THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Getting More Out of the Afterlife

Exploring Product End-of-life Management of a Component Manufacturer

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Cover Picture: The tea light symbolically burns out when it reaches its end-of-life. It is a product that, like many other products, consists of multiple components and valuable materials. Its use life is determined by two components (consumables), the wax and the wick. Two other components are largely intact after use, the aluminum wax holder and the iron wick holder, but both technical and economic factors make it unfeasible to capture and prepare them for reuse. Furthermore, the aluminum wax-holder and the iron wick-holder can be recycled separately, but if the two are stuck together, the entire tea light may end up in steel recycling where aluminum is lost as waste. Thus, although valuable components may be reusable and recyclable they may be lost as waste instead. The tea light is a small, low-cost consumable but as an example, it illustrates generic challenges in managing use and afterlife of products, large and small. (Picture from Damon Hart-Davis/ DHD Multimedia Gallery)

Chalmers Reproservice
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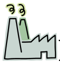
To my wife, Elisa, and daughters, Noelle and Linnea, who love me even when my attention to them fades and my thoughts wander into the world of scrap.

ABSTRACT

Material intensity related to product consumption has become part of societal discourse and reducing it has become a priority of some industrial actors. Focusing on product end-of-life (EoL) 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. The project presented here explores ways in which a large component manufacturer may improve the EoL management of its products. The project was conducted in the format of a case study of a multi-national component manufacturer (the case company) that has committed to the principles of life cycle management (LCM). Although the company remanufactures some of the products sold and knows that its products are generally recycled, it wanted to know more about the downstream material flows and related loss of material, function and value and find improvement potentials. Two contrasting business areas were chosen as study subjects – one *Industrial* and one *Automotive*. Eight hypothetical EoL improvement opportunities were identified from literature and evaluated during the course of the project. Using material flow analysis (MFA) and analyses of company sales data from the two areas, snapshots of the company's downstream (mostly) low-alloyed steel flows were taken. The circumstances of product EoL were evaluated and product liberation from parent products was of particular focus. In addition, remanufacturing potential was evaluated based on existing company preferences. The results from the two cases give indications of what types of expected and unexpected opportunities might be available to a component manufacturer. Results from the *Industrial* case indicate that that the potential to remanufacture the company's products is substantial. It appears that many products that meet the company's remanufacturing size and condition preferences are not currently remanufactured. If all products identified for the case were in proper condition to be remanufactured and if they were remanufactured one time, the potential would represent a 30% reduction of material use for the business area studied. The *Automotive* case shows that design trends might hinder future repair and recycling of some automotive products. In addition, although the studied products are not remanufactured themselves, the company may have an opportunity to contribute to the quality control of parent product remanufacturing. Many of the products from both cases are liberated at EoL and there appears to be an opportunity to sort and recycle these low-alloyed products to realize more "functional" recycling. However, whether the volumes of the company's EoL products are sufficient to justify such dedicated material recycling requires additional investigation. These results along with societal interest to increase functional recycling imply the need to further investigate what a recycling program for specific material grades could yield.

APPENDED PAPERS

Paper I. An Industry-focused case study

Derek L. Diener, Anne-Marie Tillman

Product end-of-life management of a component manufacturer: Exploring improvement potential

Manuscript submitted to scientific journal April 2014

 Paper II. An Automotive-focused case study

Derek L. Diener, Anne-Marie Tillman

Automotive component end-of-life management with a LCM perspective: Exploring improvement potential

Manuscript submitted to scientific journal April 2014

PUBLICATIONS BY THE AUTHOR

Diener, Derek L., Tillman, Anne-Marie & Harris, Steve (2013). Lessons Learned from Conducting a Company-level, Downstream MFA in *Re-engineering Manufacturing for Sustainability: Proceedings of the 20th CIRP International Conference on Life Cycle Engineering, Singapore 17-19 April, 2013*, Springer-Singapore, pp. 559-564. http://dx.doi.org/10.1007/978-981-4451-48-2_91

Table of Contents

1. Introduction

Humankind currently requires more than one earth to sustain its existence (Wackernagel et. al. 2002). Trends of specific types of resource use indicate impending challenges. For example, use of non-renewable materials such as polymers and metals has quadrupled over the past 50 years. It is expected that the cost of extracting their parent materials (oil, and ores) will at some point exceed the utility provided by the materials (Allwood et. al. 2011). Increasing material demands from developing nations are projected to result in demands for steel, aluminum and copper that are five times greater than current production (Donella Meadows Institute 2014).

In addition, the manner in which materials are obtained, used, and disposed places burdens on ecosystems and people alike. These burdens are realized in the modification, weakening or destruction of ecosystems as well as the endangerment of human health and survival (Donella Meadows Institute 2014). Excessive material use is also directly apparent in drastic increases in municipal waste produced and associated problems can be observed in the form of filling landfills and pollution to air, water, and soil in their surroundings (King et. al. 2005).

Society has enacted policy in response to these material use and waste alarms. Governments have implemented more stringent landfilling legislation and have applied extended producer responsibility (EPR) for some products (King et. al. 2005). In the E.U., EPR-based policies such as Restriction of Hazardous Substances (RoHs) and Wastes from Electric and Electronic Equipment (WEEE), have assigned the responsibility for the costs of product collection, treatment and recovery to producers (Gehin et. al. 2008). The end-of-life vehicle directive ("ELV" Directive 2000/53/EC) uses another approach and establishes minimum levels of ELV material reuse and recycling, maximum levels for disposal and requires OEMs to publish vehicle disassembly guidance (EC 2014). Japan and the U.S. have implemented similar policies (Rose 2000). In addition, indicators for material use have been integrated into some policy in Europe, the U.S. (Mazzanti & Zoboli 2009) and China, and non-governmental and voluntary programs have been instituted to support the same (Allwood et. al. 2011). At the local level, prevalence of municipal recycling programs has increased (Jenkins et. al. 1999). Industry has responded with efforts to better utilize waste and towards industrial ecology and symbiosis (Ehrenfeld & Gertler 1997; Jackson & Clift 1998) and to reuse and remanufacture products (Sundin 2004; Stahel 2005).

As a result of societal efforts and industrial efficiency programs, material use per produced unit has decreased but at the same time, total production and ultimately, material use, continues to increase (Rossy et. al. 2010). Hence, continual efficiency improvements do not appear to solve the problem of increasing material use. The rebound effect is one often-cited theory for why such efficiency improvements are not enough to solve the problem. It holds that the economic gains of increased efficiency are often invested in more production which reduces the intended positive effect of resulting efficiency (UNEP 2011a).

Because of the rebound effect, some have called for an absolute decoupling of the economy from resource use (Baines et. al. 2007). The linear nature of the current economy is cited as the reason for the economy's dependency on resource use. Economic growth depends on material throughput, efficient or not. The so-called circular economy (or service economy) is advocated as an alternative to the normal linear one. In it, functions or services are sold instead of things, and old things become new things instead of waste. Instead of requiring throughput, or sales of products, the circular economy requires that the function or service be delivered. Proponents claim that this would incentivize "round-put" or re-cycling of materials (Ellen MacArthur Foundation 2014; Stahel 2005).

1.1. Project impetus – But what can a company do?

This discussion alludes to a fundamental problem in the macro-level economy. It suggests, by many measures, a radical transformation in the way society uses materials. Considering the magnitude of the problem and the societal transformation suggested, how can an individual manufacturing company respond? Despite any inherent will to contribute to a solution, results from any action taken by a company are dependent on other actors and the mechanisms of the economy of which it is a part. A company operates under its own pressures too – shareholders expect dividends and decisions must be made with consideration to the company's profit margins and ultimately, its survival (Jackson & Clift 1998; Welford 2003).

Fortunately, some material intensity reduction efforts contribute to wider profit margins by reducing costs (Jackson & Clift 1998). Reducing material intensity can be pursued by continuing with well-established cleaner production efforts source reduction and waste minimization (Jackson 2002) and by pursuing underutilized *material efficiency* opportunities such as reuse and product life extension, advocated by Allwood et. al. (2011) as being critical to breaking the societal trend of increasing material use.

Hence, there are some activities that strengthen the viability of the company and that contribute to a less material intense society. However, since a company's area of influence is limited, 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-life (EoL), a critical point for shaping ultimate material intensity and when a product can be reused, recycled or disposed.

The purpose of this project was to investigate how a component manufacturing company can reduce material intensity via improved product EoL management. The project was conducted with case studies of two contrasting customer segments of a multi-national component manufacturer. For each case study, the EoL material flows of mostly-steel products was mapped using material flow analysis (MFA). Improvement opportunities were identified and evaluated. Results from the two case studies were then compared and contrasted to one another to gain insights with interest the question: *What product EoL opportunities does a component manufacturer have and how much can they actually reduce material use?* This question was the primary one for the project. The secondary question and one that will likely become a focus for project continuation is: *What factors appear to facilitate or limit the component manufacturer's possibility to enact such opportunities?*

1.2. Thesis outline

The project is presented in this licentiate thesis in seven chapters. First, in *Chapter 2*, a literature review of the project theme, product EoL management, is provided followed by a background of two key disciplines, life cycle management (LCM) and material flow analysis (MFA). Next, in *Chapter 3*, the methods used during this project are explained. In *Chapter 4,* results of the two case studies are presented. *Chapters 5-6* present reflections on this project and discussion of future work. Finally, *Chapter 7* provides conclusions from the project. Two papers are appended to this paper, one generated from each of the two case studies.

2. Literature background

This project was conducted with focus on product EoL management, set in the realm of life cycle management (LCM) and executed to a large degree following the principles of material flow analysis (MFA). The following sections give some background into these three areas of research.

2.1. Product EoL management

What are EoL products and why are they interesting? EoL (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. 2005). They are interesting to society and companies for two reasons. First, EoL 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 EoL 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 EoL management dependent on what processes are used to dispose of the products or make them, or the materials they are made from, usable again (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 (European Commission 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 substantial benefits in resource efficiency despite that it sometimes requires replacement components and sometimes extensive processing to make the used product “like new” (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. Economically, the remanufacturing process is often less expensive than manufacturing (Lund 1985). As one example of a manufacturer of steel production machinery, costs were 40-50% less (Bras and Mcintosh 1999).

The waste hierarchy’s third recommended option, material recycling, offers benefits as well. For example, by avoiding raw material acquisition and refining, recycled steel is 44% 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. Thus, functional recycling occurs only if substances such as alloying elements end up in the right place (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 2011b; 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 2011b).

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 2011b).

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 EoL 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- *RSC*) and product-service systems (PSS) try to capitalize on some (if not all) 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 or *RSC*s are centered on the physical take-back of product and involve often change of product ownership (Rose 2000), whereas PSSs involves selling product function or service and without change in product ownership (Mont 2002; Baines et. al. 2007).

