Scrapping steel components for recycling – Isn't that good enough? Seeking improvements in automotive component end-of-life

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Abstract

Life cycle management (LCM) suggests that companies take responsibility for the entire lifecycle of their products, either alone or together with other lifecycle actors. This paper examines the case of an automotive component manufacturer that has committed to LCM and wants to investigate product end of life (EoL) management despite the fact that it is a couple stages removed from the vehicle end-user and EoL vehicle (ELV) handling. Material flow analysis (MFA) is used to estimate and create Sankey diagrams of the downstream flows of two components made of low-alloyed steel, one wheel component and one gearbox component. Product sales data was analyzed and composition and design trends were considered to add perspectives beyond those yielded by looking at the bulk material flow. The components of interest are not remanufactured themselves but the gearboxes in which they sit are. Remanufacturers of gearboxes visited indicated a great variability in how much they replace the components of interest suggesting an opportunity for the case company to support remanufacturers in quality control and extension of use life. In regards to component EoL, many components are sent through shredding as part of ELV treatment but a comparable amount is liberated from vehicles and scrapped during vehicle maintenance. Regardless, the components end up in mixed scrap and alloying elements are rarely functionally recycled. According to commodity experts, an alternative to handle such components separately for functional recycling is practically limited. Component quantities and their values do not appear to justify additional administration and transport that would be require to sort, store and collect them. Accordingly, when considering societal interest to increase functional recycling and to activate the circular economy, it seems warranted to investigate what a recycling program for similar material grades could yield and subsequently, to consider what collaborative efforts or policy intervention would be relevant.

Keywords: Product end-of-life management, functional recycling, ELV, life cycle management (LCM)

Introduction

Life cycle management (LCM) is a concept that implies that companies take responsibility for the entire lifecycle of their components and services *or* that multiple organizations cooperate to do the same. Whereas traditional standards for management systems, such as ISO 9001 for quality, and ISO 14001 for environment place focus on individual organizations (Jörgensen 2008), LCM encourages interaction of life cycle actors (Westkämper et. al 2001).

Operationally, LCM can be implemented by a company with a wide range of approaches, ranging in scope from making transformational changes to evaluating specific phases of the life cycle. 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, such as by selling function or service instead of products (Williams 2007; Mont 2004). It is also possible to make smaller changes to the existing business or organizational structure by integrating life cycle thinking into already-used management systems, such as those for component design, sourcing, health and environmental risk management, and even component labelling (Jörgensen 2008; UNEP/SETAC 2007). Finally, a company can look at the details and assess the lifecycle of an individual product or possibly on different phases of the life cycle, from the supply chain, production (Löfgren et. al. 2011), and customer use (Price and Coy 2001; UNEP 2007) to product end-of-life (EoL) processes waste handling, recycling (Rose 2000) and remanufacturing (Kerr and Ryan 2001).

This paper focuses on the end-of-life phase and presents the case study of a multi-national component manufacturer (the case company) and one of its mechanical component types, which is prolific in automotive and industrial equipment alike. In this paper, the case company's automotive components are in focus. The case company had already addressed and continues to work on the environmental impacts related to manufacturing and component use but wanted to know if there were improvement opportunities in end-of-life. As a component manufacturer and supplier, the case company does not have direct contact with the end-user nor does it have much influence on decisions related to component EoL. The case company knew nonetheless that its mostly-steel components are recycled to a significant extent. However, it wanted to know more about the fate of its components, where potential points of used component capture might exist, as well as with which actors it could potentially cooperate with to improve the EoL of its components. (Note: Due to confidentiality agreements, neither the case company's name nor the common component name is disclosed.)

The purpose of this study was to answer the question: *What possibilities to improve component EoL management are there for a component manufacturer that is a couple levels upstream and does not have direct influence over the EoL of its components?* Material flow analysis (MFA) was used to evaluate the case company's component-material flows and place them in context with processes and actors. As a complement to the MFA, an analysis of the case company's sales data, referred to here as *component flow analysis*, was done to learn more about the mass and number of components sold and to screen potential opportunities.

The concrete results of the case contribute examples and analysis of an auto component manufacturer's component-material flows. In more general terms, it shows where in the system EoL components are separated from vehicles. In addition, it provides a snapshot of one mechanical component type that is commonly consumed in automotive and industrial equipment alike. Moreover, results provide an indication of what types of opportunities and challenges for improving the end-of-life of mechanical components, regardless of sector. Finally, the case offers insights into the process of seeking opportunities to improve component end-of-life.

1. Background – Automotive sector and EoL

There are several factors that make component EoL management in the automotive sector interesting. These factors include: (1) prevalence of and drivers for automotive component reuse, (2) remanufacturing successes by respected automotive companies, (3) legislative initiatives that focus on the material efficiency of end-of-life vehicles (ELVs), (4) environmental benefits and opportunities related to additional or improved reuse and recycling, and (5) EoL challenges related to the light-weighting of automobiles.

Prevalence of reuse

Component reuse is prevalent in the automotive sector (Kumar and Putnam 2008). Since all vehicle parts do not become functionally obsolete at the same time, EoL vehicles (ELVs) invariably contain some parts that are reusable. BMW estimates that 60% of parts are reusable at the end of their specified lifetime (BMW 2014) and dismantling and salvaging parts from ELVs is a common source of second-hand parts to the automotive aftermarket (market for replacement parts). As an example of a well-developed dismantling system, about 24% of vehicle weight from dismantling in the Netherlands was estimated to be reused as second-hand parts (ARN 2011).

There are reasons that component reuse is so prevalent in the automotive aftermarket. Traditionally, drivers for reuse in the automotive sector include: simplifying and ensuring future aftermarket part supply (Seitz and Peattie 2004), economic savings compared to new component manufacturing (Lund 1985, Bras and McIntosh 1999) and competitive-advantages from being able to offer customers different price alternatives (Lund 1985) such as those represented by Bosch remanufactured parts, which are typically 30-40% less expensive than new ones (Bosch 2014).

Remanufacturing

Remanufacturing is a process that makes extensive reuse possible – this is evident when looking at the automotive aftermarket. According to Polk (2013), 45% of gearboxes and 23% of engines on the aftermarket inventories of original equipment manufacturers (OEMs) are remanufactured.

Many companies within the automotive sector are successful remanufacturers. Examples include: Scania, Volvo trucks, Ford, Renault, Fiat, Cummins (Sundin 2004, Kumar and Putnam 2008, Mont 2002, Bras and McIntosh 1999, Rathore et. al. 2011). Many of these and other companies prominently market remanufactured components (e.g. BMW 2014, Ford Parts 2014, Volvo Trucks 2014). In order to be able to offer remanufactured components, ‘cores’ (used components) must first be retrieved. The logistics of core retrieval (reverse logistics) is well-developed for many companies as they have been retrieving and remanufacturing for decades and there are even shared services that provide the same. For example, Bosch, a prominent provider and remanufacturer of brake calipers, starters, and many other components, has developed an expansive logistics system for retrieval of component cores called CoremanNet, which is available to other auto part providers as well (Bosch 2014, CoremanNet 2014). Thus, not only is reuse prevalent in the auto aftermarket, but it is supported by, as Guide (2000) calls it, the infrastructure of a closed-loop business, which includes remanufacturing, marketing, and reverse logistics.

Material and ELV focused legislation

In addition to economic drivers to reuse components, there is also material-focused legislation, which in recent years has provided additional reason to reuse and recycle automotive components. One example of legislative action is the European Union directive 2000/53/EC (ELV directive). The directive establishes required levels of ELV material reuse, recycling, and disposal, but also requires OEMs to publish vehicle disassembly guidance. Required recycling levels increase over time – the next target is to be reached by 2015 and allows only 5% of ELV mass to be disposed. The directive further stipulates that only a maximum of 10% mass can be sent to energy recovery – the remaining 85% has to be sent for reuse or material recycling (EC 2014a).

Environmental opportunities and challenges related to reuse and recycling

The fourth factor of interest is the environmental benefits of reuse and recycling. First, material recycling reduces energy use in comparison to refining new (virgin) raw material. By avoiding raw material acquisition and refining, recycled steel is 44% less exergy intensive than virgin steel (Michaelis et. al. 1998). Material recycling also reduces the need for raw material. However, it does result in tangible material losses (UNEP 2013).

When material is recycled, some of the material's original function is often lost (UNEP 2013). *Functional recycling* occurs only when the function of a material is retained for the next use. *Non-functional recycling,* a common result of the society's mostly open-loop recycling infrastructure, results when original material qualities are simply not utilized in the next use (UNEP 2011; Dubreuil et. al. 2010). 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. These mixings of different grades result in constant function loss and result in the continuous need to replace alloying elements with newly mined materials (Yellishetty et. al. 2010, UNEP 2011, Johnson et. al. 2006, and Daigo et. al. 2010). Replacing alloying elements means that additional environmental impacts are incurred. In fact, Diener and Tillman (2015) estimated that for components similar to those studied in this paper, global warming potential incurred from replacing alloying elements could represent as much as 20% of the component's total global warming potential. In summary, functional recycling allows benefits but in order to achieve such benefits, it is important that different material types and qualities are recycled as separate fractions, not together (UNEP 2013).

