a function sales model, the truck OEM would be more apt to choose and encourage the development of even longer lasting parts, since any parts change or service would be a cost, not a potential revenue stream. In addition, since the truck OEM would have more access (and control) over used parts for a function sales model, it was indicated that the already existing remanufacturing of gearboxes, engines, and other parts, would increase, and the types of parts remanufactured would become broader.

Considering the longer component lifetimes and increase remanufacturing of other systems suggested by in interviewees, it was estimated that function sales would lead to a 20% reduction in material needed for the case *component* type. This was based on estimates of the *component* and its use in three main subsystems, the wheel, gearbox and engine. Since the truck OEM would attempt to reduce maintenance occurrences as much as possible during the lifetime of the truck, wheel *components* that are designed to last longer would be chosen, resulting in over 30% less material use for the wheel *component*. The lifetime of gearboxes and engines would be increased with more controlled maintenance and more remanufacturing, which would result in a slight decrease in material use for those *components* (est. 8%). Reductions were not estimated to be more because current gearbox and engine remanufacturing practices involve changing out the *components*. It was acknowledged however, that these practices could change, especially with the help of the *component company* to conduct quality control and/or to review and adjust current practices.

Looking beyond the component-level, it was noted that the material efficiency could be increased at other levels as well, including the subsystem (e.g. gearbox), truck and fleet levels. Subsystems could be remanufactured and reused more often and could be exchanged amongst all trucks in the fleet, maximizing their use.

In addition, customers are said to choose trucks partially based on their resale value. It was said that trucks that are better equipped have a tendency to be in higher demand on the used truck market. This means that some customers choose trucks that have more equipment and are larger and more powerful than they may need, demanding more material for parts, subsystems and the truck itself. Hypothetically, under a function sales model, the customer could gain utilization of just the right truck for the jobs they do, nothing more. It follows also that the truck OEM could manage trucks at the fleet level allowing pooling and reduced need of trucks.

Other benefits of function sales were also noted that could reduce material intensity even more. With control of the trucks, the OEM could better collect use and failure data of the trucks and their components. This would allow for improved product development and maintenance planning. They could also better utilize existing condition monitoring equipment to help identify component and other failures before they occur.

All in all, function sales could stimulate component choice focused on max durability and could allow optimizing maintenance for a fleet of products, pooling product resources, matching the best suited product to the customer, and collecting use data and monitoring systems for best possible use. Each of these things could lead to better material efficiency at the component level and beyond.

5.4 Defining obsolescence

RQ5: How can obsolescence be defined in a way that is conducive to identifying opportunities for product life extension and use intensification? (Paper V)

Obsolescence is one type of disuse, and according to our preference, a state of a product being obsolete rather than as a process of becoming obsolete. We suggest the following definition.

Product obsolescence is a contextual condition and time of disuse during which there is a mismatch between product, function, application, duration and user as judged by the user(s).

According to this definition, obsolescence represents one period of disuse during the lifetime and is not equivalent to product end-of-life. It may occur collectively as the product becomes “out-of-date” or “not useful” at the societal or market level. Concrete obsolescence decisions, however, are contextual and made based on individual product characteristics, individual needs, and in the current setting. They are made largely based on current, local and personal norms and needs and based on user expectations of product function (Cooper 2010; van Nes 2010; Sivaloganathan et al. 1995; Rai & Terpenny 2008). True obsolescence of an individual product is determined in a specific context, nowhere else. Also importantly, product obsolescence means disuse for all parts contained in the product regardless of the parts’ individual conditions.

This definition attempts to capture the main elements of obsolescence and acknowledges that there are hard, physical elements, and soft, social elements that can lead to obsolescence. While they cannot be completely drawn apart, product obsolescence is described here with more objective elements – the product (what is it?), the function (what does it physically do?), the application (where does it do it?), the duration (how long it does it for?), the user – (for whom does it do it?) – and a more subjective element, user judgement (what does the user think?).