Since these business strategies involve product take-back with or without change in product ownership, managing product-related values throughout the product lifecycle is especially important to reaping all available market values. For example, product service life can be extended for certain products by service during installation or condition monitoring throughout use (Cooper 2005; Cooper 2010). This is especially relevant in the case of PSSs, for which ownership is not transferred to the customer and in which premature end to a product's service life is detrimental to the selling company's bottom line.

In addition, adapting product design has a tangible impact on product life extension, reuse, remanufacturing, and recycling opportunities. 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 EoL management including: preventing EoL through *extension of product life*, *direct and cascading reuse*, *reusing of a component after parent product EoL*, *remanufacturing or repair*, *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*. This list of opportunities is used later as an analytical framework to assess and compare information gained from the two case studies.

2.2. LCM and MFA

This project was conducted in the context of life cycle management (LCM), which 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 2001; 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 2001) 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. First, a company can consider making a transformational change with consideration to the life cycle perspective. For example, a company can assess its very foundations and change the very way it does business to maximize life cycle resource efficiency (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). Finally, a company can focus on the lifecycle of an individual product or on different phases of the life cycle, from 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-life (EoL) (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 LCM 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), material flow analysis (MFA), and tools for eco-design (UNEP/SETAC 2009), to name a few.

MFA is a tool used commonly in an older discipline, industrial ecology (or metabolism) (Ayres & Ayres 2002). Harper et. al. (2006a) groups 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).

EoL 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 and 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, including related trade, use and EoL. 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. 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 EoL 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, albeit focused on specific products and functional units, not bulk company-level flows (Baumann & Tillman 2004). Hence, in EoL management as well as other pursuits, LCA is often tailored to assessing one scenario or multiple defined alternatives. Examples include: life cycle inventory of mobile network components at EoL (Scharnhorst et. al. 2005), comparisons of manufacturing and remanufacturing alternatives (Kerr & Ryan 2000; Smith & Keolian 2004), comparing lightweight cars and standard cars in EoL processes (Schmidt et. al. 2004), assessing the waste hierarchy of waste paper (Schmidt et. al. 2007), and the environmental benefits of composting (Blengini 2008).

Economic values yielded from EoL alternatives have also been compared, such as the investigation conducted by Low et. al. (1998) for telephone headsets, Smith and Keolian (2004) for engines, and the valuation conducted by Dahlström et. al. (2005) as part of a value chain assessment for iron and steel flows.

Beyond comparison studies, product EoL management alternatives are otherwise often presented as descriptive lists of options (e.g. King et. al. 2006; Cooper 2010; Pigosso et. al. 2010), looking at societal opportunities (e.g. Yellishetty et. al. 2011; Allwood et. al 2011; UNEP 2013), as case studies of already existing EoL management "successes" (e.g. Paton 1994; Sundin 2004; Östlin et. al 2008).

Despite these specific comparison studies, and documentations of alternatives and their benefits, few (from the author's knowledge) exploratory case studies of company product EoL have been published.

3. Methods

The purpose of this project was to *investigate how a component manufacturing company can reduce material intensity via improved product EoL management.* Based on this purpose, the primary question addressed was – "*What product EoL opportunities does a component manufacturer have and how much material use do they actually reduce?"* The secondary question – "*What factors appear to facilitate or limit the component manufacturer's possibility to enact such opportunities?*" was not a priority but provided indications to be used in framing project continuation.

The project was commissioned and supported by a component manufacturer (the case company), so a case study format was both intended and suitable. Researchers had access to the company, and hence, access to a contemporary source of what product EoL may look like and what related opportunities there may be. The study results were to provide specific insights for the case company and generalized "theoretical propositions", those generic ideas that Yin (1994) notes are what a case study can provide in regards to generalization.

The case study was conducted in an exploratory and abductive manner, resembling the "systematic combining" process proposed by Dubois & Gadde (2002). The process involves (1) establishing a "preliminary analytical framework" and adjusting or improving it throughout the study (2) constant comparison between theory and empirical observations, and (3) successive fine-tuning of the precise direction of the case study and inherent data collection based on the evolving framework. Thus, data collection and analyses were conducted not linearly, but interchangeably throughout the study.

The preliminary analytical framework here consisted of EoL opportunities identified in literature and some preconceptions of these opportunities yielded from initial company collaboration. This framework, including these preconceptions helped in selection of the two case studies, one *Industrial* and one *Automotive,* as well as the product types of focus. Collaboration with stakeholders, especially company representatives, provided dynamic feedback. Material flow analysis (MFA) and other analysis tools were selected based on the perceived need dictated by the direction of the case study.

The following section describes each of these and other main study elements in brief including: the *Analytical framework, The case company, Collaboration with stakeholders, Case study selection, Assessment tools,* and *Empirical observations*. There were slight variations in the manner in which the two cases were conducted and so, variations are discussed in a section titled, *Divergence of methodology used in the two cases.*

3.1. Analytical framework

The *analytical framework* below consisted of a list of opportunities together with preconceptions of how relevant they were to the *Industrial* and *Automotive* cases at hand. Potential opportunities were compiled from the literature review. Preconceptions were constructed after initial discussions with company representatives. A mere snapshot of preconceptions of the relevance or feasibility of each opportunity is in *italics*.

(1) ***Extend product life***: Reducing product replacement rates contributes to lesser material intensity and to product EoL management by delaying obsolescence. *Was considered possible but is already something on which the company focuses*

(2) ***Cascading reuse:*** Reuse in different applications or markets through use life that may require repair or remanufacturing to be feasible (see #4). *Was not considered to be feasible due to quality demands.*

(3) ***Reusing of a component after parent product EoL***: This is considered a possibility when a higher-level product (such as end-of-life vehicles) reaches its EoL prior to its components. The components themselves may not be obsolete and may be directly reusable. *Was not considered to be feasible due to quality demands.*

(4) ***Remanufacturing (or reconditioning):*** Maintaining the value-added in a product by systematically preparing it for reuse. *Was considered possible for the Industrial case.*

(5) ***Increasing capture for recycling***: This possibility refers to components that are not recycled, e.g. they are landfilled or stored indefinitely. *Was not considered likely; most products were thought to be captured already.*

(6) ***Increasing functional recycling***: Enhanced sorting or control of specific products with specific metal grades. *Was considered possible considering known alloy content in product material.*

Two non-EoL activities are thought to directly affect the potential of realizing the above opportunities or are closely related:

(7) ***Offer product-service option to capitalize on each of the previous***: Selling service or function instead of product allows added manufacturer control and learning during use and maintenance, facilitating product take-back and reuse or improved recycling. *Was considered to be possible especially because such contracts exist.*

(8) ***Change product design and composition characteristics:*** The way a product is designed determines how much material it contains (re: dematerialization) and how reusable or recyclable a product is. *Was considered to be possible since product improvement is a continuous process but difficult since products are already fine-tuned to application demands.*

These hypothetical opportunities helped determine system boundaries for the study and acted as a reminder of what to look for during the study. However, as they in some way encompass many phases other than product EoL (e.g. extend product life), some of these had to be considered on the periphery – the focus of this study was EoL, i.e. the point at which a product is deemed obsolete and the processes that occur after that.

The process of using this framework is most explicit in *Paper II,* for the *Automotive case*, wherein preconceptions of some of the opportunities are presented as hypotheses, and strengthened, disproved or modified (*Paper II, Method-section 3- & Discussion-section 5*).

For the project as a whole, an evaluation of the opportunities as well as conceptions related to their potential is presented in the results section of this document.

3.2. The case company

The case company is a multi-national manufacturer of machine components and offers a wide array of mechanical products and services. It is recognized as a leader in sustainability and has made efforts to integrate life cycle management (LCM) into its business culture and sees resource (both energy and material) efficiency as a primary objective. Resource efficiency is critical to their customers and their competitiveness as a company. The company has also specifically made social and environmental pursuits a priority. In regards to product lifecycle improvements, it has focused mostly on production and product use, where estimated impacts for many environmental impact categories are the most substantial.

In regards to product EoL management, the company develops products with longer product life, offers services and support to extend product life, has existing and profitable remanufacturing operations that facilitate some reuse, and knows that its mostly low-alloyed steel products are recycled after use.

3.3. Collaboration with stakeholders

A number of stakeholders were involved during the course of the project to include: company representatives (*project support group* and *business and technical experts*), customers and experts and actors from the material handling and recycling world.

Company representatives were involved from the very beginning of the study. Based on company research interests and other ongoing work in LCM, they helped decide a theme and identify company-specific knowledge gaps. They also contributed to the preliminary analytical framework by providing some preconceptions about the company's product EoL.

A specific group of company representatives – *the project support group* – was formed to support the research. In the beginning of the study, the group helped reformulate questions and find relevant contacts. *Business and technical experts* gave crucial insights into business models, customers and products and identified customers for interviews and site visits.

3.4. Case study selection

As the case company has many business and application areas, it was necessary to choose cases to study. Business areas were determined to be a suitable basis for this. The project was conducted as two separate case studies focused on the EoL management of the products in two of the company's many business areas (see Table 1).

The first case (*Industrial)* was chosen according to company representatives' preconceptions related to the internal interest in the EoL topic and compatibility of the business area with existing remanufacturing operations (previous section-*Collaboration*). The second case (*Automotive)* was chosen for its importance to the company and because it served as a great contrast to the *Industrial* case.

Such contrast was considered critical for building a nuanced understanding of product EoL and to generate more generic lessons learned. While the *Industrial* case involves products used in stationary factories in such applications as motors and moving production lines, the *Automotive* case 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 the *Industrial* case end-users, and almost never has direct contact with *Automotive* end-users. Products evaluated for both cases are mostly steel but are larger and more expensive for *Industrial* and smaller and less expensive for *Automotive*. Products of interest for the study are sometimes remanufactured for *Industrial*, but never for *Automotive.* Due to these and other factors, the opportunity for the company to improve product EoL while at the same time maintaining or improving business competitiveness was perceived to be high for *Industrial* and low for *Automotive*.

Characteristic	**Industrial**	**Automotive**
Example use	Motors and moving production lines	Wheel and drivetrain
End-user - business or consumer	Entirely business-to-business	Mostly consumer
Distributor involvement	Some	Some
Relation with end-user	Direct business	None (only via OEM or distributor)
Use setting	Industrial use	Road use
Product size	Big	Small
Product cost	More expensive	Less expensive
Product composition	Mostly steel	Mostly steel
Remanufacturing	Sometimes	Never
Perceived opportunity for improved EoL	High	Low

Table 1: The two cases chosen, *Industrial* and *Automotive* with short description for each characteristic.