Considering this, functional recycling of a mixed-material item such as a vehicle is a big challenge. Parts and components of different material compositions are potentially bolted, riveted, welded or glued together and these connections sometimes remain intact after shredding and sorting (van Schaik and Reuter 2007). The result is a number of fractions with varying levels of impurity and value, and naturally, some substances ending up in incinerators or landfills (van Schaik and Reuter 2010; Jensen et. al. 2012, Santini et. al. 2010). These proven shortcomings in the recycling system for heterogeneous components highlight the importance of separating components of unlike materials for functional recycling.

The shortcomings in recycling also support the mantra of reusing first, and recycling later. Moreover, the environmental benefits of reuse of mechanical products can be substantial. For example, Smith and Keoleian (2004) 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. This is not surprising as reuse (with or without remanufacturing) reduces the need for more material and often foregoes some manufacturing steps (Bras and McIntosh 1999; Allwood et. al. 2011; Rathore et al 2011). There are, however, challenges to achieving reuse. Stated simply, there has to be a demand from customers, cores (used products) have to be available and in the right condition, and if required (as it often is), remanufacturing has to be technically and economically effective (Guide 2000; Ostlin et. al. 2009).

Emissions reductions and related EoL challenges

Recycling and reuse is complicated by other challenges in the automotive sector. While the ELV directive places a focus on material resources, another perhaps even larger driver has been to reduce use phase emissions (such as CO_2) and energy use. For example, under EU legislation for passenger cars adopted in 2009 (2009-443-EC), automotive manufacturers are to be fined if their sold fleet does not meet an established CO_2 emissions per distance average (EC 2014b). One strategy to meet these requirements is to make vehicles lighter, which often requires replacing steel with lighter materials, such as aluminum and polymers (plastics) and even carbon fibers (Schmidt et. al. 2004; UNEP 2013). This presents a challenge for recycling – current shred and sort material handling systems are adapted to bulk metals steel and aluminum, not mixed materials and composites (Reuter et. al. 2006, UNEP 2013). In fact, Reuter et. al. (2006) states that future car designs will make the 95% ELV target impossible to realize.

Summary

In summary, component EoL management in the automotive sector is enabled by an established infrastructure for component reuse and recycling, knowledge of business and environmental benefits, and by legislation. However, there are at least two challenges related to recyclability. First, there are sizable material and function losses in recycling. Second, the changing vehicle composition driven partially by emission reduction goals causes additional difficulties in the recycling system.

2. Methods and data collection

For sake of feasibility for the case study, two main component types of the case company were chosen as foci: Component W (a wheel-end component, one for each wheel) and Component X (a gearbox component, multiple in each gearbox). From initial discussions with company representatives, hypotheses about the fates of these two component types were formulated. The intent was to strengthen, disprove, or improve them during the study.

I. EoL of Component W occurs upon failure or it is scrapped with the entire vehicle.
II. EoL of Component X occurs upon failure or during repair (or remanufacturing) of gearboxes or when scrapped with entire vehicles or gearboxes.
III. Remanufacturing of Components W does not occur.
IV. Recycling of Components W and X occurs always upon component EoL. EoL components are placed with mixed steel scrap.

These *component fate statements* provided a snap-shot of what was believed about the components' EoL before the study began. In order to evaluate these hypotheses and create more depth of knowledge around component EoL, it was deemed necessary to address two related aspects: *component-material flow and fate* and *destinations and masses of different component types*. Mapping *component-material flows* and *fates* would give an overall picture of *where* materials go, *what processes* they go through, *who* controls those processes, and what the *circumstances* (where and why components are determined to be obsolete) of component EoL are. This would be done with some consideration to component design and composition, which is a determining factor in recyclability (UNEP 2013) and repair-ability or remanufacturability (Kerr and Ryan 2001, Santini et. al. 2010, Pigosso et. al. 2010), as well as common recycling (shredding, sorting, metallurgy) systems. *Component types, destinations and masses* would be likely critical to determine the magnitude of EoL opportunities. Assessing component sales data would help answer the question – *Which components types and destinations, such as customers and regions, represent the most material mass?*

Three main methods were used: MFA, interview and site visits, and *component flow analysis*. Expected deliverables were (1) Sankey diagrams showing material flows and highlighting potential opportunities for improved EoL management (such as remanufacturing or improved recycling), (2) an improved knowledge about component fate with indications of barriers and enablers in the EoL system, and (3) a breakdown of component masses by customers, regions, and component types. In the following sections, methods and data collection are described more thoroughly.

2.1. Material flow analysis (MFA)

MFA was used to create a map of the system, and to estimate the physical flows in the system, and to identify opportunities for improved EoL management. Basic guidelines for conducting an MFA from Brunner and Rechberger (2004) were used. The MFA was conducted in two phases. First, the system of interest was defined. Second, specific cases in the Swedish market were evaluated with use of the defined system and transfer coefficients specific to those cases.

<u>*What is an opportunity for improved EoL management?*</u>

Improved EoL management was considered to be anything that improved the current EoL material efficiency. The current EoL fate for the alloyed components W and X was believed to be non-functional recycling, either via ELV shredding or placement in a mixed scrap recycling container. Hence, improvements included, but were not limited to, dedicated sorting for functional recycling (*dedicated recycling)* and reuse precluded or not by remanufacturing. It was reasoned that in order to enact any of these improvements, components must be liberated from the vehicle or gearbox and captured separately. If separated, components could be processed and recycled together with other components of similar metal grades. Thus, this study looked primarily for *possible points of liberated component capture*, where components could be captured given current activities.

<u>*First phase: System description*</u>

Considering the components of interest (W and X), system boundaries and relevant activities and processes were determined. From initial discussions with company representatives, a literature review, as well as general knowledge about steel recycling from a previous study (Diener & Tillman 2015), a conceptual diagram (Figure 1) was created to represent the system and display throughputs.

In the following paragraphs, the system of interest (the large rectangle in the figure) is described and generic transfer coefficients are presented for *Vehicle Manufacturing*, *Material Handling*, *Steel Production*, and *Slag Handling.* Component flow *a* (including components X and W) is sold from the case company to *Vehicle Manufacturing and Remanufacturing*, which includes vehicle OEMs (e.g. car/truck manufacturers) as well as vehicle component OEMs (e.g. gearbox manufacturers). Components in *flow a* are often ordered specifically for a vehicle or larger component in production. Thus, there is no overstock. In addition, failure during assembly was thought to be rare. Once assembled, cars are mostly sold to consumers while trucks are sold to businesses. Components X and W are used in *Use* as part of a vehicle.

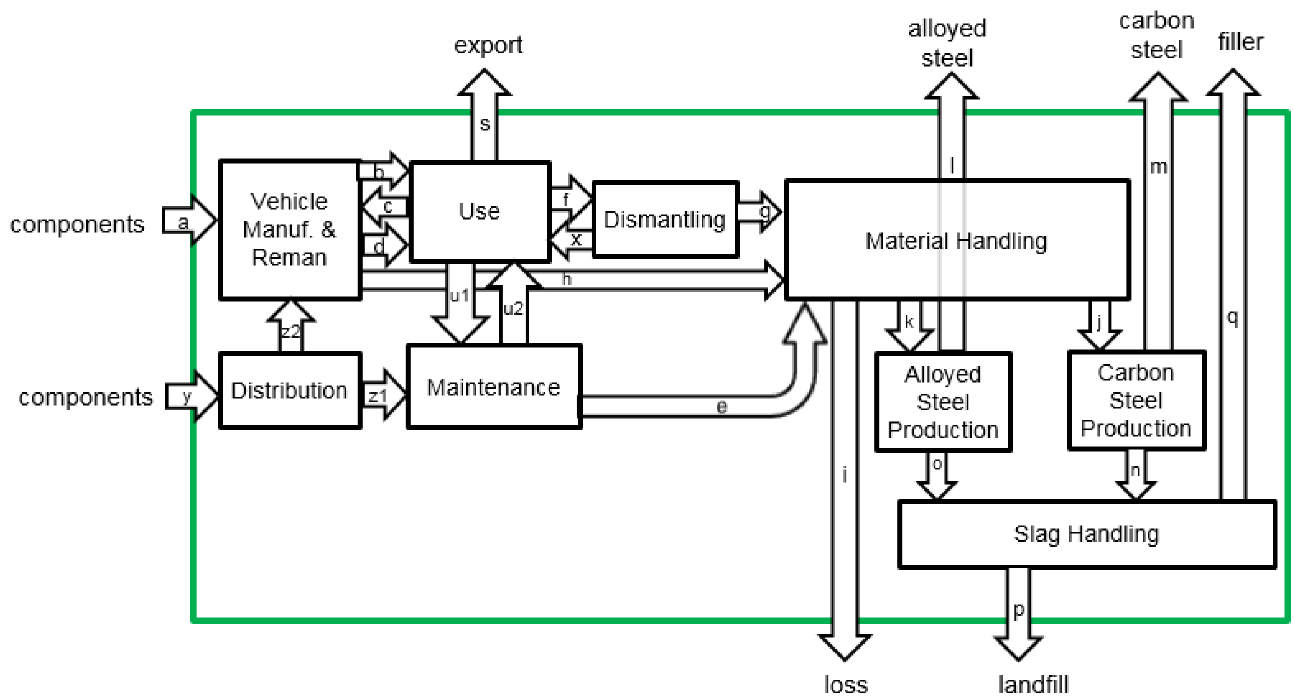


Figure 1: Conceptual diagram of the *EoL System* in which function and form descend from top to bottom. The *EoL System* includes processes of interest (boxes) and material flows, shown as arrows between processes or entering or exiting.