Based on the definition, a product can be deemed obsolete for one combination of function, application, duration, and user and can become usable again with another combination. This is an observable phenomenon both with the case component, with component end-users shifting used components to other applications in their factories, and in society in general, with consumers repurposing their Friday night clothes as gardening wear.

Each of these reuses mean that the product lifetime is extended. Defining obsolescence as a period of disuse also highlights its place as a natural part of a product lifetime.

A product’s lifetime is the period of time that includes periods of use and disuse and that starts when product manufacturing is complete and ends when the product is completely destroyed or consumed.

> *Where use periods can be characterized by a context in which there is a match between product, user, function, and application. Disuse periods are times during which there is no match, perhaps no user at all, e.g. transport. Use periods themselves include passive use, during which the product is idle and not utilized, and active use.*

This definition does not take one user's, one function's, or one actor's perspective, but the product's perspective. According to the definition, the product's end of lifetime occurs only when the product is physically completely destroyed, not when it is discarded or changes ownership or goes through a restorative process.

Based on this definition, the true goal of extending product life is not to extend product life but to increase the sum of use periods by lengthening use periods and/or making more of them. Restorative actions (repair, resell, etc.), which are disuse periods, are only the means to allow more use periods and by themselves, decrease use intensity. By the definition, intensifying use involves increasing the active use in comparison to the entire lifetime:

Use intensity = active use per product lifetime (function/ time)

Operationally then, use intensification involves reducing the length of disuse periods, such as storage and passive (idle) use (including obsolescence), and increasing active use. Active use may be measured by function, which depending on the product could be measured by time, or other measure of function delivered (e.g. occasions, kilometers).

Each of the distinctions provided here are intended to promote the reduction of disuse periods and passive use and clarify the intent of product life extension as to extend *use periods*, not *disuse periods* and to present product obsolescence as a natural transition (and opportunity) from one use to the next.

6 Discussion

This thesis is aimed to contribute to *science*. What does that mean?

Science is defined as both an activity towards something and as the something itself. Oxford defines it as an activity, *"The intellectual and practical activity encompassing the systematic study of the structure and behaviour of the physical and natural world through observation and experiment,"* and as a something, a product, *"A systematically organized body of knowledge on a particular subject."* Merriam Webster offers a bit broader view of science as a something, *"The state of knowing: knowledge as distinguished from ignorance or misunderstanding"*. We perform the activity of *science* to hopefully contribute to this state or body of knowledge.

This thesis contributes could be classified as relevant to a couple subject matters, product end-of-life and life cycle management, to name a couple. For better or for worse, this project was designed for studying one case. While this allowed the single case to be viewed from multiple angles and to provide a more rich description than would have been possible with multiple cases, the potential for generalization is less (Thomas 2011).

How much can we contribute to the body of knowledge with the *single case* used? There are some limitations to using cases (especially single ones) in theory development. As Stake says, qualitative studies describe how "things were at a particular place at a particular time." (Stake 1995). Although we didn't describe the systems we studied only qualitatively, this statement is still relevant.

According to this reasoning, the study provided conclusions only directly relevant to the case itself.

> *Critic: You mean your results can't be directly applied to anything else?*
>
> *Me: Directly, no, probably not. While I'm quite sure of what I observed, I'm not sure the results could even be applied to the case component itself, generically speaking.*
>
> *C: What do you mean?*
>
> *Me: I have looked at the case component from many different angles but with only several samples during a particular period of time. I have not looked at all perspectives. Things may have changed. Other business segments, other end-users may be different. While I have no reason to believe that's the case, that's the reality.*
>
> *C: Then why is your work worth anything at all?*
>
> *Me: Well, I think it's worth something because I document what really happens, albeit for the case at hand… Lessons learned from this case could be used as a starting point in another case or context, something to look for… right?*

How conclusions garnered from this study can or should be utilized depends on one's point of view. (Un)fortunately and complicatedly, each person who is a party to this study, from the one with the most responsibility, the researcher (me), to those who read (and cite) it, have a role in determining how these conclusions are used.