3.5. Assessment tools

Both case studies included two major tasks – to define and estimate the *EoL material flow*, and to identify opportunities for improved EoL management. Deliverables for the study were material flows (Sankey) diagrams showing the flows and highlighting potential opportunities for improved EoL management (such as remanufacturing or recycling). The MFA also improved knowledge about product fate with indications of barriers and enablers for identified EoL opportunities.

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.

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 product EoL are. The MFA was paired with a *product flow analysis*, i.e. an analysis of company sales data augmented with product mass, which was expected to deliver an assessment of masses related to product types, customers or regions, again in order to give indications about opportunities to improve product EoL management. Together, these two types of analyses provided answers to the questions:

- *How big are material and function losses after use?*
- *What opportunities exist to reduce these losses?*
- *Which products types and destinations, such as customers and regions, represent the most material mass?*

The main steps of the MFA for both cases 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. Examples of customers or types of products were chosen as it was deemed to be less practical to map in detail entire business areas. In addition, examples were considered to be more constructive in comparing and communicating real outcomes.

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.

According to MFA guidelines the first step in an MFA is to construct a conceptual system diagram (Brunner & Rechberger 2004). Such a model for the case studies is depicted in Figure 1. The *EoL system*, as it was named, was considered to be generically similar for the two cases. Given a basic knowledge of the distribution and use channels and of the steel recycling system, a conceptual diagram of the *EoL system* was drawn (Figure 1). In the diagram, function and form descend from top to bottom, processes are shown in boxes, and material flows are shown as arrows (not to scale).

Preparation for Use (outside of the *EoL System)* includes two *Manufacturing Realms, namely Manufacturing of Alloyed Steel Product* and *Manufacturing of Carbon Steel Product*. This is where the studied products are produced, but also where other steel products are produced from recycled products. The *EoL System* includes the *Production, Use,* and *Recycling* phases. The *Production phase* includes original equipment assembly, remanufacturing and distribution (*OE Assembly, Reman. & Distrib.*). This is where products are prepared (potentially as part of another product, i.e. original equipment) for delivery to *Use*. The *Use phase*, which includes *Use and Maintenance*, is where products deliver the intended function. The *Recycling phase*, which includes *Material handling* and *Steel Production* is where products are only valued for their material content and handled as such. Flows that reach the system boundaries are shown in gray. Flows enter from the *Manufacturer* as product (a) and replacement flows (z). Flows to and from *Reman* include: used product for remanufacturing (b), remanufactured product (c), replacement material (z) and scrapped product (e). Material from *Use* also goes to *Material Handling* (d) (scrap transport/processing) or directly to *Carbon Steel* (x) or *Alloyed Steel Production* (y). Material from *Material Handling* is lost (f) or sold to *Carbon Steel* (g) or *Alloyed Steel Production* (h). Recycled steel (i, l) goes to *Product Manufacturing*. Waste fractions (j, k) are sent to *Slag Handling* and eventually to *Disposal* (n), or *Preparation for Use* (m) in such applications as road construction material.

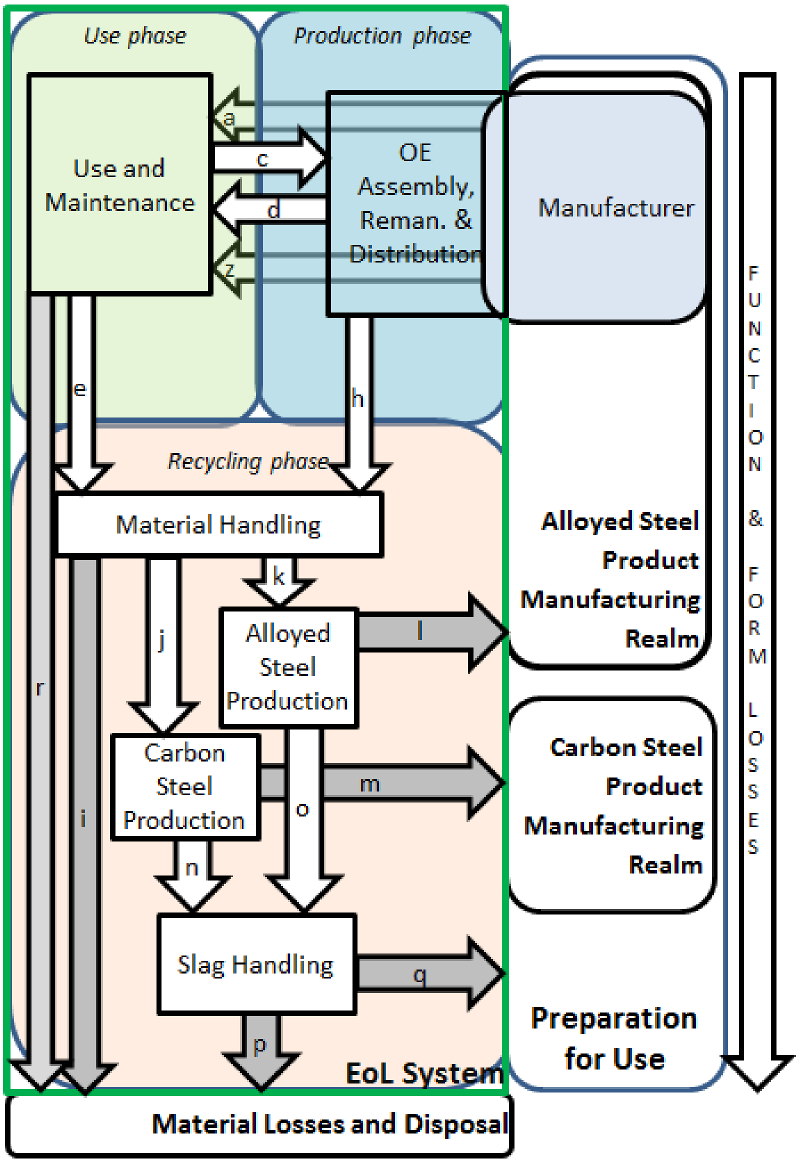


Figure 1: Conceptual diagram of the *EoL System* (solid rectangle) in which function and form descend from top to bottom. The *EoL System* includes processes of interest (boxes) and material flows, shown as arrows between processes or entering or exiting. Flows that reach the system boundaries are shown in gray. The *Production*, *Use* and *Recycling phases* are indicated in the *EoL System* as rounded rectangles.

3.6. Empirical observations

Empirical observations consisted of interviews and site visits. 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).

Interviews of company business area 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. 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 the Industrial case (*Paper I - Method*), *Use*, *Maintenance* and the point of product *EoL* was explored with end-user customer questionnaires and follow-up questions, some follow-up interviews, and one site visit.

For the Automotive case (*Paper II, Method-section 3.2*), end-users were not consulted, but *Maintenance, Remanufacturing* and the point of product *EoL* were investigated with interviews and site visits of 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 two 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.

3.7. Divergence of methodology used in the two cases

The two case studies were conducted with the same goal – to map flows and identify improvement opportunities and both cases resulted in example Sankey diagrams (*Paper I: Results-section 3.1, Paper II*: *Results-section 4.1*) and *product flow analyses* (breakdown of company sales). However, these primary results were complemented with other types of analyses, which differed between the cases.

First, since influencing what customers did upon product EoL was deemed to be the greatest opportunity to improve product EoL, the *Industrial case's* flow diagrams were done with a customer perspective and customers were chosen for comparison. The question posed was, "What is the difference in material use between a customer that chooses remanufacturing and one that does not?" The results were compared partially by normalizing function for the two customers. Also, because immediate opportunities to remanufacture were indicated for the *Industrial* case, the MFA was complemented with an estimation of economic and environmental values saved or lost based on different EoL management options, investigating:

- *How much value can be gained from remanufacturing?*
- *How much value can be gained from recycling?*

Simplified forms of *life cycle assessment (LCA)* (as in Baumann & Tillman 2004), and *value chain analysis (VCA)* (as used by Dahlström et. al. 2007) were used for the environmental and economic valuation tasks, respectively (*Paper I, Method, section 2.3*).

In the *Automotive case* another focus was yielded from taking an ELV and spare parts perspective (*Paper II, Method-section 3*). Since ELVs are commonly shredded which often results in impure recyclates (fractions), an important aspect for improved EoL management of automotive components is product liberation or separation. If there was any opportunity for improved EoL for the studied components, it was thought that products separated from the vehicle should be the ones to focus on. Following this reasoning, questions posed were:

- *What share of products does actually enter the shredder as part of an ELV?*
- *What share of the products enters the recycling system as product separated from a* vehicle, perhaps after product (or part) replacement?

In order to create example material flows, key product types were chosen. Flow diagrams were created based on the estimated use and EoL of these product types in the chosen vehicle models.

In addition, and partially due to design trends in the automotive sector towards more efficient and lightweight products, an assessment of product design was performed focused on the question:

- *Are the products repairable, able to be dismantled, and compatible with current shredding and sorting systems?*

4. Results and analysis

The results highlighted in *Paper I* (*Industrial case)* and *Paper II* (*Automotive case)* indicate that (1) the remanufacturing potential for industrial products is much larger than the amount currently done (*Industrial*), (2) that functional recycling might be possible with more extensive cooperation in the value chain (*both*), (3) that design trends for automotive products are detrimental to repair-ability and recyclability (*Automotive*), (4) that change-out of components in remanufacturing varies largely, why there may be an opportunity for extending component life through quality control (*automotive*) (5) that aftermarket products make up a tangible portion of a the material flows of (A*utomotive*).

These results were highlighted in the appended articles. However, more insights can be gleaned from contrasting the two cases against one another. For this, the analytical framework (Methods, section), consisting of potential product EoL improvement opportunities was used. The following section contains an evaluation of each opportunity for the two cases, summarized in Table 2 (next page), as well as a discussion about what the implications for the company as well as other actors in the system might be.