Components are also sold to on the vehicle aftermarket via *Distribution (flow y).* These components are sold by distributors and retailers as replacement parts for *Maintenance (z1)* or *remanufacturing (z2)*. Car maintenance is typically “managed” by an individual consumer, whereas truck maintenance it often strictly managed by truck fleet managers. Maintenance garages and remanufacturers can be both OEM-certified or stand-alone businesses. Distributors and retailers come in all shapes and sizes: pure distributors that only buy, transport and sell, pure retailers that only buy and sell in the storefront, or companies that distribute, retail in storefronts, maintain and/or remanufacture.

Components are ultimately exported as part of vehicles (*flow s)*, sent for remanufacturing (*flow c*) as part of another system, such as gearbox, sent for *Dismantling (flow f)*, or scrapped to *Material handling (flow e).*

At *Remanufacturing* and *Dismantling*, a decision is made whether or not to reuse or salvage components. Non-salvaged components are sent to *Material handling*. Material from *Material handling* is lost (i) or sold to *Carbon Steel* (j) or *Alloyed Steel Production* (k). Recycled steel from the two steel productions (l, m) goes to new products. Waste fractions from *Carbon* (n) and *Alloyed Steel Production* (o) are sent to *Slag Handling* and either disposed (p), or used in another function (q), such as a filler in road construction. Transfer coefficients for *Material Handling*, *Steel Production*, and *Slag Handling* were taken from Diener and Tillman (2015). Combined losses of steel substances Fe, Cr, Mn, Mo, and Ni were estimated to represent no less than 1.3% of input from *Material Handling* and 2.8% of input from *Steel Production*. Remaining steel after both processes was estimated to be approximately 96% of system input and the proportion at which steel scrap is sold to carbon steel producers versus alloyed steel producers was assumed to be no less than 3:1. Regarding slag, 61% was considered loss and the remaining 39% was considered to be reused in some manner (Diener and Tillman 2015).

Second phase: Data collection and applying the system to specific cases

Using the defined system, three cases of component flows for the company were chosen for evaluation – (1) Component W (a wheel-end component) to *C-cars* (a common car make) for the Swedish market, (2) Component X (a gearbox component) in Swedish car fleet, and (3) Component W to *T-trucks* (heavy truck make) for the Swedish market. In addition to the aforementioned system definition, the following information was also known and used to calculate system throughput:

Vehicle Manufacturing: Losses such as those due to failure during vehicle assembly are essentially non-existent. Hence, flow a to *Vehicle Manufacturing* was assumed to be equal to the flow to *Use (flow b*).

***Distribution*:** It is known that overstocks sometimes lead to components reaching obsolescence prior to use. However, in this case, this loss is considered to be marginal and is assumed to be 0%.

***Use and point of obsolescence*:** The amount of throughput of Component W and X depends also on how much is replaced during the vehicle use life. Component W and X replacement was estimated using information about the vehicle fleet and component lifespan estimates. For car fleet information, quantities of dismantled EoL cars (by make and year group) was received from Bilsweden (2013a). For trucks, current fleet information from Bilsweden (2013b) was used. It was assumed that for every new vehicle entering the system that one old vehicle exits the *Use* phase. This is justified because the size of both the car and truck fleet in recent years has been relatively constant (Bilsweden 2013b).

There were two component lifespan estimates for car Component Ws – one by running distance (150 kkm) and one by time (10 years). The average Swedish car is driven 6,500 km per year (Miljömålen 2014). By applying component lifespan estimates to the car fleet quantity and age information, it was possible to estimate how many Component W replacements were needed in the average use life of a C-car. The two lifespan estimates (150kkm/ 10 yrs) yielded two rates of Component W replacement, 0.85 and 1.5. These figures provided a range of how often Component Ws are replaced during a typical C-car life, which is 18 years according to dismantling data (Bilsweden 2013b). The example shown in this study uses the figure 1.1 replacements per C-car. This means that for every Component W used in a new C-car, that an additional 1.1 Component Ws are used during the C-car use life.

For truck Component Ws, the component lifespan estimate was 1 million km. It was also known that heavy trucks in Sweden have an average use of 125,000 km per year (Trafikverket 2012). These two figures were combined with truck fleet data to yield an estimate of 0.7 Component W replacements per truck.

For Component Xs, the lifespan was deemed to be correlated to gearbox failure. Estimates for gearbox failure in Germany presented by Polk (2013) were assumed to be applicable.

The amount of gearbox failure (per year) ranges from 1% for cars that are 4 years of age or less, to 5% for cars 8 years of age and older (Polk 2013). These estimates were applied to car fleet data.

However, gearbox failure estimates do not indicate what happens to failed gearboxes or to Component Xs. Upon gearbox failure, the gearbox is repaired or remanufactured (which often involves some Component X replacement), scrapped and replaced with a new or salvaged gearbox, or scrapped with the vehicle. According to statistics, about half of gearboxes requiring repairs are replaced with a new one and about half are repaired or replaced with a remanufactured or used one (Polk 2013; Lansforsakringar 2013). Beyond this, since gearbox repair or replacement represents the most expensive vehicle repair (costing around $2,500 to $3,500) (Lansforsakringar 2013; CarMD 2014), car owners sometimes choose not to pay for repair or replacement and simply scrap, sell (or abandon) their vehicles. It was not known how often the choice not to repair is made. In addition, the amount of Component X replacement during remanufacturing or repair was still not known. Information was sought during site visits in order to make reasonable estimates.

System exits, Dismantling, and Material handling**:** Approximately 5% of cars (along with contained Components X and W) are estimated to be exported and 1-5% (2% used here) are never recycled and left to rust (M. Abraham, personal communication, November 2013). Thus, an estimated 7% of total cars exiting use in Sweden are exported or left to rust. Only a couple percent (2%) of cars exiting use go directly to *Material handling,* where they are (by law) prepared for shredding, which includes hazardous material removal.

Those cars remaining (91%; approximately 184,000) are taken to dismantlers, who also salvage components and materials for reuse and recycling (M. Abraham, personal communication, March 2014). Some cars, however, are newer cars (*insurance objects*) that were obtained by insurance companies post-collision. These approximately 50,000 cars (25% of total) are more valuable and are dismantled extensively for parts resale (Jensen et. al. 2012). The remaining 66% (91%-25%; the *regular ELVs*) are dismantled only to a small degree (M. Abraham, personal communication, March 2014). The amount of component Ws and Xs salvaged for reuse and dedicated recycling at dismantling was estimated for each component after discussions with experts. After dismantling, all materials, besides those salvaged for component resell, are sent to *Material handling.*

Regarding trucks, approximately 50% of trucks was assumed to be exported after 5 years of domestic use (Mathieux 2007) but because of higher part values, losses of trucks due to abandonment or rust are assumed to be negligible.

Transfer coefficients specific to the cases of interest were estimated for *Use-Maintenance*, *Dismantling*, and *Remanufacturing* using data above in combination with estimates from relevant experts as described in the subsequent sections. Finally, it should be noted that interviews focused on component types W and X in general, not only the case company's components; component brand was not differentiated except in determination of use life. Thus, the resulting flow estimates are considered generic for component types W and X, and not specific to the case company's components.

2.2. **Interviews and site visits**

Interviews and site visits were conducted to be able to estimate transfer coefficients for the MFA (*Use-Maintenance*, *Dismantling*, and *Remanufacturing*) as well as add some depth and actor insights to the remainder of the study. The four hypotheses presented at the start of *section 3* as well as transfer coefficient needs for the MFA acted as guidelines for discussions.

Case company representatives were consulted about the case company's components and activities in the automotive aftermarket as well as basic component design and related trends. These interviews yielded a general description of the product chains in question including: customer types, other actors in the product chain (and relationships between them), component types as well as preconceptions about component fate. In addition, the basic process of working with a vehicle manufacturer was described, from the product request, to the point when the component becomes part of the vehicle.

Users (vehicle owners) were not consulted in the study. Rather, those who perform maintenance, remanufacturing (namely component change-out) and dismantling activities were interviewed. This selection was made since the focus of the study was on component EoL and not on other aspects such as performance or component life length.