There are at least two critical activities that determine whether and how the conclusions from this study become part of the body of knowledge. One critical activity in this is the communication of the research itself. I have the responsibility to conduct and communicate my findings (the manuscripts, this thesis and related presentations) in a "responsible" way. In regards to the limits to which one can draw her conclusions, I think we've been pretty careful in these works. Paper IV provides the most assertive style, although the results are still presented as propositions, ideas for others to consider.

The other critical activity is how others read, interpret and utilize the texts (and other media) we publish and communicate. How would I suggest that propositions from this study be utilized? What is their relevance?

First, there are a couple characteristics of bearings that do arguably make them interesting for learning about generic product end-of-life management (previously mentioned in section 4.2). Bearings have one main material type, are recyclable and remanufacturable in their design, and their individual obsolescence is seldom (if ever) affected by fashion and only sometimes affected by technological advancements. Hence, *the bearing is quite the generic and simple widget that is free from some of the challenges that make product end-of-life for many products difficult*. The bearing represents (on the surface) a relatively bare-bones case of product-end-of-life… without all the clutter. This lack of apparent complexity in the product itself arguably allows one to look beyond product complexity to see other matters at hand.

Beyond the favorable profile of the component studied, conclusions from a case study can act as "theoretical propositions" (Yin 1994) that can be applied more broadly. How these theoretical propositions provided from this study could be applied depends on one's point of view, and the focus of each proposition. Some of the propositions are aimed at and derived from studying the product or material, while others are derived from interviewing product end-users.

Considering the products of the study, one could start with applying the propositions to the same type of company or type of component. Following this reasoning, a multi-national manufacturer of bearings (a competitor) would be the ideal match. However, such a "match" only considers the apparent (and likely superficial) characteristics of the objects in question, in this case, the products and companies.

The end-of-use outcomes of bearings result from, in part, the specific construction and material make-up of the bearing as well as the specific supply chains, manufacturing processes, organizational structures and people in the product chain. As such, such a match does not necessarily include situational and temporal aspects specific to the studied case and is not a true match, per se.

Even so, at their least usable, the product-specific results provide knowledge of three different types: (1) knowledge from yet another product case and assessment, (2) theory support, one more example for which existing theories (e.g. the waste hierarchy – *reuse is better than recycling which is better than disposal*) – holds true and more generic (3) pictures of how downstream flows of components can look, indications of their level complexity and points at which intervention could be possible. Each of these types of knowledge contributes (to however small magnitude) to the "body of knowledge".

The body of knowledge for any field, is invariably made up of lessons learned and propositions, some of them from specific cases. Lessons learned for the company like, *there are many bearing that are of the "right size" for remanufacturing that are not remanufactured*, exemplify a case in which there are opportunities, possibly even "low-hanging fruit". Assuming that the company's situation is not unique, these type of opportunities is at least something to look for. In fact, *something to look for* is a decent way to describe some of our case-based conclusions. These contextual and *case-based conclusions* may, in the end, be used to create, modify or bolster theory (*the way things are* OR *the way we think things are OR the way we describe how we think things are),* but it is the contextual nature which makes it important to understanding and so-called expertise.

> *Context-dependent knowledge and experience are at the very heart of expert activity. (Flyvbjerg 2006 p.222)*

Finally one can consider the real world "problem" we studied. As one of my brother's friend has (half) joked a few times about the component type I studied,

> *"You just take em, melt em down and make new ones. That's it! Problem solved, project done!"*

Yes, that is true. Given the environmental angle of this study, the component studied is not commonly (if ever) seen as a menace to society. There are not exposés of these components laying in the bottom of the ocean, being burned in barrels in Southeast Asia, or poisoning water supplies. They are, on the contrary, according to best knowledge recycled. They are made up of mostly low-alloyed steel, which is valuable and is "compatible" to international steel markets, so while some substances go astray, the components and most materials end up in the "right place". However, from the environmental and resource perspective, they can, according to the results from this study, be dealt with in much "better" ways.