	EoL improvement opportunity	Indications from Industrial Case: Is there a feasible improvement potential?	Indications from Industrial Case: Enablers(+) & barriers(-)	Indications from Automotive Case: Is there a feasible improvement potential?	Indications from Automotive Case: Enablers(+) & barriers(-)
1	Extending product life	Yes: Already a focus of company	(+)Product EoL is commonly due to preventative maintenance (+)Company has existing efforts towards extending product life	Yes: Already a focus of the company	(+)Improper installation is a sometimes a reason for product failure and is addressed in design (+) Focus for heavy truck segment (+)Possible relevance for remanufactured parent products
2	Cascading reuse	Unclear: May happen already to a certain degree. Example: putting new product into most stressed locations	(+)Product function remains (+)Remanufacturing could be used as quality control step (-)Remanufacturing does not involve change in ownership (-)Quality control challenge (-)Specialization of products	Unclear: Happens to some degree within domestic markets and transfer to other country markets	(+)Product function remains (-)Product price vs cost to salvage (-)Quality control challenge (-)Cascading between markets requires transport (-)Specialization of products
3	Component reuse after parent product EoL	Unclear	(+)Parent product EoL represents a few % of product EoL (+)Product price may justify salvage (-)Compatability of products	Unclear: Common type of reuse and there may be a potential to increase such reuse	(+)Parent product EoL is common EoL scenario (+)Product function remains (-)Product price vs cost to salvage
4	Remanufacturing	Yes - Large additional potential according to preferences	(+)Existing remanufacturing (+)Many products of preferable size (+)Preventative maintenance is common product EoL (+)Company commitment to service business (-)Customer awareness (-)Training and incentives	No	(+)Existing reverse logistics in automotive sector (+)Some truck products are of minimum size for reman. (-)Product value vs. cost to reman (-)New products hard to dismantle (-)Product failure common EoL
5	Increasing capture for recycling	Capture for recycling appears to be high already			
6	Increasing functional recycling	Unclear: Difficult with current infrastructure	(+)Material value higher than for mixed scrap (-)Current infrastructure not set up for different steel grades	Unclear: difficult with current infrastructure	(+)Material value higher than for mixed scrap (+)Existing dismantling & sorting (-)Current infrastructure not set up for different steel grades (-)Product design becoming multi-material (-)Volumes are likely small at maintenance sites
7	Offer product-service or function sales option	Yes: Company already offers such options	(+)Existing company offers (-)Customer acceptance	No, but warrants investigation	(+)Future leasing/ car sharing schemes may facilitate (-)Product part of vehicle that is largely sold, not leased
8	Change design and composition characteristics for remanufacturing and recycling	Unclear: Warrants investigation to avoid future challenges seen with automotive case	(+)Some brass (-)Current design favorable for reman. and recycling (-)Products possible to disassemble (-)Current products are mostly steel	Unclear: Warrants investigation as design and composition becoming less favorable	(+)Newer products multi-material (+)Newer products not able to be disassembled (-)Current products are mostly steel

Table 2: Eight opportunities to improve product EoL evaluated for the two cases *Industrial* and *Automotive*. A brief indication of improvement potential, and enablers and barriers is added for each. For example, for the first opportunity (*Extending product* life), there appears to be a feasible improvement potential based on enablers (+) that preventative maintenance is a common reason for EoL and because the company already focuses on long-lasting products. Green boxes indicate opportunities highlighted in *Papers I & II*.

4.1. Opportunities 1, 2 & 3: Extending product life; Cascading reuse; Reuse after parent product obsolescence

For the *Industrial* products studied, preventative maintenance appeared to be a common EoL circumstance, which means that many products never reach the true end of their functional life. This is due to the fact that failure of studied components can mean a bigger problem in the parent machinery and longer downtime. Hence, fine-tuning when such products should be taken out of service could contribute to the *extension of product use life*. Proper installation of components is also critical to determining the component's use life. However, these matters, from installation to maintenance during use and condition monitoring, are things on which the case company already focuses extensively.

For the *Automotive* products studied, it was noted that improper installation is the most common reason for premature product failure. Newer products are assembled in a different way and generally easier to install than older generation products. This difference apparently reduces instances of improper installation and *extends product life*. *Extending product life* was noted as specifically important for the heavy truck segment, for which maintenance cost reduction is a priority of the ultimate truck owner.

In addition, *the Automotive* case demonstrated that there are likely differences in the degree to which remanufacturers reuse components from cores. This may be important for the component manufacturer, who despite not being able to remanufacture their own products, may support remanufacturing of a higher level product (as noted in *Paper II* with gearboxes). In such cases, the component supplier may have the opportunity to support remanufacturers in deciding which of their components need to be replaced. This could improve quality control and contribute to *extended product life*.

Cascading reuse appears to already occur to a certain (perhaps small) degree. For the *Industrial case,* it was also indicated by company subject matter experts that, for one application, it is not uncommon practice to cycle new products into machinery locations in which stresses are the greatest. This is apparently done to reduce the perceived risk of failure. *Is there an opportunity to do more cascading reuse?* There may be. Since preventative maintenance appears to be a common reason for product EoL, product function remains in products which are exchanged for preventative reasons. There are potentially other customers or applications for which these products could be suitable.

However, there appears to be a couple barriers to cascading reuse. The studied products are high-precision products and quality control is of the utmost concern for customers and the company alike. Remanufacturing could be hypothetically used as an intermediate quality step but current remanufacturing is only a service during which the customer retains product ownership. Thus, product cores are not to be exchanged between customers. In addition, the specialization of many products for specific machines or applications makes finding cascading opportunities more difficult.

In the *Automotive* sector, *cascading reuse* between markets and market segments occurs. Vehicles and parts, to include example products for this study, are handed down to less demanding market segments domestically and to less affluent markets internationally. This cascading reuse (and component reuse described below) is facilitated partially because parent products, i.e. vehicles, reach EoL and potentially contain a number of marketable used products. However, according to dismantlers, there is little demand for the studied products and the price received for used products does not justify the salvaging, storing and marketing costs. Cascading to different applications appears to be less likely due to the specialized nature of the products – the example products chosen for this study are offered in tens if not hundreds of variations.

From the *Industrial* case, *component reuse after parent product EoL* appears to occur sometimes. Customers indicated that just a fraction of components studied were scrapped due to parent product (machinery) obsolescence. A couple customers indicated that components would be possibly salvaged conditional to them being compatible with the new machinery.

Reuse after parent product EoL appears to be common in the *Automotive* sector and with example products studied. Remanufacturing of parent products such as gearboxes is common and components are reused within remanufactured cores to a certain extent. Salvaging of parts from ELVs is generally common (see discussion about *Cascading use* above) although only a few percent of the products studied appear to be salvaged and reused.

4.2. Opportunity 4: Remanufacturing

For the *Industrial case (Paper I)*, remanufacturing appears to be a big opportunity for a few reasons: (1) material efficiency gains, (2) environmental and economic value savings, and (3) there appears to be many products that are of a preferred size and condition for remanufacturing but that are not sent to be remanufactured.

First, benefits in material efficiency are revealed when comparing EoL material flows of one example customer that sends a lot of product to remanufacturing and another which used the products in a similar manner that does not (Figure 2). 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.

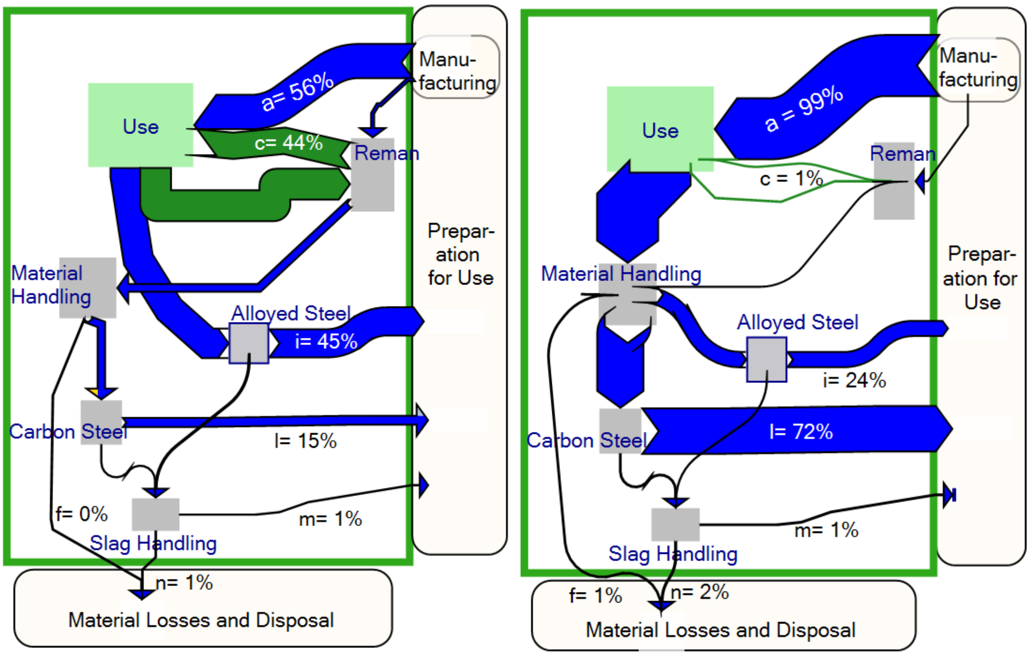


Figure 2: Sankey diagrams for *Customer 1* and *Customer 2*. Percentages (rounded to nearest percent) are normalized to functional product flow (a + c = 100%). Manufactured product *a* is sent to the customer (Use). It is then either sent back and remanufactured (*c*) or sent to *Material handling* or *Steel production* (*Alloyed* or *Carbon*). In the end, materials are either reused as steel (*i*, *l*), as slag filler in e.g. road construction (*m*) or lost (*f*, *n*) to disposal.

Second, Figure 3 shows that, as expected, environmental values (measured in CO_2 avoided) for remanufacturing are greater than for recycling and greater for recycling than for replacement (i.e. the results are consistent with the waste hierarchy and literature reviewed). Potential economic values for remanufacturing were even more convincing and were many times greater than recycling (scrap) values.

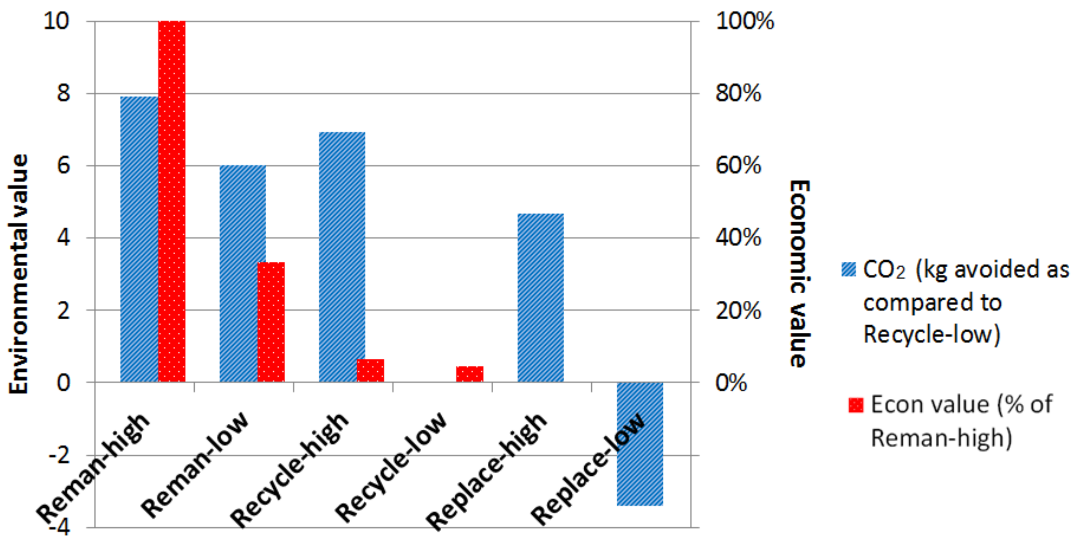


Figure 3: The potential value that can be salvaged from one example profitably remanufacturable product for six EoL options. Environmental values are measured in kg CO2 avoided compared to *Recycle-low* (left axis), whereas economic values are presented in % of *Reman-high* value, i.e. the highest value yielded from remanufacturing (right axis).