Seven maintenance garages were visited. Mechanics, who do the hands-on work of maintaining vehicles and changing the components, were asked about (1) why, when and how Component Ws and Xs are deemed obsolete, and (2) the prevalence of repair and remanufacturing of related components.

Two entities that remanufacture engines and transmissions and one that only remanufactures gear-boxes and transmissions were visited. Here, managers were interviewed and technicians (those who do the remanufacturing) were consulted while they worked. The foci of visits were (1) basic remanufacturing procedures, (2) circumstances of Component X replacement, and (3) share of Component X replaced during remanufacturing.

Six managers of dismantling firms were consulted: three that focus on trucks and three that focus on passenger vehicles. Questions specific to the components of interest were posed including the share of Components W and X salvaged for reuse and for recycling during dismantling, and to whom the salvaged parts are sold.

All mechanics, remanufacturers and dismantlers were asked about component EoL recycling practices. This involved identifying what actors do with Component Ws and Xs once they are deemed obsolete and what recycling fractions they separate onsite (with focus on steel).

These and similar questions helped give indications of enablers and barriers for improved EoL management of Component Ws and Xs.

2.3. Component flow analysis

The MFA was paired with an analysis of component sales statistics from the case company to determine and breakdown component material masses in different ways (component flow analysis). Component sales to two portions of the car and truck sector were analyzed. For this purpose, sample component sales spreadsheets were gathered. The spreadsheets contained different levels of detail with the more detailed containing all sales line items for an entire year. Line items contained data that could be important to EoL management preferences were: customer, geographical location, component type, component dimensions, quantity, price and weight.

Spreadsheets were analyzed by simply sorting and counting components or related material weight or sales (e.g.) by one criterion, such as by customer or region. The first analysis aimed to determine how many of the sold components were hypothetical candidates for remanufacturing. Component size was used as the sole indicator of remanufacturing feasibility; bigger components are preferred technically and economically in the case company's remanufacturing operation, which currently services non-automotive sectors. The case company has informal guidelines for which size of components to remanufacture, one of them being the *minimum*, the smallest size accepted for remanufacturing. This *minimum* size was compared to component sizes in the sales spreadsheet to identify how many components were as big as or larger than the *minimum* size.

The second analysis aimed at assessing if dedicated recycling would be feasible for the components of interest. This analysis was conducted in two parts: (1) identifying general factors that makes dedicated recycling feasible for a certain steel grade and (2) determining how much material such recycling could include if all the components of interest were captured. First, two scrap sourcing experts (one in *Material handling* and the other in *Steel production*) were consulted to determine what factors make dedicated recycling of a scrap steel grade feasible. Then, sales data was used to determine an annual component mass sold in Sweden. By using this mass data along with factors determined by experts and component composition, it was possible to reflect on the potential for dedicated recycling of the steel grade in question and to identify potential barriers towards the same.

3. Results and analysis

Two types of results are presented. *MFA* results with Sankey diagrams and bar charts displaying component fates, and *component flow analysis* results.

3.1. What does the component flow through the EoL system look like and what are component EoL fates? *MFA*

The three example component flows for the company on the Swedish market are shown here. Primary opportunities to capture Component W and X for potential dedicated recycling or reuse/remanufacturing are identified. They are based on quantities and circumstances of component EoL and highlighted with (red) rings in Figures 2-4.

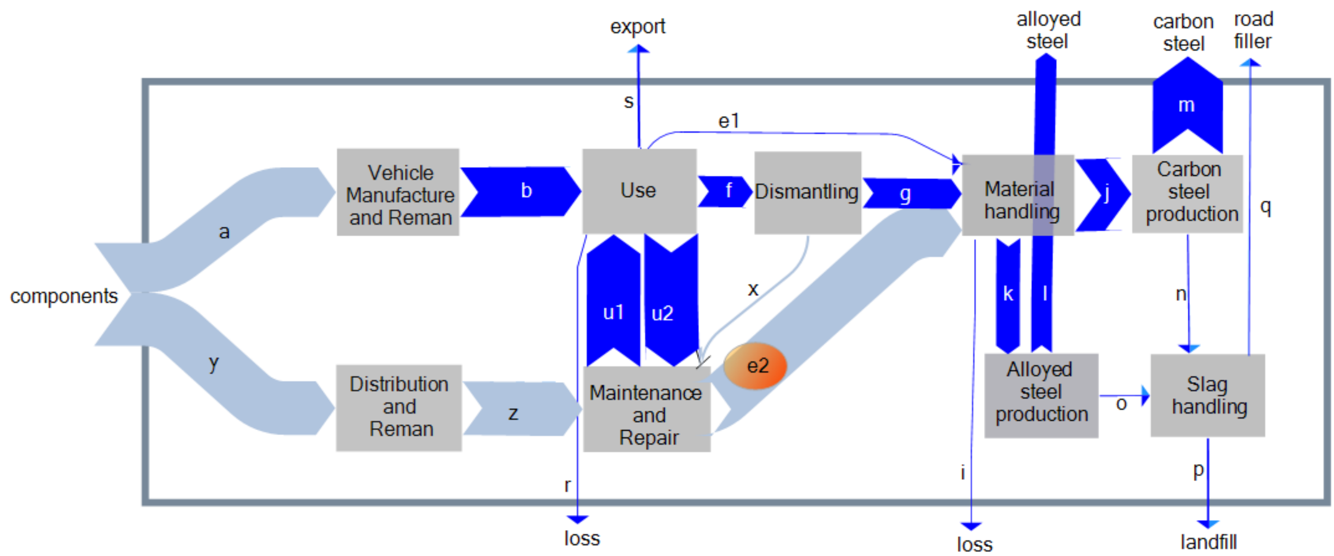
A comparison of circumstances (activities, and component liberation status) of component EoL is shown in Figure 5. It must be noted that all numbers are rough estimates resulting from the study. Although the estimates do not provide statistical accuracy, they fulfill the aim of the study – to give a general picture of what component flows look like as well as give an indication of what locations or actors may be most important for realizing improved component EoL management.

3.1.1. Component W use in C-cars in Sweden

Figure 2 displays results for Component W use in C-cars in Sweden. It was estimated earlier in *section 3.1* that the average *C-car* requires a replacement of all Component Ws 1.1 times during its use life. A fraction of these Component Ws are replaced with salvaged component from dismantling. Dismantlers estimate that only a couple percent (2% used here; 5% for insurance objects, 0% for others) of the Component Ws that go to dismantling (*flow f*) are salvaged for reuse (*flow x)*, and none are salvaged for functional recycling.

Thus, salvaged components for resale satisfy only 2% of the need and a 108% addition of Component Ws via aftermarket distribution (*z via y*) is needed. The total input flow for the system (a + y) is then 208% (100% representing the original input to production of new cars, *flow a*).

Calculating percentages from this figure (208%), the fate calculated for the Component Ws sold for use in *C-cars* on the Swedish market is as follows: 43% reach EoL as part of a C-car after dismantling (*flow g)*, a little more than 2% are exported for reuse as part of a *C-car (flow s)*, less than 1% are never recovered (*flow r)*, and about 1% go directly from *Use* to the scrap yard (*Material handling*) for shredding (*flow e1)*. Finally, about 52% is scrapped after replacement (from *Maintenance)* and sent to *Material handling (flow e2)*. This is considered the best opportunity to capture components for dedicated recycling for this type of component (see ring in Figure 2) due to the quantity (estimated 52% of the total) and because at this point, Component Ws are separated from the vehicle. Regarding reuse, less than 1% of the total input is reused in another vehicle after dismantling.



flow	a	b	e1	e2	f	g	i	j	k	l	m	n	o	p	q	r	s	u1	u2	x	y	z
nearest %	48	48	1	54	45	43	1	73	24	24	71	2	1	2	1	1	2	54	54	2	52	52

Figure 2: Sankey diagram for Component W to use in C-cars. Lightest flows (like *a*) represent components not installed in cars (liberated). Darkest flows (like y) are where components are part of the car, and after *material handling*, part of vehicle scrap material and subsequently, recycled steel. The most favorable opportunity to improve component EoL is shown as a circle (*e2*) both due to the quantity and because components are liberated from cars here. The table shows nearest percent of total input for each flow.

3.1.2. Component X use in the car fleet in Sweden

Figure 3 displays results for Component X use in gearboxes in the car fleet in Sweden.