7 Conclusions

Components are often the change-outs, the consumables, the bits that get worn and replaced many times over. A paper machine may be used for more than 50 years but the components in it will be replaced several times. A truck may be used for many million kilometers while the components in them will be used only a part of the truck's lifetime. If looking at the material stewardship suggested by the circular economy, they represents a key area for improvement.

With RQ1, we asked: *Why do industrial end-users scrap otherwise remanufacturable components?*

Components' lifetimes come to an end after an end-user decides the components (or products in which they sit) are not usable anymore. Each end-user (and maintainer) operates in their own system and have their own expectations and needs. One end-user may be more risk averse than another and one end-user's obsolete component may be usable for another end-user.

Our case studies showed that there are end-users who utilize remanufacturing as a part of the component's maintenance cycle while others in a similar industry never utilize remanufacturing. Some end-users that rarely choose remanufacturing still are open to it due to its environmental profile. Others mention the moral dilemma of scrapping a component that looks like it might be reusable but lament that *they have to be sure*. Ensuring component quality via remanufacturing could be an attractive alternative for these end-users.

However, end-users (and maintainers) operate in complicated systems. They do their best to manage their system with protocols to determine *when a component should be replaced* and *if it should be sent for remanufacturing*. These protocols take account of the component's perceived condition and/or its time in use and are derived considering costs and benefits on the system-level. Hence, gains of using a component longer (or remanufacturing it) may be considered too small given the possible risks and associated costs at the machine or factory level. That being said, an actual cost-benefit analysis may have not been done. An end-user may not have the time or information to properly assess the remanufacturing alterative or have never even considered it as an alternative in the first place. Moreover, they may be satisfied with the current state and may not want to risk disturbing it for a relatively a small reward. As a consequence, a status quo in which remanufacturing is not the common practice may be hard to break.

The following research questions were: *Where in the life cycle of products do components become obsolete* <u>*and*</u> *where do they and their materials go? (RQ2)*

AND

What are the environmental benefits of functional recycling and remanufacturing? (RQ3)

For the case at hand, remanufacturing does occur but non-remanufacturing is a more common end-of-use outcome. Even though components are changed out before they fail and are remanufacturable, they are commonly scrapped anyways. This represents a huge opportunity to remanufacture more. Furthermore, remanufacturing represents sizable savings in energy, material, and emissions. For a manufacturer like the sponsor company that produces similar components in many sizes, capturing the largest components could allow remanufacturing a large share of the total mass of components sold, even though these components would represent only a small percentage of the number of components sold. This would mean a great improvement in the material efficiency and environmental performance related to their product.

For the studied steel components, recycling is distant second best in terms of environmental performance and has its pitfalls. Scrap steel is often handled as one fraction, in which steels of all alloy types are mixed. While the iron from them is mostly recycled, some is lost to slag. Most of the valuable alloying elements end up in carbon steel, where they are not needed and are actually contaminants. Thus, while recycling happens, it does not result in all elements ending up where they can be used again.

Functional recycling, or recycling of substances (such as alloying elements) to a material where the substance's intended function can be realized, is a potential for better recycling. The study showed that there may be opportunities to catch many components and to recycle them in a functional way. Components changed out from machinery such as a paper machine or a truck sometimes represent a larger mass than those that remain in the machine when it is scrapped. Components not scrapped with their product are liberated and could be sorted for more functional recycling, which would mean saving alloying elements, and in essence, the energy and emissions associated with digging and refining them. That being said, infrastructure and markets for such fractions are not well developed if at all. As such, widespread functional recycling for the components does not appear to be feasible in the current system, with the current infrastructure.

RQ4: Can a function sales model for a higher-level product result in better material efficiency for a component?