Third, these results are complemented with indications that there may be a big potential to remanufacture more. Although some products, especially those that have failed during use, are not in the proper condition to be remanufactured, many products are known to be replaced prior to failure for reasons of preventative maintenance. This indicates that many products are in the proper physical condition to be remanufactured.

In addition, an analysis of product sales data indicates that there are many products that meet the company's preferences for remanufacturing and that they make up a large share of the mass sold.

The company has profitable remanufacturing operations with well-established preferences for product size and type. *Smallest* are not practically remanufacturable, *minimum* are if given the right volume, promoted is the size marketed by the company for remanufacturing, *preferred* is the rule of thumb size for remanufacturing profitability, and *biggest* are generally remanufacturable and the largest sized products sold.

Figure 4a shows the share of material in product sales that would be captured if all products of a particular preference size and greater were captured. Lines are drawn in the figure for *promoted* size and show that if all products greater than or equal to the *promoted* size were captured, almost 50% of sold material weight would be netted. From looking at remanufacturing logs, it is estimated that only a small percentage of product weight is currently being remanufactured by the company. If the company were able to recover and remanufacture all these *promoted* and greater sized products one time, it is estimated that material use related to the studied products for the business area could be reduced by around 30%. While this estimate considers only remanufacturing products one time, it is known that some products actually are commonly remanufactured more than once. It should be noted, however, that this estimate considers only remanufacturing size preferences and current remanufacturing operations and not product condition upon EoL. Although product obsolescence due to preventative maintenance appears to be common, it is not known how many obsolete products are in proper condition to be remanufactured.

Figure 4b displays the share of weight and product count (pieces) of products greater than or equal to the *promoted* size for remanufacturing. It shows that products greater than (or equal to) the *promoted* size represent almost 50% of sold material weight (like shown in 6a) but only a very small portion (around 1%) of the product count (pieces). Thus, there appears to be a large potential to increase the share of material weight remanufactured. The results also indicate that re-handling only a "few" of the myriad of product count would yields a big difference in material flow.

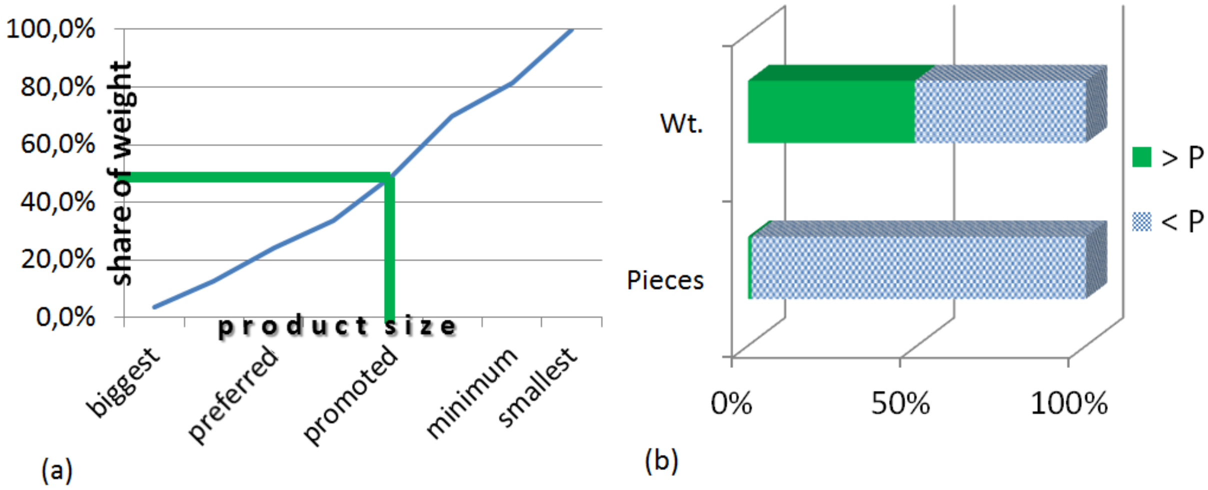


Figure 4: Sales data analyzed with respect to company remanufacturing preferences. (a) Captured material weight when assuming collection of *all* products of a certain size according to company remanufacturing preferences (rules-of-thumb). *Smallest* are not practically remanufacturable, *minimum* are if given the right volume, promoted is the size marketed by the company for remanufacturing, *preferred* is the rule of thumb size for remanufacturing profitability, and *biggest* are generally remanufacturable and the largest sized products sold. Example capture for *promoted* size depicted with lines. (b) Products measured in product count (pieces) and weight that are greater or less than *promoted* size for remanufacturing.

Remanufacturing appears to be a good solution to decreasing material intensity and it appears that more products can be remanufactured than currently being done. *Why then, are more products not remanufactured?* First, some products are simply not in good enough condition to be remanufactured. Besides this technical limitation, discussions with company representatives and customers indicated some other barriers. They include: (1) there may be a lack of customer confidence in remanufactured products, (2) company incentives and training may be more aligned to new product sales, and (3) incentive structures for distributors may not be aligned to remanufacturing offers.

Remanufacturing for the *Automotive* business area does not currently appear to be feasible. The cost of remanufacturing and administration is estimated to be much more that product sales prices. In addition, mechanics indicated that the reason for changing the studied products is almost always because they have failed. This means that their condition is less favorable for remanufacturing. Another barrier exists in product design – products are becoming harder (if not impossible) to dismantle. The reason noted for this change is to reduce maintenance requirements during the use life and to extend the product life. Thus, while the reparability (or remanufacturability) has decreased, the use life may have increased.

Despite this negative outlook for remanufacturing for the *Automotive* business area, there are a number of truck products that meet the company's current minimum size for remanufacturing and the company does have remanufacturing operations for other off-road applications. In addition, any attempt to enact a product take-back and remanufacturing program might be facilitated by already existing practices and reverse logistics networks in the automotive sector.

4.3. Opportunities 5 & 6: Increase recycling & Functional recycling

First, it is known that societal rates of steel recycling are not 100% and that an estimated 10% of machinery metals are never recovered (UNEP 2011). It is thought that recycling of the studied products is close to 100%. There was no indication from the *Industrial* case that the studied products are not captured for recycling, but researchers did not walk multiple sites to look at rusted machinery either. However, it is known from the *Automotive* case that vehicles and the components in them are sometimes, but rarely, left to rust or are never recycled. In Sweden, this outcome is apparently more likely during times when there is no vehicle scrap premium provided by the state (M. Abraham, personal communication, March 2014). Regardless, these outcomes are considered rare and extremely difficult for a component supplier to address but could be something to consider at a societal level.

Functional recycling requires that materials with similar compositions end up together "in the same pile" so that they can be recycled together and not with materials of different compositions. Sorting of material grades at the place of product obsolescence is one opportunity to achieve the proper sorting. However, dedicated sorting of different materials is not always administratively and economically feasible. According to discussions with two scrap sourcing experts, four factors determine the potential of dedicated sorting for functional recycling for the products studied: (1) commodity values, (2) common product composition, (3) scrap load size required, and (4) composition confidence.

Commodity values and product composition determine the raw material value. However, according to scrap steel sourcing experts, alloying elements that are embedded in steel are valued at much less than market value of pure alloying elements. Regardless, products of interest, which have small amounts of alloying elements, could currently yield a potential scrap material price that is somewhat higher than the mixed scrap steel price. According to the consulted experts, receiving this potential price requires that the scrap in question can be delivered in loads of several tonnes. In addition, the scrap composition needs to be guaranteed within a fraction of a percent.

In order to estimate the potential opportunity for this case, the total sold weight of products studied from the case company was divided by example load sizes indicated by experts. According to information from the business areas studied for the *Industrial* and *Automotive* cases, there is a yearly combined potential in Sweden of 4 to 40 recycling loads of product-related material from the case company.

This may not seem convincing, but if the products of interest were combined with other products of similar composition, the potential for dedicated recycling would be greater. However, there are barriers that would undoubtedly have to be addressed first. In reality, the exact steel composition is rarely known by the scrapping entity (in this case, the maintenance garage, dismantler or remanufacturer). Also, products have to be collected, stored and transported in order to achieve the proper scrap load size. This process is not cost free, and according to scrap sourcing experts, cost is a major factor limiting the number of scrap types that are collected and sold.

Despite the barriers, almost all the products studied for the *Industrial case* and almost half of the mass of the wheel product (*Paper II*, *Product W*) studied for the *Automotive* case are liberated from the parent product at EoL. Thus, there is an opportunity at product EoL to sort a great deal of these components for functional recycling. For the *Automotive* case, this opportunity is complemented by an existing infrastructure in which most ELVs are treated and dismantled to a certain extent prior to being shred. In Sweden, as well as in many other countries, there is already a parts and material salvaging activity with dedicated sites, manpower, and some equipment. More material could be salvaged and sorted if there was an economic (or other) incentive.

The results from the *Automotive* case are in particular relevant to discussion surrounding vehicle recycling. Often, perhaps due to ELV legislation, the focus is on the ELV and dismantling, shredding, sorting and recycling. Results in *Paper II* (seen in Figure 5 below) show that the EoL product flow of interest is not only in the ELV. Replacement components added during the vehicle's use life represent a measurable quantity of EoL product flow (almost half for the wheel Product W shown). Consistent with knowledge that the automotive aftermarket is large, this means that there are a lot of automotive parts that are liberated and discarded before the vehicle reaches ELV status. Thus, when considering societal interest to increase functional recycling, it seems relevant to investigate what a sector-wide recycling program for specific material grades or products could yield and subsequently consider what collaborative efforts, possibly supported by, policy intervention would be relevant.