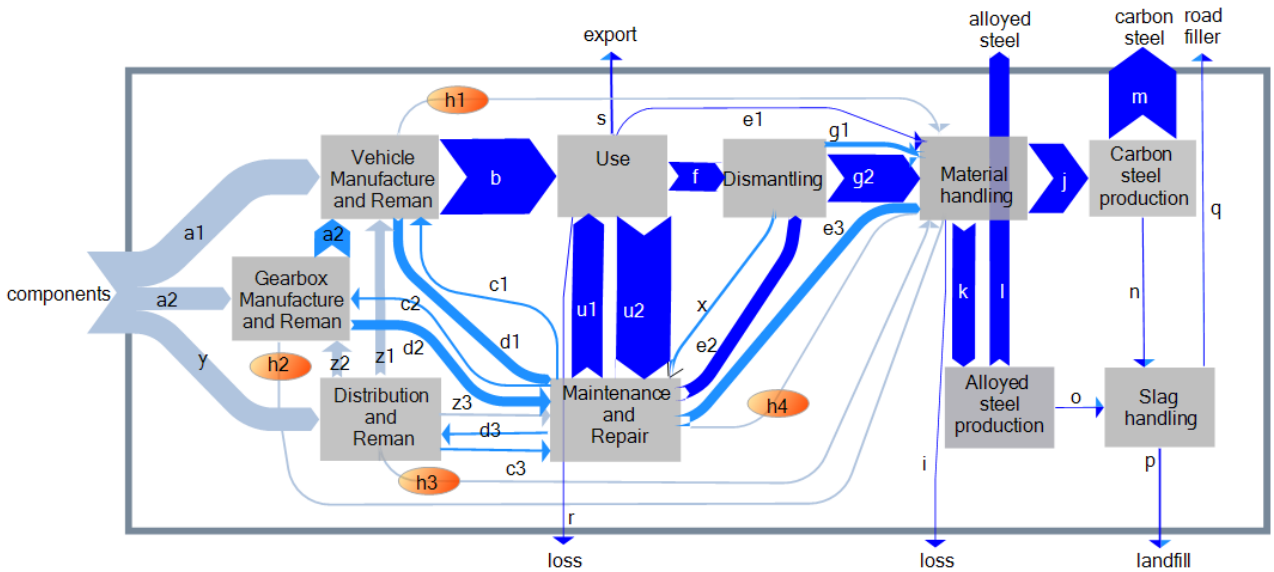
Additional information was obtained from mechanics, dismantlers and remanufacturers to estimate what happens when gearboxes fail. First, not all car owners choose to repair or replace gearboxes when they fail – some deem their car not worth saving. Naturally, as cars get older, the cost of such a repair or replacement represents a larger portion of the car's value and car owners are less likely to choose repair or replacement. For some car models, car value at 10 years is exceeded by the cost of gearbox repair or replacement. For simplification, it was assumed that for cars less than 10 years old, 100% of gearboxes are repaired or replaced and that for cars that are 10 years and older, 50% of gearboxes are repaired or replaced. The other cars are assumed to be sold for parts or scrapped. From this generalization as well as car fleet data and gearbox repair rate (*section 3.1*), it was estimated that an equivalent of 43% of non-exported cars during their lifespans require gearbox repair or replacement. Another 37% of initial Component Xs are scrapped as part of a vehicle or gearbox when owners decide against repairing them.

Ninety-one percent (91%) of total cars go through the dismantling process (*from section 3.1*). From the dismantled cars, 5% of gearboxes is estimated to be salvaged for dedicated aluminum recycling. Six percent (6%) of the gearboxes (20% of insurance objects and 1% of regular ELVs) is estimated to be salvaged for reuse; some of these are remanufactured. That means about 5% of the original input flow are recirculated to *Use* from *Dismantling (flow x),* and 87% are sent to *Material handling (flow g)*. The remaining 38% gearbox replacement (the 43% requiring gearboxes minus 5% recirculated) are new (21.5% of original) and remanufactured (19% of original). This means that an additional 19% Component X flow (*y)* is added to the original input flow as part of new gearboxes.

Regarding Component X replacement during remanufacturing and repair, remanufacturers visited indicated a great variability in the amount of Component Xs they replaced, from no replacement to total replacement. For the sake of estimation, it was estimated that 50% of the Component Xs are reused. This means that replacement Component Xs represents a 9.5% addition to the original input flow (half of the 19% remanufactured). Thus, summing the original input to production of new cars (100%, *a1+a2*) and both the additional Component X aftermarket flows to both new (21.5%) and remanufactured (9.5%) gearboxes yields a total component input of 131% (*a1+a2+y*).

Calculating percentages of the total input from this 131%, the fate of the Component Xs sold for use in *cars* on the Swedish market is as follows: 1% is lost (*flow r,* abandoned, rusted), 4% are exported (*flow s)* for reuse as part of a car, 7% are removed and scrapped in conjunction with gearbox remanufacturing (*flows h1-h4*), 4% is sent to *Material handling* as part of a liberated (separated) gearbox (*flow g1),* 48% are scrapped as part of a car after car dismantling (*flow g2)*, 25% are scrapped as part of a gearbox after gearbox replacement or repair (*flow e3)*, and about 1% goes directly with a car from *Use* to the *Material Handling* for shredding (*flow e1*). Finally, it is estimated that 8% of Component Xs are reused at some point in Sweden, either after remanufacturing or as part of a gearbox in another car.

Thus, there is an indication that the quantities of Component Xs at the points of remanufacturing are relatively small (estimated 7%). However, these points are nonetheless considered to be the best opportunity for improved component EoL for a few reasons – (1) Component Xs are liberated from gearboxes here, they are not attached which could facilitate dedicated and functional recycling (see circles around the flows *h1-4* in Figure 3), (2) the variation in the amount of Component Xs replaced during gearbox remanufacturing indicates that there may be an opportunity for the case company to help customers to determine when changing Component Xs is actually necessary, and (3) in some cases (e.g. OEM remanufacturing), the case company has direct contact with remanufacturers. Other points of fate appear to be harder to address. Here, Component Xs are attached to gearboxes and/or cars, making them practically inaccessible.



flow	a1	a2	b	c1	c2	c3	d1	d2	d3	e1	e2	e3	f	g1	g2	h1	h2	h3	h4	i	j	k	l	m	n	o	p	q	r	s	u1	u2	x	y	z1	z2	z3
nearest %	38	38	76	3	3	3	11	11	3	1	24	15	29	4	47	2	2	1	2	1	70	23	23	68	2	1	2	1	2	4	55	31	3	24	11	11	2

Figure 3: Sankey diagram for Component Xs for use in gearboxes and Swedish cars. Lightest flows (like *a1*) represent components not installed in gearboxes (liberated). The medium-dark flows (like *a2*) are components installed in gearboxes. Darkest flows (like *b*) are where components are part of the car, and after *material handling*, part of vehicle scrap material and later, recycled steel. Circles around flows *h1-h4* indicate best identified opportunities for capture, as components are liberated here after use. The accompanying table shows nearest percent of total input for each flow.

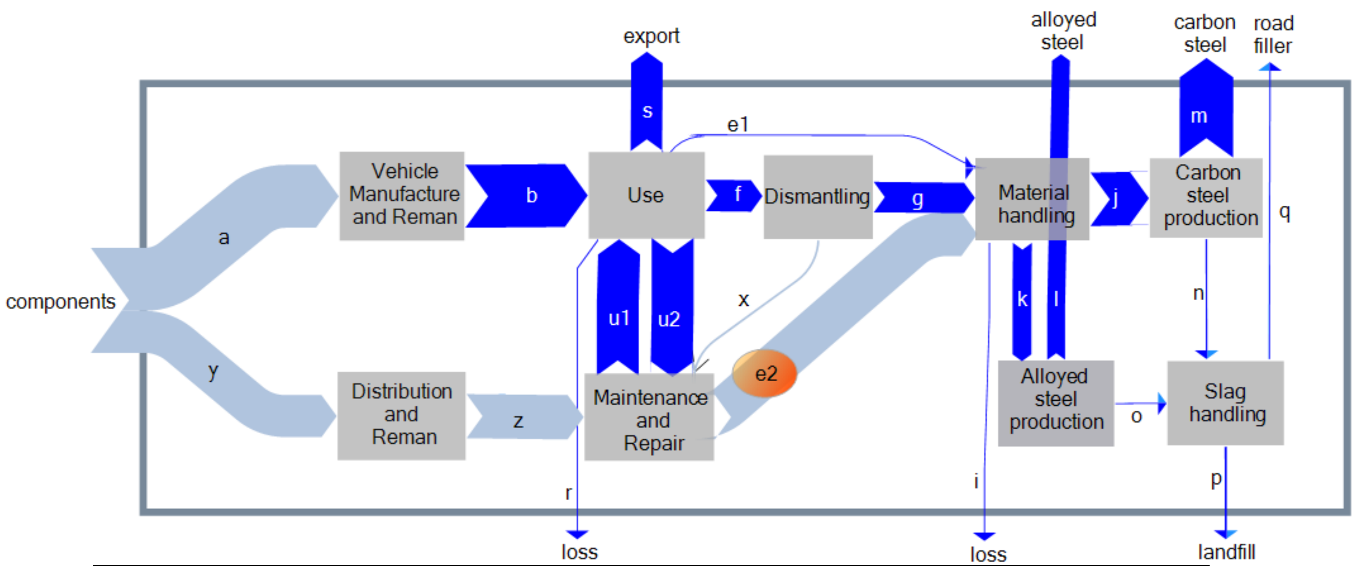
3.1.3. Component W use in T-trucks in Sweden

Figure 4 displays results for Component W use in T-trucks in Sweden. It was estimated earlier in *section 3.1* that the average T-truck in Sweden requires a replacement of all Component Ws 0.7 times.