Function sales is being advocated as one of the means for a circular economy. While this study did not investigate the potential of a function sales for the component, it did investigate how the component's material efficiency could be affected by the function sales of a higher-level product, a truck. It was concluded that such a business model could lead to tangible material efficiency gains at the component-level, most notably by creating a preference for components designed and constructed to last longer. Selling truck function would also allow long-term quality control and improvement of components through monitoring and performance data collection and analysis, allow the pooling and interchanging of components between trucks, and considering the control of large volumes of components, create better conditions for remanufacturing and functional recycling.

RQ5: How can obsolescence be defined in a way that is conducive to identifying opportunities for product life extension and use intensification?

Scrap happens! It happens where humans and machines interact and for a bunch of reasons not easily explained or understood. To make things even more complicated, *scrap is only scrap* *because someone said it was scrap*. Obsolescence is contextual and is suggested to be defined as a period of disuse during a product's lifetime that is not necessarily terminal. Because contexts can be changed and products in disuse can be used again, there are possibilities for extending lifetimes. An obsolete product can be shifted with or without restoration to another use.

OVERALL, the study set out to explore *what a component manufacturer can do to improve the end-of-use management of its product? It was found that* a component manufacturer can influence the material efficiency of their components by (1) taking on some of the risk associated with using and reusing components to make it easier for end-users to choose remanufacturing, (2) assisting end-users and maintainers with quality control of components to allow more reuse and remanufacturing, (3) shifting used components between end-users and industries where expectations and needs are different (4) changing their own business and remanufacturing processes and in some cases, product design, to allow for more obsolete components and parts become usable again, and (5) dissolving the differentiation between new and remanufactured. Operationally, besides more remanufacturing, these measures could mean function sales or performance-based contracts, controlled cascading of components between end-users and applications, and combined production lines, incorporating both new and used parts.

8 Recommendations for the company

At the beginning of the study, a view some employees at the sponsor company had was, "*it's 100% recyclable". Isn't recycling good enough?* and "*Reuse a component?! Why, they're like lightbulbs. Just install a new one*." While these views were not always expressed, they permeated through the common view of their product.

There seem to be a few that have changed their view in the course of this project and are a bit more open to the idea of remanufacturing as a rule, not as the exception. This can be, in part, based on the reality presented from this project. While the product is "100% recyclable", the actual results are less perfect. Some of the material, including iron and alloying elements ends up in slag and most of the alloying elements end up where they aren't wanted. Thus, every time through the recycling system, new alloying elements have to be dug from the ground and added, meaning near 0% recycling for these elements, not 100%.

My conclusion is: *Recycling is not good enough*. In fact, it appears as if the scrap-and-recycle model is just a truly sub-optimized standard practice (for the case at hand). The component at hand, like many products out there, is made of many parts. To make the parts and make a new finished component requires over 100 processes (could be many hundreds depending how you count) even without the mining of ores. Remanufacturing the same component requires between 5-10 processes. Even by this simple measure, there are great benefits. Every process requires time, material, energy, and precision. Remanufacturing is less resource intensive by nearly every measure (perhaps with exception of manual labor, currently). This is no surprise; it just makes sense. Surprising is that, there is a huge opportunity for the company to remanufacture more (only a fraction of the components sold are remanufactured). Intact and partially functional components are scrapped as a precautionary measure and some of the faults indicated are those that can be remediated with remanufacturing.

Admittedly, there can be hidden faults in used components that may demand more time to detect and repair, but these limitations in the remanufacturing system can likely be fixed. The sponsor company is an industry leader in all things mechanics *and* precision processes *and* have great expertise in material sciences. As such, if remanufacturing became a priority, refining the 5-10 already-functioning already pretty-good processes might not be very difficult. There are already-existing quality control processes used within the company that could be added to the remanufacturing procedure.

It should be remembered however, that end-users have reasons for not choosing remanufacturing. If the company wants to break this state and really wants to increase remanufacturing of its components, it may attempt (1) to assist the end-user's with evaluating the implications of the remanufacturing offering to alleviate the end-user's lack of time and information burden, and/or (2) alleviate the end-user's risk burden by taking on risk, perhaps by offering component function (or performance) instead of selling the component itself.