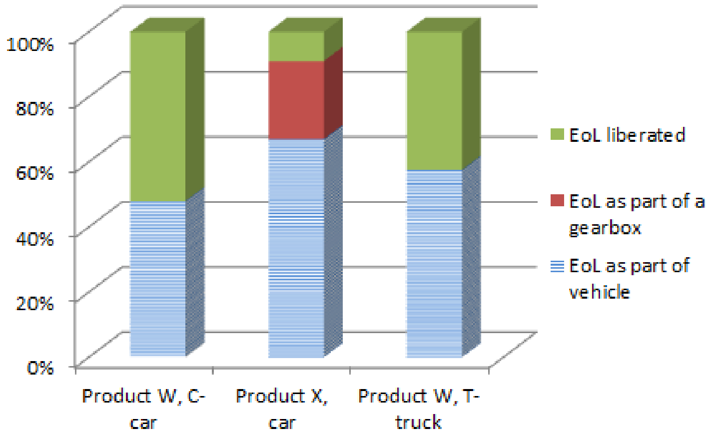


Figure 5: Three examples of product EoL fate with product fates grouped into liberation statuses – liberated or connected to vehicle or gearbox.

4.4. Opportunity 7: Offer product service system

This opportunity could potentially facilitate or complement the previous opportunities mentioned. The company already offers product-service contracts and has delivered services for which the performance of an operation and not the products used are billed to the customer. This existing business offering and gained experience from delivering it could bode well for more of such contracts. They could also enable more remanufacturing and the implementation of functional recycling. However, according to company representatives, due to their rarity and the degree in which the differ from the norm, most sales representatives and customers are not as comfortable with product-service contracts as they are with product sales and more traditional service contracts.

Although product-service sales for automotive products might seem unlikely in the current economy, such offers may be worth investigating. If car sharing programs and truck fleet rental programs get larger, selling of function in such systems may not be out-of-the-question.

4.5. Opportunity 8: Change product design or composition

If only looking at EoL opportunities, *changing product design* does not seem to be justified according to the *Industrial case*. Products do sometimes contain a brass sub-component, which, due to its copper content, would be a very undesirable contaminant if it would end up in steel recycling. However, the products are able to be disassembled and according to discussions with material handling experts, the brass sub-components are likely liberated during shredding. Despite the fact that dismantling of studied products is not always extremely easy, the product design does not appear to hinder remanufacturing.

The results from the *Automotive* case demonstrated something different. Trends in product complexity are apparent in the products of interest. An originally all-steel product has become increasingly multi-material (e.g. aluminum and steel components) and infused with additional function that requires wires and sensors. These additional materials and components have led to a product that is more difficult to separate and recycle to materials of equal quality.

This design trend towards products that are less repairable and less recyclable seen in this case emphasizes research advice that companies could benefit from (1) considering what it would take to make repairable products and (2) assessing product construction and if materials liberate during shredding or if improvement is needed.

Regarding dematerialization, the company offers products made of lighter weight steel in certain business areas and continuously investigates the potential of additional uses but the feasibility of using such products for the business areas studied was not addressed for this study.

5. Reflections about exploration, the case studies, and methods

As Dubois & Gadde (2002) states in regards to case studies, “empirical observations might result in identification of unanticipated yet related issues” that can be explored further. This statement rings true for this study as the open and exploratory nature may have led to some of the more interesting results.

For example, at the beginning of the study, researchers constructed a study foundation of research questions, a conceptual diagram (Figure 1) of the system, and a list of opportunities (*Analytical framework*). Based on this foundation and due to an initial interest in physical flows and product weights, if pressed, researchers would have “required” only five data fields for product sales data from the company. At that point in the study, it would have been difficult to justify the need of some data fields, especially since some of them contained potentially sensitive information.

Fortunately, when researchers asked for sales spreadsheets “ideally, with everything”, company representatives provided the real unpruned sales spreadsheets, which contained more than 20 data fields. Some of the 15 fields that researchers didn’t have strong justification to have at the beginning, such as product size and exact product type, became the most crucial. For example, some time after remanufacturing preferences had been revealed, it was realized that it was possible to use product size and type fields to do analyses like shown in Figure 6 and in *Paper I, section 3.2, Figure 5.*

Although in hindsight, it seems obvious that such analyses would be conducted, such analyses and the charts they provided was not foreseen at the beginning of the study. They merely became apparent when looking at the unpruned data at hand.

Another example of unanticipated results occurred during the *Automotive case.* The main goal of visiting remanufacturers was to gain basic understanding of gearbox remanufacturing and to get estimates for reuse of products of interest. In the process, not only were these two goals met but something unexpected was revealed in addition. It became apparent during one visit that product sub-components might be salvaged and reused, which is especially notable because such salvaging is far from being endorsed by the case company. This strengthened the indication that the component company could possibly help with remanufacturing quality control and (maybe) called into question an institutional belief that sub-components are not interchangeable. It also added one true LCM-spirited opportunity to the hypothetical opportunity list – *help other actors with product EoL management.*

Both of these examples demonstrate the kind of value gained that was brought to this study due to the study’s exploratory nature. They also emphasize the relevance of the old adage: *you don’t know what you are looking for (or what’s important) until you see it.*

Collaboration with the case company was especially important to the study process and the results yielded. The *project support group* and experts provided regular feedback. Researchers provided updates and results regularly during meetings. New results or analysis lead to discussion and identification of additional contacts or new data or insights from the company. Thus, collaboration with company representatives was critical as it facilitated interview and site visit activities and bolstered data quality and quantity.

Regarding methods used, although there were many important activities, following the product flow with MFA provided the backbone of the study. The exploratory nature of the MFA revealed three main types of results (as named here): (1) the *traditional MFA*, (2) *product flow analysis,* and (3) *product chain description.* Each of these activities was found to be necessary given the context of the study – product EoL management. The *traditional MFA* was strictly focused on defining the system boundaries and determining the physical flows in the system. This activity provided an answer to the question, "*What is the fate of products after use?*" The *product flow analysis* involved analyzing *raw* sales data () based on many characteristics potentially relevant to EoL management. The *product chain description,* which was done at a cursory level for this study, included noting basic non-technical aspects of the system, such as actors, their activities and decisions, market factors, and organizational aspects. Together, the *product flow analysis* and *product chain description* helped reveal potential answers to the question, "*Are there opportunities to prevent losses?"*

Finally, as always, improvements could be made to the formation of the system model and the data used. Using a few sources to represent reality limits the ability of the study and its results to represent exact reality. However, the aim of the investigation was not to exactly replicate the system and inherent processes. It was to represent the system well enough to allow insights for the manufacturer and to generate lessons learned from the process itself.

6. Discussion of future research

Two aspects of future research are discussed here: (1) insights into the tentative plan for the remainder of this doctoral project and (2) other research needs of interest.

6.1. For this project

This project was the first part of a larger project and was focused on physical flows and technical processes. The second part of the project will be aimed at evaluating opportunities further and how they could be enacted.

Future investigation will be aimed at "softer" aspects. Though material intensity will still be the aim and results will be undoubtedly measured in physical material flows, future investigations will look more at actor influences, organizational aspects, and business strategies and the question – *What business and organizational factors appear to facilitate or limit the component manufacturer's possibility to enact product EoL opportunities?*

There are a couple possibilities for project continuation. One strategy involves evaluating hypothetical implementation of alternative (product-service system- PSS, closed loop) business strategies for both the investigated *Industrial* and *Automotive* cases. This would involve measuring hypothetical change in material flows, potential changes in design and organizational logic, and identifying barriers and challenges in implementation.

Regarding barriers, literature provides some indications of what to look for. For example, selling function instead of products likely demands transformational change that requires learning and adaptation by both company and customer (Williams 2007). Regardless of the strategy, common conflicts arise both internally and externally. Internally, the risk of over-diversifying business offerings has to be evaluated. Gaining internal support for business offerings are often difficult and conflicts between existing product sales and service sales business units may arise. Externally, conflicts of interest may exist with suppliers, distributors, and retailers who simply aim to sell more (Atasu et. al. 2010; Guide 2000; Mont 2002). In regards to customers, making them aware of remanufacturing options is not the only challenge – customers are often cautious and demonstrate a lack of acceptance to used products (Lund 1985, Ferrer 1996; Mont 2002; Paton 1994).

Investigating what it would take to enact identified EoL opportunities such as remanufacturing at the case company could contribute to this literature and would provide another set of insights into the transition from a product to service economy.

6.2. Additional needs identified

While reuse (with or without remanufacturing) is a critical element to material intensity that requires additional focus and support, research focused on how to realize functional recycling seems to be lacking. In the past few years, "functional recycling" (first used by Guinée et. al. 1999) appears to have become a guiding principle to achieving our future recycling system. So far, it appears that research on the topic has proven that much metals recycling is not functional (Graedel et. al. 2011; UNEP 2011). It has also revealed a few insights on material liberation in shredding systems based on product design (Van Schaik & Reuter 2007) and has emphasized the importance of knowing metals compositions, metallurgy and thermodynamics (UNEP 2013). In addition, ideas of how different types of materials and products should be handled have been proposed such as the material-centric and product-centric approaches to recycling (Graedel et. al. 2011; UNEP 2013).

Based on these efforts, it seems that the theoretical benefits of functional recycling and general approaches to how it could be done on the system level have been established. However, it does not appear that specific cases have been evaluated to determine what a functional recycling system could look like, what quantities of relevant recycling fractions 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. Thus, when considering societal interest to increase functional recycling, it may be warranted to conduct such investigations and to evaluate what sector or market-wide recycling program for specific material grades or products could yield and subsequently, to consider what collaborative efforts or policy intervention would be relevant.

7. Conclusions

The purpose of this project was *to investigate how a component manufacturing company can reduce material intensity via improved product EoL management.* The two case studies *(Industrial* and *Automotive*) provided findings that are directly applicable for the company and that provide reflections for component manufacturers in general. First, the *Industrial* case study indicated that many more products could be profitably remanufactured for the industrial business area. If the identified products are in the proper condition to be remanufactured, remanufacturing them one time (some can be remanufactured more than once) would be enough to reduce material use by around 30%. This finding was derived according to the case company's current remanufacturing operations and product preferences as well as an indication that many products reach obsolescence due to preventative maintenance, not functional deficiency. Thus, it appears that the form of many EoL products is still intact, function remains, and that already existing remanufacturing operations could profitably recover, process, and return some of the products to use, thereby reducing material intensity. More generically, such a finding hints at low-hanging fruit for the case company's business areas, and provides a point of investigation for other manufacturers – could more be remanufactured even given current circumstances?