Some of this requirement is provided by salvaged Component Ws from *Dismantling*. Due to the high value of truck parts and the high export rate (50%), truck dismantlers interviewed believed that only a small percentage of EoL trucks go directly to *Material handling* (in Sweden). Thus, for this study, the same estimate used for cars (2%) was used for trucks. The remaining 48% are assumed to be dismantled. Only 5% of the Component Ws sent to *Dismantling* was estimated to be salvaged and resold. The salvaged Component Ws satisfy about 2% of needed replacements. By subtracting this 2% from the 70% needed (noted above), a requirement of an additional 68% Component Ws from the aftermarket is yielded.

The total input of Component Ws is then 168% (100% representing the original input to production of new trucks, *flow a*).

Calculating percentages from this 168%, the fates of the Component Ws sold for use in T-trucks on the Swedish market are as follows: 30% exported for reuse as part of a T-truck, 27% is scrapped by a dismantler, and 1% directly from *Use* to the *Material handling* for shredding. Finally, 42% is scrapped after replacement (*Maintenance*) and sent to *Material handling*. Due to the quantity and because the component is separated from the vehicle, this is considered the best opportunity (see ring in Figure 3) for improved component EoL.



flow	a	b	e1	e2	f	g	i	j	k	l	m	n	o	p	q	r	s	u1	u2	x	y	z
nearest %	60	60	1	42	29	27	1	52	17	17	50	1	0	1	1	0	30	42	42	2	40	40

Figure 4: Sankey diagram for Component W to use in T-trucks. Light flows (like *a*) represent components not installed in gearboxes (liberated). Dark flows (like y) are where components are part of the truck, and after *material handling*, part of truck scrap material and subsequently, recycled steel. The most favorable opportunity to improve component EoL is shown as a circle (*e2*) both due to the quantity and because components are liberated from trucks here. The table shows nearest percent of total input for each flow.

3.1.4. Summary – possible points of liberated component capture

These three examples give an insight into the fates of the company's components and give a rough view of where opportunities for material capture or extending component life may lie. As mentioned in the introduction and visualized by the Sankey diagrams, most scrap steel is used in carbon steel production where alloying elements do not fulfill a function – they are, on the contrary, often considered contaminants. It is hence interesting to identify where these low-alloyed component could be captured for dedicated, functional recycling. Figure 5 aims to break down possible points to capture liberated components. It compares the EoL and export flows for the three examples (flows *e, g, h, s*). In Figure 5a, flows are shown as portions of the total exiting domestic use (scrapped, exported or lost). For both Component W examples, it is shown that *Maintenance* is the activity at which the largest portion of the component flow is scrapped (*e* flows).

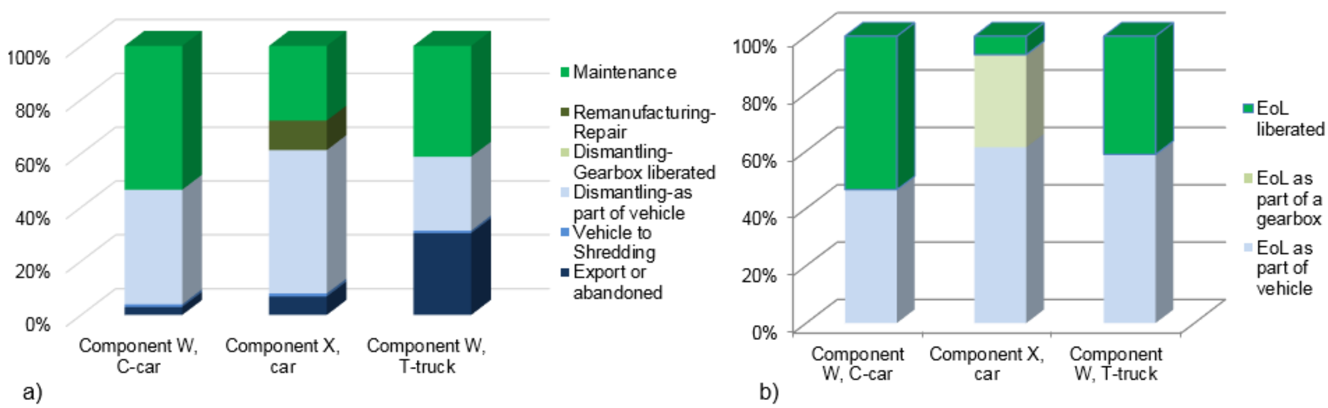


Figure 5: Three examples of component EoL fate compared: (a) component fates classified by activities at which components become scrap material or exported and (b) component fates grouped into liberation statuses (liberated or connected to vehicle or gearbox).

In Figure 5b, flows (*e, g, h, s*) are grouped according to how liberated they are, attached to vehicle, attached to gearbox, or totally liberated. Due to high levels of component replacement during vehicle use, both Component W examples show a high frequency of being liberated (detached) at EoL, whereas Component X is often attached as part of the gearbox or the vehicle itself. Hence, in regards to quantities liberated, Component Ws appear to be better targets for dedicated recycling than Component Xs because large quantities could be hypothetically captured during *Maintenance*. However, as mentioned earlier, the replacement of Component Xs during gearbox repair or remanufacture (*Reman*) could also be a point of improvement in two ways: (1) increasing reuse or improving quality in reuse and (2) capture for dedicated recycling.

3.2. Which individual component flows make up what portion of the mass material flow? *Component flow analysis*

For purposes of assessing or prioritizing EoL management possibilities, the component sales, expressed in terms of weight, was divided by customer, component size, type, and quantity (count).

Results demonstrated that two customers receive approximately 75% of the component weight and 60% of the component count (number of pieces). This indicates that cooperating with a few key customers could be a favorable way to influence the end-of-life management of a large amount of its components. For example, it is known that both customers operate certified maintenance centers. In addition, the customers, like many truck OEMs, sell truck service contracts and lease or rent some trucks. Maintenance of these trucks is often done at the truck OEMs' centralized maintenance locations. This means that some of the components are changed out and scrapped at centralized locations and that these locations are under the control of customers with which the component company already has contact. Hence, if the component company were to coordinate with these customers, they could gain access to a tangible flow of used components.

When contemplating component capture, size and weight was considered interesting both based on the ultimate goal of mass capture (the more the better) and because larger components are considered to be more technically and economically remanufacturable. Regarding mass capture, components sold to the truck sector that have an individual weight of 5 kg or greater represent about a third (33%) of the total component weight but only a few percent of the component count. This could be an indication of administrative feasibility – a lot of material could be captured while only targeting some of the components.

Although Component Ws are not currently remanufactured, there is a rule-of-thumb minimum size at the case company for remanufacturing of components that are similar to

Component W. For the truck sector, components that that are equal to or greater than this minimum size represent about 15% of the total component weight and only a few percent of the component count.

When comparing the results of the analyses of the truck and car sectors, the smaller size of car components is noticeable. None of the car components are greater than the rule-of-thumb minimum remanufacturing size. When looking at individual component weight, components greater than 5 kg in weight represent less than 10% (compared to 33% for trucks) of the total component weight. Hence, Component Ws for trucks are (unsurprisingly) larger and heavier than Component Ws for cars. Even so, this 5 kg measure gives an indication of the dissipative (and small) nature of these components. While the total mass flow of these components represents many tonnes, individual components – even at 5 kg a piece – represent relatively tiny bits of scrap in a market that focuses on gathering tonnes of new scrap from factories and tonnes of old scrap in the form of obsolete ships, industrial machinery, end-of-life vehicles, and consumer appliances.

4. Discussion

Here, the hypotheses (introduced initially in section 3) are first evaluated and a short discussion is presented on the value of conducting such a study and its representativeness. Finally, at the conclusion of this section, main findings generated from this study are summarized in a table.

I. **EoL of Component W occurs upon failure or when scrapped with the entire vehicle**.

Mostly true – Component W failure is detected by feel and sight of the mechanic. Only faulty Component Ws are changed. It does not appear common to change the other three Component Ws on the vehicle for reasons of performance or preventative maintenance, like recommended with tires. Because Component Ws are faulty upon replacement, they are in a more worn condition and possibly less easily repaired or remanufactured than if they had been changed for reasons of preventative maintenance.

It was also noted that there are different versions of Component W for different vehicles. One particular type of Component W is integrated (and attached) physically with other components; this makes the EoL of Component W and these other components dependent on each other. In the case of that version, the EoL (or failure) of component W causes the other component to need replacing and vice versa.

