



Component end-of-life management: Exploring opportunities and related benefits of remanufacturing and functional recycling



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ABSTRACT

Over the past few decades, concerns about resource scarcity along with interest in resource efficiency have become part of the societal discourse. Many companies and research entities have documented efforts to increase resource efficiency with improved management of product end-of-life (EoL) and more specifically, with remanufacturing (reuse) and improved recycling. This paper does something complementary; it presents a case study of a multi-national component manufacturer (the company) and one of its main product types, low-alloyed steel components that are utilized in a myriad of applications and industries. Although the company knows that its products are generally recycled and sometimes remanufactured (by its own operations), it wanted to know more about the downstream material flows and related loss of material and function. Using material flow analysis (MFA), simplified LCA and analysis of company sales data, downstream material flows of the components were mapped out and potential environmental benefits related to remanufacturing and recycling were quantified. Results show that there are large differences in the amount of material needed and global warming potential (GWP) incurred depending on what end-users chose to do with the components at EoL. Unsurprisingly, remanufacturing and functional recycling (recycling to alloyed steel) are shown to result in great reductions with regard to both material efficiency and global warming. Notably, many of the EoL components end up in mixed scrap and later, carbon steel, where the function of the alloying elements (Ni, Mo, Cr, Mn) is lost. Combined MFA–LCA results indicate that replacing these lost alloying elements make up a tangible part of the component's total contribution to global warming. Finally, the analysis of company sales data and remanufacturing preferences indicate that there is a large potential to remanufacture more. In total, findings indicate that the limits of “feasible” remanufacturing have not been reached. They also show that dedicated recycling of even low-alloyed steel components into alloyed steel rather than carbon steel could yield tangible environmental gains.

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1. Introduction

A multi-national component manufacturer with a strong environmental profile (the company) wanted to gain understanding about the fate of its alloyed steel products after end-of-life (EoL). What the company did know was that the steel products of interest are recycled to a significant extent and that some products are even remanufactured by it and others. The company wanted to know if it was possible to get more value out of products and material after use. Ultimately, it wanted to find business opportunities and improve environmental performance through improved product

EoL management. This paper presents key results from analyzing the company's EoL product flow and explores ways in which a large company may find improvement potentials in the EoL management of its products.

EoL products contain values in the form of material, shape and function, and embodied energy. These values can be lost depending on what processes are used to dispose of the products or make them (or the materials) usable again. Ultimately, saving these values reduces the need for more material and foregoes material extraction and at least some manufacturing steps (Bras and McIntosh 1999; Allwood et al., 2011; Rathore et al., 2011). Following this reasoning, 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

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in policy. Exceptions exist with less recyclable materials but from the material perspective, the hierarchy is a reliable rule of thumb (Schmidt et al., 2007).

Research offers a more nuanced view of the EoL possibilities waste prevention, reuse and recycling. Some occurrences of product EoL can be mitigated and different types of reuse and recycling can yield products of considerably different quality (Allwood et al., 2011; King et al., 2005). Reuse sometimes requires remanufacturing, a process that involves preparing products for reuse. Literature gives examples of the benefits of remanufacturing. 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. Allwood et al. (2011) complements these assertions and notes that remanufacturing (generally) of products results in material and energy uses that are 30–90% less than for manufacturing of new products, while Smith and Keoleian (2004) presents an analysis of engine remanufacturing demonstrating that remanufacturing can result in almost 90% less CO₂ emissions than new manufacturing. Besides these benefits, the remanufacturing process is often less expensive than manufacturing (e.g., Lund 1985; Bras and McIntosh 1999).

Material recycling offers benefits as well. For example, by avoiding raw material acquisition and refining, recycled steel can be as much as 44% less exergy intensive than virgin steel (Michaelis et al., 1998). Other sources show that virgin steel production requires two to three times as much energy as steel production from scrap (Yellishetty et al., 2011). There are limitations however, and all material recycling paths are not alike (UNEP, 2011). Material function is dependent on the substance composition of the material. Functional recycling results when the full function of a material is retained and utilized in next use, as when alloyed steels of composition are used to make a new alloyed steel. Thus, functional recycling of metals occurs only if substances such as alloying elements end up in the right place (UNEP, 2011). 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 retains their function. As a consequence, when steel grades are mixed, individual grades are diluted or contaminated with undesirable elements, rendering the alloying elements in them functionless, or if ending up in the wrong grade, making the alloying elements contaminants themselves (Yellishetty et al., 2011; UNEP, 2013; Johnson et al., 2006; Daigo et al., 2010). Thus, the rate of functional recycling is less than 50% for many substances (UNEP, 2011).