The *Automotive* case study pointed to a great variability in the amount of the company's components that are replaced during parent product (gearbox) remanufacturing. Hence, it appears that there is an opportunity for the component company to help remanufacturers decide what components need to be replaced, an idea that could be investigated for other business areas as well. Such support could improve quality control and contribute to extended product life either for the parent product or the component itself. Generically stated, supporting remanufacturers may be an opportunity for a component manufacturer to reduce material intensity associated with function delivered by its own products and parent products.

The two case studies also provided two notable insights for one other. First, although most of the *Automotive* products are not currently remanufactured and are much smaller than the *Industrial* ones, some of them are nonetheless as large as the company's preferred minimum size for remanufacturing of *Industrial* components. However, although some of these products are hypothetically remanufacturable, newer generation products studied for the *Automotive* case are often impossible to disassemble without damaging them. This points to the second insight – the *Automotive* case showed that the design of newer products may facilitate longer product life but may hinder remanufacturing as well as material recycling success, which depends greatly on product composition and construction. With a strategic perspective, these design trends indicate that the company could benefit from more thoroughly evaluating product design with regard to material liberation in dismantling, shredding and sorting.

Finally, both cases indicated that obsolete products are often liberated from parent products during parent product maintenance and could be sorted for dedicated functional recycling. However, volumes and current material values may not be large enough to justify such dedicated sorting, transport and recycling. When considering societal interest to increase functional recycling, it may be warranted to investigate what sector or market-wide recycling program for specific material grades or products could yield and subsequently, to consider what collaborative efforts or policy intervention would be relevant.

8. References

Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E. (2011): Material efficiency: A white paper, Resources, Conservation and Recycling, 55(3), 362-381, ISSN 0921-3449, http://dx.doi.org/10.1016/j.resconrec.2010.11.002

Atasu, A., Guide Jr, V.D.R., Van Wassenhove, L.N. (2010): So what if remanufacturing cannibalizes my new product sales? California Management Review, 52(2): 56–76.

Ayres, R.U. & L.W. Ayres (eds.) (2002): 'A Handbook of industrial ecology', Cheltenham: Edward Elgar.

Baines, T., Lightfoot, H., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., Shehab, E., Braganza, A., Tiwari, A., Alcock, J., Angus, J., Bastl, M., Cousens, A., Irving, P., Johnson, M., Kingston, J., Lockett, H., Martinez, V., Micheli, P., Tranfield, D., Walton, I., Wilson, H. (2007): State-of-the-art in Product Service-Systems, Proc. IMechE Part B: Journal of Engineering Manufacture, 221: 1543-1533.

Baumann, H., Tillman, A-M. (2004): The hitchhiker's guide to LCA: an orientation in life cycle assessment methodology and application. Lund: Studentlitteratur. ISBN 91-44-02364-2.

Blengini, G. (2008): Using LCA to evaluate impacts and resources conservation potential of composting: A case study of the Asti District in Italy. *Resources, Conservation and Recycling*, 52(12): 1373-81.

Bouman, M., Heijungs, R., Voet, E.V.D. (2000): Material flows and economic models : an analytical comparison of SFA , LCA and partial equilibrium models. *Ecological Economics*, 32, pp.195 - 216.

Bras, B., McIntosh, M.W. (1999): Product, process and organizational design for remanufacture – an overview of research. Robotics and Computer Integrated Manufacturing 15: 167–178.

Brunner, P.H., Rechberger, H. (2004): Practical Handbook of Material Flow Analysis, Lewis Publishers, Boca Raton.

Clift, R., Wright, L. (2000): Relationships between environmental impacts and added value along the supply chain. Technological Forecasting and Social Change, 65:281–295.

Cooper, D.C., Allwood ,J.M. (2012): Reusing steel and aluminium components at end of product life. Environ. Sci. Technol. 46: 10334–40. (doi:10.1021/es301093a)

Cooper, T. (2005): Slower Consumption: Reflections on Product Life Spans and the "Throwaway Society", Journal of Industrial Ecology 9(1/2): 51-67.

Cooper T. (2010): Longer lasting products: alternatives to the throwaway society. Farnham, UK: Gower.

Dahlström, K., Ekins, P., He, J., Davis, J., Clift, R. (2004): Iron, Steel and Aluminium in the UK: Material Flows and their Economic Dimensions. Final Project Report, March. Joint Working Paper. Centre for Environmental Strategy, University of Surrey, Guildford/Policy Studies Institute, London.

Dahlström, K., Ekins, P. (2007): Combining Economic and Environmental Dimensions: Value Chain Analysis of UK Iron and Steel Flows, Ecological Economics, 58: 507-519.

Daigo, I., Matsuno, Y., Adachi, Y. (2010): Substance flow analysis of chromium and nickel in the material flow of stainless steel in Japan, Resources, Conservation and Recycling, 54(11): 851-863.

Davis, J., Geyer, R., Ley, J., He, J., Clift, R., Kwan, A., Sansom, M., Jackson, T. (2007): Time-dependent MFA of iron and steel in the UK, Part 2. Resources, Conservation and Recycling, 51(1): 118-40.

Donella Meadows Institute (2014): A Synopsis: Limits to Growth: The 30-Year Update, Retrieved from donellameadowsinstitute.com on February 1, 2014.

Dubois, A., Gadde, L.E. (2002): Systematic combining: an abductive approach to case research, Journal of Business Research, 55 (7): 553-60.

EC- European Commission (2014): Waste – End of life vehicles, Retrieved on March 1, 2014 from http://ec.europa.eu/environment/waste/elv_index.htm.

Ehrenfeld, J., Gertler, N. (1997): Industrial Ecology in Practice—The Evolution of Interdependence at Kalundborg, Journal of Industrial Ecology, 1(1): 67-79.

Ellen MacArthur Foundation (2014): Accelerating the scale-up across global supply chains, Towards the Circular Economy, volume 3.

European Commission (2008): Directive 2008/98/EC, Waste Framework Directive, viewed online at http://ec.europa.eu/environment/waste/framework/

Femia, A., Moll, S. (2005): Use of MFA-related family of tools in environmental policy-making: Overview of possibilities, limitations and existing examples of application in practice. (Working Paper 3.1 rev. final draft 22 March 2005) European Topic Centre on Resource and Waste Management: Copenhagen.

Ferrer, G. (1996): Market segmentation and product line design in remanufacturing, Working Paper 96/55/TM, INSEAD, France.

Gehin, A., Zwolinski, P., Brissaud, D. (2008): A tool to implement sustainable end-of-life strategies in the product development phase. Journal of Cleaner Production, 16(5): 566-576.

Graedel, T. E., Bertram, M., Fuse, K., Gordon, R. B., Lifset, R., Rechberger, H., Spatari, S. (2002): The contemporary European copper cycle: The characterization of technological copper cycles, Ecological Economics, 42(1-2): 9-26.

Graedel, T. E., Allwood, J., Birat, J-P., Buchert, M., Hageluken, C., Reck, B.K., Sibley, S.F., Sonnemann, G. (2011): What Do We Know About Metal Recycling Rates?, Journal of Industrial Ecology, 15(3): 355-66.

Guide, V.D.R. (2000): Production planning and control for remanufacturing: industry practice and research needs. Journal of Operations Management, 18(4): 467-483.

Guide, V. D. R., Jr. and Van Wassenhove, L. N. (2009): The Evolution of Closed-Loop Supply Chain Research. Operations Research, 57(1): 10-18.

Guinée, J.B., Van Den Bergh, J.C.J.M., Boelens, J., Fraanje, P.J., Huppes, G., Kandelaars, P.P.A.A.H., Lexmond, T.M., Moolenaar, S.W., Olsthoorn, A.A., De Haes, H.A U. (1999): Evaluation Of Risks Of Metal Flows And Accumulation in Economy and Environment. Ecol. Economics, 30: 47-65.

Gyllenram, R., Ekerot, S. & Jönsson, P. (2008): Lubricating The Recycling Machine 2. Proceedings of the 2nd International Seminar on Society & Materials, SAM2, Nantes, 24-25 April.

Harper, E.M., Johnson, J., Graedel, T.E. (2006a): Making Metals Count: Applications of Material Flow Analysis, Environmental Engineering Science, 23(3): 493-507.

Harper, E.M., Bertram, M., Graedel, T.E. (2006b): The contemporary Latin America and the Caribbean zinc cycle: one year stocks and flows. Resources, Conservation and Recycling, 47:82–100.

Herrmann, C., Frad, A., Luger, T. (2008): Integrating the end-of-life evaluation and planning in the product management process. Progress in Industrial Ecology, 5: 44-64.

Ijomah, W.L., McMahon, C.A., Hammond, G.P., Newman, S.T. (2007): Development of design for remanufacturing guidelines to support sustainable manufacturing, Robotics and Computer-Integrated Manufacturing, 23: 712–719.

Jackson, T., Clift, R. (1998): Where's the profit in industrial ecology? Journal of Industrial Ecology, 2(1): 3-5.

Jackson, T. (2002): Industrial Ecology and Cleaner Production, in *A Handbook of Industrial Ecology,* edited by R. U. Ayres and L.W. Ayres. Edward Elgar Publishing, Northampton, USA.

Jenkins, R.R., Martinez S.A., Palmer, K., Podolsky, M.J. (1999): The determinants of household recycling: a material specific analysis on unit pricing and recycling program attributes. Resources for the future- Discussion Paper. Washington DC.

Johnson, J., Schewel, L., Graedel, T.E. (2006): The Contemporary Anthropogenic Chromium Cycle, Environ. Sci. Technol. 40: 7060–7069.

Jörgensen, T.H. (2008): Towards more sustainable management systems: through life cycle management and integration, Journal of Cleaner Production, 16(10): 1071–1080. http://dx.doi.org/10.1016/j.jclepro.2007.06.006

Kandelaars, P.& van den Bergh, J.C., 1997. Dynamic analysis of materials-product chains : An application to window frames. *Ecological Economics*, 22, pp.41-61.

Kerr, W., Ryan, C. (2001). Eco-efficiency gains from remanufacturing: A case study of photocopier remanufacturing at Fuji Xerox Australia. Journal of Cleaner Production, 9 (1): 75-81.

King, A.M., Burgess, S.C., Ijomah ,W., McMahon C.A. (2005): Reducing waste: repair, recondition, remanufacture or recycle? Sustainable Development, 14(4): 257–267. DOI: 10.1002/sd.271.

Leontief, W. (1970): Environmental repercussions and the economic structure: An input output approach. Review of Economics and Statistics 52(3): 262–271. Available at: http://www.jstor.org/stable/1926294?origin=crossref.

Low, M.K., Williams, D.J., Dixon, C. (1998): Manufacturing Products with End-of-Life Considerations: An Economic Assessment to the Routes of Revenue Generation From Mature Products, IEEE Transactions On Components, Packaging, And Manufacturing Technology – Part C, 21(1), January.