II. **EoL of Component X occurs upon failure or during repair (or remanufacturing) of gearboxes or when scrapped with entire vehicles or gearboxes.**

True with modification- There appeared to be a large variability between gearbox remanufacturers with regards to what quantity of Component X is replaced during remanufacturing. One remanufacturer indicated that Component Xs are replaced almost always whereas a couple remanufacturers indicated that replacing Component Xs is only done if deemed necessary. According to these two remanufacturers, replacements occur in two main circumstances: (1) when a fault in the Component X is detected during inspection or (2) if another component that has a direct effect on Component X is deformed in a way that indicates potential damage to Component X. Thus, reuse of Component Xs in remanufactured components does occur.

Not only does Component X reuse occur, but it was indicated that sub-components from Component X are reused. One visited remanufacturer salvages sub-components from Component X and reuses them interchangeably. This involves taking one Component X apart, visually inspecting the sub-components, and then salvaging some sub-components and scrapping others. Scrapped sub-components were replaced with previously salvaged sub-components to make a newly assembled Component X.

This represents a form of repair of Component Xs and repurposing of its components. This activity was surprising, if not unheard of (and not recommended) by the case company representatives. The activity nonetheless puts the idea of sub-component interchangeability up for discussion and is an indication that there may be an opportunity for the company to improve the quality control related to remanufacturing *and/or* extend use life of Component Xs. This could be done by helping remanufacturers determine when Component Xs need to (or should) be changed.

III. Remanufacturing and repair of Components W does not occur.

True **–** Mechanics at maintenance garages indicated that it was formerly possible (but not common) to conduct minor Component W repair for both cars and trucks but that now, repair is not usually possible.

Conducting a cursory view of Component Ws over the past decades demonstrates that while Component W has become lighter and more efficient (consistent with vehicle light-weighting and emissions goals), and more functional and easier to install, this change has resulted in less repairable Component Ws. Many newer Component Ws are assembled in a way that prevents repair and added sub-components such as sensors make the component more sensitive. Disassembly of these newer components is not recommended and is likely to result in component damage. Hence, any potential repair or remanufacture of Component Ws would have to be precluded by a change of component design.

Direct reuse of Component Ws that have not failed is more prominent. Dismantlers of both passenger vehicles and trucks sell used Component Ws (this is apparent on a multitude of web-shops as well). However, dismantlers indicated that the Swedish market for used Component Ws is very small. A number of interviewees (two maintenance garages, two remanufacturers) indicated that the market for used parts was much greater outside of Sweden, especially in the Middle East, Africa and South America.

IV. **Components W and X are recyclable and are always recycled. EoL components are placed with mixed steel scrap.**

Mostly True – Some vehicles and the components in them are invariably left to rust or are never recycled. This outcome is considered rare and extremely difficult for a component supplier to address but could be something to consider at a societal level.

Regarding EoL component sorting, it was noted that most of the visited sites (and all maintenance garages) had only one container for scrap steel, but a couple dismantlers consulted sort steel by three levels of purity or “cleanliness” (Swedish classes 11 and 12, and vehicle scrap). In addition, some gearboxes have aluminum housings and some dismantlers separate them from the other scrap to get a premium for aluminum. Dismantlers also separate other components and materials, such as catalytic converters for platinum content (due to regulatory requirement) and cables for copper. Thus, dismantlers and material handlers already conduct some types of component-focused recycling, which in the case of catalytic converters is done with specific substances in focus.

Why component-focused recycling is not done with components like Components W and X is apparent when looking more closely. Despite the fact that there is a large amount of Component Ws and Xs that is liberated from the vehicles before vehicle EoL, the components are not recycled separately. Speaking to material (scrap) experts including two brokers and one buyer revealed four factors that determine the potential of dedicated recycling for components like Components X and W: (1) *commodity values, (2) common component composition,* (3) *scrap load size required,* and (4) *composition confidence*.

Commodity values and *component 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, Components W and X, 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 and the scrap cannot be excessively rusted. These requirements are based on load sizes and technical aspects of transportation and electric arc furnace scrap melting.

In order to estimate the potential opportunity for such dedicated recycling, the total sold weight of components X and W from the case company was divided by example load sizes indicated by experts. It appears that there is a yearly potential in Sweden of between 2 to 20 loads of components X and W from the case company, only.

Thus, it appears that there are some relevant loads of the case components out there and according to current scrap valuation, they could yield some value beyond normal scrap value. This may not seem convincing, but if the components of interest were combined with other components of similar composition, the potential for dedicated recycling would be greater. For instance, the automotive components of studied here could be combined with some of the company's other non-automotive components or with other components from the automotive sector to possibly achieve economies of scale.

There are barriers that would undoubtedly have to be addressed first. In reality, the type of steel is rarely known by the scrapping entity (in this case, the maintenance garage, dismantler or remanufacturer) and even if they did, there are not special containers in which to put different types. Also, components have to be collected, stored and transported in order to achieve the proper scrap load size. This process of handling and storage 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.

Regardless of current barriers, it appears that there may be a potential for the case company, but also the automotive sector and society to achieve more dedicated and functional recycling. The potential and corresponding barriers could be investigated with company, lifecycle (or value chain), or automotive sector perspectives. For instance, the case company could investigate instituting its own reverse logistics program to retrieve its own components or how it could cooperate with other lifecycle actors to achieve the same. Another wider perspective for investigation could involve evaluating the potential for the entire automotive sector to sort like-composed components.

Finally, another impending barrier appeared when looking at the components and composition of Component Ws over time. These components appear to be getting more complex and as a consequence, less recyclable. Former versions of Component W were made almost entirely of steel while later versions have been integrated with cast iron components. Some of the more advanced versions also now include aluminum parts and copper wires. If not liberated from the steel during shredding, aluminum follows along with the steel and is lost to slag. Considering that aluminum on a weight basis has a considerably higher carbon footprint than steel, losing it after one use and not recycling it is a relevant concern. Copper, on the other hand, acts as an unwanted contaminant during scrap metallurgy if it is not liberated from steel. If the copper wire is liberated, it is likely to end up in auto fluff, which is disposed of, incinerated or sent for hand-sorting with an unknown success rate. This barrier is something the case company could address by investigating the fate of its components in shred and sort recycling systems more thoroughly.

In summary, the combination of methods used for this study provided a number of findings relevant to a few of the components' life cycle phases (see Table 1, below). While normal business practices place focus on components, their utility and sales quantities, this study placed focus on something else – materials and product end-of-life. This focus is valuable for a few reasons. The MFA with accompanying Sankey diagrams gives the company something they didn't have before – generic pictures of what component and material flows (may) look like. The *component flow analyses* put component weight in focus instead of component quantity and sales amounts. Finally, the investigation served to strengthen or improve existing hypotheses related to component fate (as discussed above).

Life cycle phase	Findings
Design and end-of-life	• Alloying elements from the studied components likely become residual elements in carbon steel, rendering them useless. They are not functionally recycled. • Increasingly complex components have provided higher performance and longer life but make recycling more difficult and remanufacturing virtually impossible. • Aluminum-steel hybrid components likely result in Al losses to slag while small copper wires likely go to fluff, meaning that they are not likely to be recycled. • Disassembly (and remanufacturing) of many newly-designed, more advanced components is not possible without damaging them.
Use and replacement	• Amount of components replaced during vehicle use represent an amount comparable to that contained in end-of-life vehicles (ELVs). • Replacement components are liberated from vehicle making it more possible for them to be recycled separately. • A few customers (truck OEMs) purchase a large percentage of the components. Considering that these customers have some centralized maintenance centers where trucks are serviced, efforts to collect used components from these locations may be worth investigating.
Remanufacturing	• Although the case company does remanufacture other similar components, the components studied here are not remanufactured. • Some of the components studied are as large as the case company's rule-of thumb size for remanufacturing, but are currently not considered economically feasible to remanufacture. • Depending on local practices, gearbox components are replaced during gearbox remanufacturing at varying amounts, from 0-100%. This variability indicates an opportunity to increase quality control and/or reuse of components during remanufacturing.
Material/ scrap handling	• The components contain alloying elements that make them hypothetically more valuable that regular scrap steel. • The scrap value of the components is practically limited by logistics and scrap steel quality standards.

Table: Main findings for each component life cycle phase

Regarding matters of applicability and representativeness, this study was done mainly with information from the case company, a vehicle manufacturer, as well as some mechanics, remanufacturers, dismantlers, and material (scrap) brokers in Sweden. Obviously, reliability could be improved if more information and actor input were to be obtained. However, a statistically representative study would require much more data. Such a study was not intended here. Also, although Sweden is likely unique in some ways, vehicles there are not and the dismantling, remanufacturing, and recycling infrastructure is known to be not all that different in other developed countries. Thus, the generic lessons learned about component design, use and fate should be relevant elsewhere.

5. Conclusions and implications

There is often distance between a component manufacturer and the point at which its components reach EoL. This presents a challenge for its component EoL management for two reasons (1) the component manufacturer does not have direct contact with end-users, dismantlers and material handlers, and (2) the component is embedded in a vehicle, which is the component-level at which EoL management often occurs.