Even with the best material sorting system, there are losses to slag in recycling metallurgy and to forming and cutting in steel-making. Moreover, the second law of thermodynamics is a barrier to achieving 100% recycling (Reuter et al., 2006; Amini et al., 2007). These imperfections can be complemented with the fact that some products never make it into the recycling system. For example, it is estimated that 10% of machinery metals are never recovered (UNEP, 2011).

The losses that occur in material collection and recycling accentuate the importance of reuse. In industry, remanufacturing for reuse is already a well-established business activity and many companies are involved. Examples (to name a few) include manufacturers of appliances (Electrolux), wheeled-vehicles and engines (Scania, Volvo trucks, Ford, Renault, Fiat, CAT, Rolls Royce, Cummins), tires (Michelin), imagery and photography (Xerox, Fuji, Kodak, Canon), medical devices (Gambro) and bearings (Timken) (Sundin, 2004; Allwood et al., 2011; Kumar and Putnam, 2008; Mont, 2002; Bras and McIntosh, 1999; Rathore et al., 2011; Baines et al., 2007). Despite remanufacturing being common, the potential to reuse is still large according to some estimates. For example,

Cooper and Allwood (2012) estimates that 30% of all steel and aluminum in current products could be reused.

In summary, research provides evidence that remanufacturing (reuse) and recycling can provide environmental benefits, documents company success stories in remanufacturing, and indicates opportunities for product reuse and improving recycling. The objective of this paper was to contribute a complementary case study aimed at mapping a certain type of steel components and quantifying potential remanufacturing and recycling improvements and related benefits. The study provides (1) empirical support to previous research regarding environmental benefits of remanufacturing and recycling of steel components, (2) an industrial case in which opportunities to improve a particular steel component's EoL appear to be abundant, (3) a rare illustration estimating the potential benefits of functional recycling for a single alloyed steel component and (4) an example demonstrating the combined use of established methods to evaluate product EoL.

The main questions addressed in the case study were: *How big are material losses after component use? Are there opportunities to reduce these losses? Does remanufacturing and functional recycling offer environmental benefits?* Researchers utilized material flow analysis (MFA) and substance flow analysis (SFA), and analysis of product sales statistics to map and quantify downstream product flows, and simplified life cycle assessment (LCA) to estimate global warming potential (CO₂-eq) associated with EoL options dispose/replace, recycle and remanufacture.

2. Method and data collection

The investigation was conducted as a case study of a multinational component manufacturer. The study focuses on one of the company's main product types, steel (low-alloyed) components that are utilized in a myriad of applications and industries, from consumer appliances to metal refining equipment. The company has well-established and profitable remanufacturing operations and has a respected environmental profile. Considering these aspects, company representatives were interested in gaining further knowledge about what happens to their components after use and about the benefits of remanufacturing and functional recycling.

For the sake of feasibility, the investigation was focused within one of the non-consumer industries (or business segments) to which the company sells products and services. By using this one business segment and a few customers from it as a sample, the study aimed: to gain understanding about EoL material losses for one component type, to identify where opportunities to mitigate these losses might be, and to describe how customers choosing to dispose, recycle or remanufacture affects material use and environmental impacts. The study involved four major tasks: (1) to gauge EoL opportunities for the business segment by looking at product sales statistics, (2) to estimate and compare the EoL material flow and losses for two customers (1 & 2) from that segment, (3) to assess global warming potential related to disposing, recycling or remanufacturing the products of interest, and (4) to combine the material flow and global warming potential data to compare Customers 1 & 2 with consideration to two steel grades, one more alloyed than the other. Three main methods were used: Material flow analysis (MFA) and substance flow analysis (SFA) (as described in Brunner and Rechberger, 2004) and life cycle assessment (LCA) (as in Baumann and Tillman 2004).

Based on their ability to capture and represent bulk component-material and substance flows respectively, MFA and SFA were chosen as the primary methods instead of LCA, which deals in functional units. MFA and SFA were paired with an analysis of company sales data, which provided component flow quantities. LCA method

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