Finally, the *remanufactured* label is a blessing and a curse. For some, it says "quality" or "as good as new". For others, *remanufactured* still means "used" and creates, perhaps unnecessarily, stigma that, in turn, have to be overcome. If the warranty is the same and the function and quality is “like new”, then maybe it’s only right for new and used parts to be mixed together. Used parts are inspected and assessed for quality, sorted and put into the production line. Manufacturing and Remanufacturing then become one.

9 Reflections

The views, epistemological and otherwise, of the author have changed over time, with a change or three occurring even before he consciously considered what his view was. This section provides a couple (attempts at) explanations and excerpts that only now seem somewhat appropriate.

This study was conducted with an instrumentalist's view, a pragmatic approach which holds that while it is not possible to, beyond all doubt, prove that one theory and one theory alone properly explains reality, the best theory is the one that most effectively explains or predicts a given phenomenon (e.g. John Dewey; cited in (Ho 1994). Thus, the lessons learned and conclusions presented here are not seen as absolute but as usable (if not really good) tools to understand and possibly make changes in the system. This philosophic departure feels most suitable to the nature of the study as a dual-purpose, academic and "real world" project and fits my (current) view of how to best describe *complex systems*.

Complex systems are inherently "wicked" (Rittel & Webber 1973). Wicked problems, which include those problems that involve a mix of people with their surroundings, "are only loosely formulated", as opposed to tame ones, such as a quadratic equation (Coyne 2005).

Wicked problems persist, and are subject to redefinition and resolution in different ways over time. Wicked problems are not objectively given but their formulation already depends on the viewpoint of those presenting them. There is no ultimate test of the validity of a solution to a wicked problem. The testing of solutions takes place in some practical context, and the solutions are not easily undone. (Coyne 2005)

The purpose of this study – *how a component manufacturer can improve its product's material efficiency and end-of-use* – is a wicked problem and requires investigating a complex system. Systems thinking, one cognitive approach in gaining understanding of complex systems (Richmond 1994), explains one key aspect of how researchers looked at objects and related problems. For this study, system boundaries were expanded and contracted based on the question at hand and not to be forgotten, our own value judgments (Ulrich 1983). MFAs focused on the end-of-use systems, from when the component entered use through recycling processes to final recycling outcome. The abbreviated LCA (PI) assessed the environmental impacts of remanufacturing and recycling alternatives with consideration to the product's entire life cycle. This choice is likely taken for granted from a LCA perspective (*as is praxis*) but is an important choice nonetheless.

Where does this study belong? As I sit and write this 5 plus years into this study (some parental leave was nice), I still wonder about the answer to this question.

The study can, I believe, be placed at the intersection of technical and social sciences. I depart from a technical perspective, thinking mostly about artefacts, flows and processes, and end closer to a social perspective, thinking about how people use and abuse these artefacts, make decisions about them and just do stuff as people do. This is not an easy endeavor, but it is (was) necessary to address chosen research question and to describe the chosen system. I operated, in essence, at what Latour (1993) calls "the great divide" between studies of "nature" and studies of humans.

If I look at the types of methods I've used and abused from this projects inception, I've used industrial ecology analyses such as MFA, SFA, LCA, LCT. I've even done some basic stoichiometry and economics analyses. I've calculated values and value-added based on sales prices and scrap commodity prices (one of the many things that never made it into any manuscript), I've taken sales data and sliced and diced it without exactly knowing what I was looking for. I've spoken to experts in all of the above topics as well as some that work with brass, ceramics, gearboxes, food-rated mechanical products, lubrication, dismantling. I've read about, but not become fluent in thermodynamics, metallurgy, organizational change, cement plant maintenance, qualitative research methods, action research, communication, logistics, among others.

If I look at the areas of research I have dabbled in and borrowed from, I could name Industrial Ecology, Remanufacturing, Waste Management, Recycling, Operations Management, Maintenance Management, Decision-making, Risk sciences, to name a few.