Despite this challenge, this study revealed a few opportunities for improved EoL management of the studied components. One opportunity was revealed when observing the remanufacturing of gearboxes. There appears to be a great variability in the amount of components that are replaced during gearbox remanufacturing. This indicates that there is an opportunity for the company to support remanufacturers in deciding which components need to be replaced. This could improve quality control and contribute to extended component life.

In addition, results demonstrated that even though many components of interest reach obsolescence due to vehicle EoL, component obsolescence occurs also to a large degree at maintenance during the vehicles' use life. This presents a couple opportunities: (1) to develop components that can be remanufactured or repaired and (2) to collect sorted components for dedicated and functional recycling. The first opportunity is relevant primarily for the case company, whereas the second is also relevant to other actors, also on the societal level.

In regards to the first opportunity, it appears to be more feasible to develop remanufacturable truck components than car components. Truck components are bigger, which means that they are more valuable in terms of sales and material price. Also, some truck wheel-end components are as big as other components that are already remanufactured at the company. However, although some of these components are hypothetically remanufacturable, the newer generation components are often impossible to dismantle without damaging them.

This is due to component design trends that have delivered components that are of higher performance and more efficient but harder to take apart. In the ever-demanding race to improve performance, component design continues to get more complex. A mostly-steel component is becoming increasingly multi-material (e.g. cast iron, aluminum, polymer and steel components) and infused with additional function that requires wires and sensors. These additional materials and components have led to a component that is more difficult to separate and recycle to materials of equal quality. With a long-term strategic perspective, these design trends indicate that the company could benefit from (1) evaluating component construction and material liberation in dismantling, shredding and sorting and from (2) assessing what it would take to make remanufacturable components for trucks.

Finally, policy and research discourse related to EoL and vehicles focuses on what happens to ELVs and their inherent materials in the recycling system. The results from this study demonstrate that the ELV is not the only vehicle-related EoL component flow. Replacement of components during the vehicles' use life represents a considerable quantity of EoL component flow.

The study also indicated that the components studied as examples in this paper could yield a premium scrap price and if collected in large enough quantities. Achieving such dedicated recycling would demand mitigating collection and transport costs and making sure composition information was available to those who would sort and collect scrapped components.

However, this study considers only two types of components used in the automotive sector. Considering the knowledge that the automotive aftermarket is large, there are likely many other automotive components that are liberated and discarded before the vehicle reaches ELV status. In addition, similar mechanical components are used and consumed in industrial machines. Many of these components, regardless of sector, contain valuable substances (such as alloying elements) that require a lot of energy and resources to refine, but are principally lost in the recycling system after only one use. These substances are essentially <u>not</u> recycled. Consequently, when considering societal interest to increase functional recycling and to activate the circular economy, it seems warranted to investigate what a sector or society-wide recycling program for similar material grades or components could yield and subsequently, to consider what collaborative efforts or policy intervention would be relevant.

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6. 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

ARN (2011): Expertise centre for mobility recycling and sustainability. Presentation from Mobilis Conference 2011, Belfort, France. Retrieved on March 21, 2014 at http://www.mobilisconference.com/uploads/2011/pdf/Atelier%20A1-ZOM.pdf.

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.

Bilsweden (2013b). Statistics of Swedish car fleet including make/model in MS Excel spreadsheet. Obtained from for personal use on November 15, 2013.

Bilsweden (2013a). Statistics of Swedish car fleet in MS Excel spreadsheet. Obtained from http://www.bilsweden.se/ on November 1, 2013.

BMW (2014): Original BMW Remanufactured Parts. Retrieved February 18, 2014 from http://www.bmw.com/com/en/owners/parts/exchangeable_parts.html.

Bosch (2014): Bosch Further Expands its Range of Expertly Remanufactured Vehicle Parts. Retrieved February 18, 2014 from http://www.bosch-presse.de/presseforum/details.htm?txtID=5868&locale=en.

Bras, B., McIntosh, M.W. (1999). Component, 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.

CarMD (2014): CarMD Vehicle Health Index, Retrieved on June 15, 2015 from http://www.carmd.com/wp/carmd-press-center/

CoremanNet (2014): CoremanNet – the service for your core return. Retrieved on March 15, 2014 from http://www.coremannet.com/en/.

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), pp. 851-863.

Diener, D. and Tillman, A-M. (2015): Component end-of-life management: Exploring opportunities and related benefits of remanufacturing and functional recycling, Resources, Conservation and Recycling, 102: 80-93. doi:10.1016/j.resconrec.2015.06.006.

Dubreuil, A., Young, S., Atherton, J., Gloria, T. (2010): Metals recycling maps and allocation procedures in life cycle assessment. International Journal of Life Cycle Assessment, 15: 621–634.

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

EC-European Commission (2014b): Reducing CO2 emissions from passenger cars, Retrieved on March 2, 2014 from http://ec.europa.eu/clima/policies/transport/vehicles/cars/index_en.htm

Ford (2014): Our Components / Powertrain Components / Remanufactured Gas Engine Assemblies, Retrieved on March 15, 2014 from http://www.fordparts.com/components/powertraincomponents-remanufacturedgasengineassemblies.aspx

Guide, V.D.R., Jr., (2000): Production planning and control for remanufacturing: industry practice and research needs. Journal of Operations Management 18(1), 467–483.

Jensen, C., Felix, J., Ljunggren Söderman, M., Skenhall, S.A., Rydberg, T. (2012): Report: Utvärdering av förändrad demontering och återvinning av uttjänta fordon i Sverige. IVL rapport B2068.

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

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.

Kumar, S., Putnam, V. (2008): Cradle to cradle: reverse logistics strategies and opportunities across three industry sectors. International Journal of Production Economics 115(2), 305–315. DOI: 10.1016/j.ijpe.2007.11.015.

Lansforsakringar (2013): Länsförsäkringars maskinskaderapport 2013 (in Swedish), Retrieved on June 15, 2015 from http://www.lansforsakringar.se/globalassets/aa-global/dokument/ovrigt/aa-om-oss/rapporter-och-undersokningar/04598-maskinskaderapport.pdf

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, pp. 24–34.

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

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

Miljömålen (2014): Körsträcka med bil. Retrieved on March 1, 2015 from http://www.miljomal.se/Miljomalen/Alla-indikatorer/Indikatorsida/?iid=87&pl=1

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 Component Design, 2 (3-4): 89-103.

Mont, O. (2004): Reducing life cycle environmental impacts through systems of joint use. Special issue on ''Life Cycle Management'' of Greener Management International, (45):63-77.

Ostlin, J., Sundin, E., Bjorkman, M. (2009): Product life-cycle implications for remanufacturing, Journal of Cleaner Production, 17: 999–1009.

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.

Polk (2013): The Global Vehicle Population Aftermarket potential for remanufactured parts. Presentation at ReMaTec Conference 2013. Retrieved on December 18, 2013 at http://www.mera.org/Document-Vault/Presentations/2013

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.

Reuter, M.A., van Schaik, A., Ignatenko, O., de Haan, G.J. (2006). Fundamental limits for the recycling of end-of-life vehicles. *Minerals Engineering*, *19* (5), 433-449.

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

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.

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):405-416. DOI:10.1007/BF02979084

Seitz, M. A. and Peattie, K. (2004): Meeting the Closed-Loop Challenge: The Case of Remanufacturing. California Management Review 46(2): 74-89.
Smith, V.M. and Keoleian, G.A. (2004): The value of remanufactured engines: life-cycle environmental and economic perspectives. Journal of Industrial Ecology, 8 (1–2), 193–221.

Sundin, E. (2004): Component and Process Design for Successful Remanufacturing. Linköping University, Ph.D. Thesis.

Trafikverket (2012) Samhällsekonomiska principer och alkylvärden för transportsektorn: ASEK 5. Kapitel 14 Fordonskostnader och transportkostnader godstrafik Version 2012-06-29, Retrieved March 2, 2014 from
http://www.trafikverket.se/PageFiles/73641/samhallsekonomiska_principer_och_kalkylvarden_for_transportsektorn_asek_5_kapitel_14_fordonskostnader_och_transportkostnader_godstrafik_2.pdf

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.

UNEP (2011) 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.

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

van Schaik, A. and Reuter, M. (2010): Dynamic modelling of E-waste recycling system performance based on component design, Minerals Engineering 23: 192–210.

Volvo Trucks (2014): Volvo Reman, Retrieved on March 15, 2014 from http://www.volvotrucks.com/trucks/na/en-us/parts_service/parts/reman/Pages/volvoreman.aspx

Westkämper, E., Alting, L., & Arndt, G. (2001). Life cycle management and assessment: approaches and visions towards sustainable manufacturing. *Proceedings of the Institution of Mechanical Engineers Part B-journal of Engineering Manufacture*, *215*(5): 599-626. 10.1243/0954405011518557

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

Yellishetty, M., Ranjith, P.G. & Tharumarajah, A. (2010): Iron ore and steel production trends and material flows in the world: Is this really sustainable? Resources, Conservation and Recycling, 54(12): 1084–1094. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0921344910000674.

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