Lund, R. (1985): Remanufacturing: the Experience of the United States and Implications for Developing Countries, UNDP Project Management Report 2, World Bank Technical Paper No 31, 24–34.

Löfgren, B., Tillman, A.-M., Rinde, B. (2011): Manufacturing actor's LCA. Journal of Cleaner Production, 19: 2025-33.

Manouchehri, H. (2007): Looking at Shredding Plant Configuration and Its Performance for Developing Shredder Product Stream, Jernkontoret Report 88011, D823.

Mathieux, F., Brissaud, D. (2010): End-of-life product-specific material flow analysis. Application to aluminum coming from end-of-life commercial vehicles in Europe. *Resources, Conservation and Recycling*, 55(2): 92-105. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0921344910001679.

Mazzanti, M., Zoboli, R. (2008): Waste generation, waste disposal and policy effectiveness. Evidence on decoupling from the European Union. Resources, Conservation and Recycling, 52:1221–34.

Michaelis, P., Jackson, T., Clift, R. (1998): Exergy analysis of the life cycle of steel, Energy Int. J., 23(3): 213-220.

Moll, S., Bringezu, S., Schutz, H. (2003): Zero Study: Resource Use in European Countries. An Estimate of Materials and Waste Streams in the Community, Including Imports and Exports Using the Instrument of Material Flow Analysis. European Topic Centre of Waste and Material Flows (ETC-WMF), Copenhagen.

Mont, O. (2002): Drivers and barriers for shifting towards more service-oriented businesses : Analysis of the PSS field and contributions from Sweden, The Journal of Sustainable Product Design, 2:89-103.

Mont, O., Dalhammar, C., Jacobsson, N. (2006): A new business model for baby prams based on leasing and product remanufacturing. Journal of Cleaner Production, 14(17): 1509-1518.

Moriguchi, Y. (1999): Recycling and waste management from the viewpoint of material flow accounting, Journal of Material Cycles Waste Management, 1:2–9.

Nakajima,K., Yokoyama, K., Nagasaka, T. (2008): Substance Flow Analysis of Manganese Associated with Iron and Steel Flow in Japan, The Iron and Steel Institute of Japan International, 48 (4): 549–553.

Nakamura, S., Kondo, Y. (2002): Input-Output Analysis of Waste Management. Journal of Industrial Ecology, 6(1): 39-63. Available at: http://doi.wiley.com/10.1162/108819802320971632.

Nakamura, S., Kondo, Y., Matsubae, K., Nakajima, K., Nagasaka, T. (2011): UPIOM: a new tool of MFA and its application to the flow of iron and steel associated with car production. *Environmental science & technology*, 45(3): .1114-20.

Oguchi, M., Kameya, T, Yagi, S., Urano, K. (2008): Product flow analysis of various consumer durables in Japan, Resources Conservation and Recycling, 52(3): 463-80.

Ostlin, J., Sundin, E. & Bjorkman, M. (2008): Importance of closed-loop supply chain relationships for product remanufacturing. *International Journal of Production Economics*, 115(2):336-48. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0925527308001916.

Paton, B. (1994): Market considerations in the reuse of electronics products. IEEE-International Symposium on Electronics and the Environment, New York: 115-7.

Pigosso, D., Zanette, E., Guelere Filho, A., Ometto, A., Rozenfeld, H. (2010): Ecodesign methods focused on remanufacturing, Journal of Cleaner Production 18(1): 21-31.

Price, E., Coy, D. (2001): Life cycle management at 3M: A practical approach, Environmental Management and Health, 12(3): 254 – 259.

Rathore, P., Kota, S., Chakrabarti, A. (2011): Sustainability through remanufacturing in India: a case study on mobile handsets, Journal of Cleaner Production, 19(15). 1709-1722, ISSN 0959-6526, http://dx.doi.org/10.1016/j.jclepro.2011.06.016.

Rebitzer, G., Hunkeler, D. (2003): Life cycle costing in LCM: ambitions, opportunities, and limitations - discussing a framework International Journal of Life Cycle Assessment, 8(5): 253-6.

Reck, B.K., Müller, D.B., Rostkowsky K., Graedel, T.E. (2008): Anthropogenic nickel cycle: insights into use, trade, and recycling, Environmental Science &Technology, 42:3394–400.

Remmen A, Thrane M. Life cycle management. Tools for a sustainable development. In: Kørnøv L, Lund H, Remmen A, editors. Department of Development and Planning. Aalborg University; 2005.

Rose, C. (2000): Design for environment: a method for formulating products end-of life strategies, Stanford University, Department of Mechanical Engineering, Ph.D. Thesis.

Rossy, A., Jones, P.T., Geysen, D., Bienge, K. (2010): Sustainable Materials Management for Europe, from efficiency to effectiveness. Report commissioned by Flemish Government/OVAM/LNE, Brussels.

Santini, A., Herrmann, C., Passarinia, F., Vassuraa, I., Lugerb, T., Morselli, L. (2010): Assessment of Ecodesign potential in reaching new recycling targets. Resources, Conservation and Recycling, 54(12): 1128-1134.

Scharnhorst, W., Jolliet, O., Hilty, L.M. (2005): The end of life treatment of second generation mobile phone networks: Strategies to reduce the environmental impact. *Environmental Impact Assessment Review*, 25(5): 540-66.

Schmidt-Bleek F. (1994): *The Fossil Makers*, translated from - Wieviel Umwelt braucht der Mensch? MIPS- das Mass fur Ökologisches Wirtschaften. Berlin: Birkäuser Verlag, 1994.

Schmidt, J.H., Holm, P., Merrild, A., Christensen, P. (2007). Life cycle assessment of the waste hierarchy – A Danish case study on waste paper. *Waste Management*, 27(11) 1519-1530, ISSN 0956-053X, http://dx.doi.org/10.1016/j.wasman.2006.09.004.

Schmidt, W.P., Dahlqvist, E., Finkbeiner, M., Krinke, S., Lazzari, S., Oschmann, D., Pichon, S., Thiel, C. (2004): Life cycle assessment of lightweight and end-of-life scenarios for generic compact class passenger vehicles, The International Journal of Life Cycle Assessment, 9(6): 405-16. DOI:10.1007/BF02979084

Sendra, C., Gabarrell, X., Vicent, T. (2007): Material flow analysis adapted to an industrial area. Journal of Cleaner Production, 15(17), 1706-1715.

Smith, V. M., Keoleian, G. A. (2008): The value of remanufactured engines: Life-cycle environmental and economic perspectives, Journal of Industrial Ecology. 8(1-2): 193-221.

STAF (2014): Stocks and Flows Project (STAF)- Project Overview. Retrieved online from http://cie.research.yale.edu/research/stocks-and-flows-project-staf on April 1, 2014.

Stahel, W. (2005): From Products to Services: Selling performance instead of goods, Institute for Prospective Technological Studies (IPTS), Issue 27, Retrieved on March 14, 2014 at http://ipts.jrc.ec.europa.eu/home/report/english/articles/vol27/STA1E276.htm.

Steen, B. (2005): Environmental costs and benefits in life cycle costing, Management of Environmental Quality: An International Journal, 16(2): 107-18.

Steger, U. (1996): Managerial issues in closing the loop. Business Strategy and the Environment, 5(4): 252–268.

Sundin, E. (2004): Product and Process Design for Successful Remanufacturing. Doctoral thesis. Linköping.

Sundin, E., Bras, B. (2005): Making functional sales environmentally and economically beneficial through product remanufacturing, Journal of Cleaner Production, 13:913–25.

Terazono, A., Yoshida, A., Yang, J., Moriguchi, Y., Sakai S. (2004): Material cycles in Asia: especially the recycling loop between Japan and China Journal of Material Cycles and Waste Management 6: 82–96.

Tsoulfas, G., Pappis, C. (2006): Environmental principles applicable to supply chains design and operation, Journal of Cleaner Production, 14(18): 1593-1602.

UNEP (2011a): Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication, www.unep.org/greeneconomy, ISBN: 978-92-807-3143-9.

UNEP (2011b): Recycling Rates of Metals – A Status Report, A Report of the Working Group on the Global Metal Flows to the Interna- tional Resource Panel. Graedel, T.E.; Allwood, J.; Birat, J.-P.; Reck, B.K.; Sibley, S.F.; Sonnemann, G.; Buchert, M.; Hagelüken, C.

UNEP (2013): Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Reuter, M. A., Hudson, C., van Schaik, A., Heiskanen, K., Meskers, C., Hagelüken, C.

UNEP/SETAC (2007): Life Cycle Management – A Business Guide to Sustainability. ISBN: 978-92-807-2772-2.

UNEP/SETAC (2009): Life Cycle Management: How business uses it to decrease footprint, create opportunities and make value chains more sustainable.

van Beukering, P.J.H., van den Bergh, J.C.J.M. (2006): Modelling and analysis of international recycling between developed and developing countries. Resources, Conservation and Recycling, 46(1):1-26.

Van Schaik, A., Reuter, M. (2007): The use of fuzzy rule models to link automotive design to recycling rate calculation. Minerals Engineering, 20(9): 875-890.

Verhoef, E.V., Dijkema, G.P.J., Reuter, M. A. (2008): Process Knowledge, System Dynamics, and Metal Ecology, Journal of Industrial Ecology, 8(1-2): 23-43. http://doi.wiley.com/10.1162/1088198041269382.

Wackernagel, M., Schulz, N.B., Deumling, D., Callejas Linares, A., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., Randers, J. (2002): Tracking the ecological overshoot of the human economy, Proceedings of the

National Academy of Sciences, 2002 99(14): 9266-9271; doi:10.1073/pnas.142033699.

Welford, Richard (2003): Beyond systems: a vision for corporate environmental management for the future. International Journal of Environment and Sustainable Development, 2(2): 162-173.

Westkämper, E., Alting, L., Arndt, G. (2000): Life Cycle Management and Assessment: Approaches and Visions Towards Sustainable Manufacturing, in: Annals of the CIRP, 49(2): 501-522.

Williams, A. (2007): Product service systems in the automobile industry: contribution to system innovation? Journal of Cleaner Production, 15(11-12): 1093-1103.

Yellishetty, M., Mudd, G., Pathegama Gamage, R., Tharumarajah, A., (2011): Environmental life-cycle comparisons of steel production and recycling: sustainability issues, problems and prospects, Environmental Science and Policy,14: 650-663.

Yin, R.K. (1994): Case Study Research Design and Methods. Second ed., Applied Social Research Methods Series, vol. 5, SAGE Publications, Inc. 2455 Teller Road, Thousand Oaks, CA 91320, USA.