I present all this not to brag, nor to apologize. This is the reality of the system study that I undertook and the culture in which I have operated. Could it have been done better? Surely!

I could have been more productive.

The biggest factor that I think about here is confidence. It is known that fear to act, do, write, can lead to not doing, acting or writing. I feel that, unfortunately, I am a less confident individual than when I started this project. I think this can be attributed to two things (1) (perceived) failures along the way, and (2) gained awareness about how much I don't know. Both have enhanced self-criticism, for better or for worse, and at times, paralyzed me. The latter is coupled at least, to a sense of "enlightenment".

To a certain degree, both these phenomena have come due to the multi-disciplinary nature of the study. Trying to become comfortable in other people's backyards… Am I a natural scientist or a social scientist? I am not sure I belong in either. As one Hannes Johnson (2015) wrote in his dissertation (one of the more entertaining and relevant ones for me),

"I'm a bit of an academic mongrel."

The stumbles and pitfalls of doing a systems (and trans-disciplinary) study include always wondering, Where do I belong? What does my research offer anyway? With these questions comes a bit of fear. Am I good enough for either side? I hope so. I also know that I am not alone. I gather that I'm not the only one who has started with some vague research questions and an unknown destination and 5 years to get there. Nor am I the only one who used (vague) research questions (and the process of writing and re-writing them) to sketch and re-sketch a general roadmap (to an unknown destination) and to frame and re-frame results, only to finally present the study later as a linear research process.

I could have wandered down a more "fruitful" path. I am not aware of such a path but I acknowledge that choices could have been made differently.

I could have narrowed my study and maybe would have described a few things in more detail.

As a result, I would have learned more about these few things. However, I don't think I could say as much about the big picture.

Naturally, this study is imperfect. It could have been better. It is somewhat of a mixed-breed, a mutt. It is the result of telling someone to look at a product system and describe it. In the end, it is, as far as I can gather, the only one (like all theses) of its kind. Does that make it good? No, not necessarily, but is does provide new perspectives, and both context-specific (empirical) and generalizable (rationalized) knowledge. I, for one, think these perspectives can be utilized (not that utilization is the ultimate measure), and have already seen them utilized at the sponsor company. Time and critique will soon tell what the community will say (if anything).

10 Suggested research

Challenges were identified during the project that provide a few ideas for research projects. For one, functional recycling can only happen if products end up in the right place. Currently, there are not well-developed recycling infrastructures for different alloyed steel types meaning that secondary scrap steel is mixed and alloying elements are lost; they end up where they're not utilized. This project only follows one type of low-alloyed mechanical part. A more society or policy-oriented study could investigate what quantities of relevant recycling fractions of many parts may exist for a given sector or geographical location, how the infrastructure could hypothetically be set up, and what costs and benefits would be realized.

Secondly, non-remanufacturing of the studied components is the norm, both company personnel and many of their customers treat remanufacturing as a second-best alternative. Making remanufacturing the norm, would invariably require changes in sales priorities and incentives in the sales channels (manufacturers and their distributors) and changes in replacement and/or remanufacturing protocols (*Paper IV*) at customers. Studying a manufacturer or a customer (end-user) making such changes would contribute to understanding about how an organization makes such a transition.

Thirdly, cascading products between multiple uses is good in theory and already happens to a certain degree in society ad hoc at households, and within second-hand markets and refurbishers. Making it happen as part of a planned strategy for a product's lifecycle is less understood. For example, the sponsor company manufactures many different sizes and shapes of bearings. This makes matching one willing end-user's used bearings to another end-user's applications challenging. Investigating how a manufacturer could systematically cascade its products from one use to another would contribute to understanding about how this could work and perhaps give an indication of if the efforts of doing so would be worthwhile.

Finally, products don't become scrap by themselves. Someone must declare them to be so. This study follows others that declare the need of more investigations, especially non-consumer ones, focused on how *scrap happens*.

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