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End-of-life resource recovery from emerging electronic products – A case study of robotic vacuum cleaners

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ABSTRACT

Integrating product design with appropriate end-of-life (EoL) processing is widely recognized to have huge potentials in improving resource recovery from electronic products. In this study, we investigate both the product characteristics and EoL processing of robotic vacuum cleaner (RVC), as a case of emerging electronic product, in order to understand the recovery fate of different materials and its linkage to product design. Ten different brands of RVC were dismantled and their material composition and design profiles were studied. Another 125 RVCs (349 kg) were used for an experimental trial at a conventional 'shred-and-separate' type preprocessing plant in Denmark. A detailed material flow analysis was performed throughout the recycling chain. The results show a mismatch between product design and EoL processing, and the lack of practical implementation of 'Design for EoL' thinking. In the best-case scenario, only 47% of the total materials in RVCs are ultimately recycled. While this low material recovery is mainly due to the lower plastic recycling rate, other market realities and the complex material flows in the recycling chain also contribute to it. The study provides a robust methodological approach for assessing the EoL performance based on the knowledge of a product and its complex recycling chain. The lessons learned can be used to support both the design and EoL processing of products with similar features, which carry a high potential for resource recovery, especially at the initial stage of the recycling chain.

1. Introduction

The lack of efficient collection and appropriate recycling infrastructure is one of the major challenges in achieving a 'closed' loop of materials from consumer goods, including electrical and electronic products (Graedel et al., 2011). Further, the complex design of modern products adds to the challenges in the end-of-life (EoL) treatment processes, as the recycling technologies are being outpaced by emerging composite and elementally diverse products, making the resource recovery process more and more difficult. Product design and EoL management have a significant impact on the resource recovery as well as the overall environmental impacts of a product (Li et al., 2015). Efforts have been made towards linking these two stages – the product design/inception and its EoL processing – by incorporating 'design for EoL' approach for better EoL performance of products (Lee et al., 2014). Nevertheless, there are still considerable opportunities, both technological and legislative, for linking the producers and EoL managers to intensify this approach (Li et al., 2015; Mayers et al., 2011).

A typical resource recovery chain consists of three main steps: collection, preprocessing, and end processing. Being the first treatment step, preprocessing has a large impact on the subsequent pathways and fate of materials and on the final resource recovery in the whole-system perspective. Manual or mechanical, preprocessing serves as the guide for material flows in the following treatment steps. It defines the effectiveness of material liberation, sorting, and diversion to the correct downstream processing path, which ultimately influences the overall recycling rate (Chancerel et al., 2009). The challenges in the recycling process – especially the preprocessing step – have been illustrated for several products, including case studies on recovery of valuable metals from desktop computers (Meskers et al., 2009; Wang et al., 2012), computer hard disk drives (HDDs) (Habib et al., 2015), and electrical and electronic components in vehicles (Widmer et al., 2015). A common conclusion of these case studies is that the existing preprocessing infrastructure is not sufficient, as it causes significant losses of valuable resources in the process.

Manual dismantling and positive sorting of the valuable components like high-grade printed circuit boards (PCBs) and HDDs is

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common for products such as computers. This step is usually more expensive, especially in developed countries, given the high labor cost and varying product types with unfamiliar product properties (Basdere and Seliger, 2003). As a rule of thumb, the EoL products with enough valuable materials to cover the cost of dismantling are processed manually for component recovery, while the rest is sent to generalized processing. Generalized mechanical shredding and separation is the most preferred way of handling low-grade waste electrical and electronic equipment (WEEE) such as household appliances category (Chancerel et al., 2011).

As the technology advances, the ubiquitous use of electronics in our daily life has only been increasing. It has led to the rising use of products such as photovoltaic panels (Cucchiella et al., 2015), electronic textiles (Köhler, 2013), wearable electronics such as smart watches, and unmanned aerial vehicles (drones) used for amateur photography. Examples of household appliances include smart weighing scales with communication capabilities and robotic vacuum cleaners (RVCs) that can operate autonomously. As products evolve, more household appliances are incorporating complex electronic components, such as PCBs, sensors, and display panels. With this changing product features and material composition comes the challenge of addressing them under the existing EoL management setups, which are evolving slower than the products. The treatment options relying on conventional physical processing technique cannot handle every product with the same efficiency of material recovery.

The recovery of valuable metals from the high-grade electronic waste has been the major research focus, whereas household products get less attention. Moreover, the possibilities of improving the design of these emerging products to allow an efficient resource recovery remain largely untested. The EoL-targeted design improvements need to be based on the knowledge of the EoL fate of the product. In order to do so, it becomes crucial to understand the performance of such products in the existing recycling chain, and the role of product design in improving the overall resource recovery efficiency. In this study, we give a more nuanced and differentiated view on these aspects, including an elaboration on which materials and components in the product are influenced the most by lack of efficient preprocessing separation. We use RVC as a case to illustrate the fate of an emerging product in the existing recycling chain and identify the potential for the improvement in product design. We aim to answer three main questions:

a) Where are the main material losses in the existing recycling chain?
b) For which materials and components is the problem of inefficient separation in the preprocessing step most significant?
c) What is the connection of these losses to the design features of the product and how it can be addressed?

RVC illustrates the trend of programmable household appliance that requires minimal human involvement. One study reported almost a quadruple growth of RVC sales in Denmark between 2010 and 2014, with the total volume reaching from 12,500 units to 48,100 units (Euromonitor, 2015). Another study forecasts 3 million units of RVCs will be marketed globally in 2016, (Euromonitor, 2012), which would add 10.5 kilo tons into the WEEE stream at the end of their lives. Although this volume of EoL RVC is not of a huge significance on its own compared to total WEEE flow, it exemplifies the trend of emerging electronic appliances and serves as a representative case product.

2. Materials and methods

The study consists of two main parts – the first part (product characterization) studies the product characteristics, while the second part (EoL assessment) focuses on the performance of the case product in the existing recycling chain. The methodological approach is illustrated in Fig. 1 and is described in the following subsections.

2.1. Product characterization

The purpose of this step was to understand the design features and the material composition of the case product. For that, ten RVCs of different brands were disassembled with the help of basic handheld tools such as screwdriver, pliers, and hammer. The different connection types and sequence of disassembly of different components were noted, which can be related to the ease of manual dismantling. An example of step-wise disassembly is illustrated in Appendix A.

After the disassembly, the materials of each component were identified, and if required, the components were further dismantled to reach the material-level identification. Materials were identified using techniques including visual recognition based on the physical properties (e.g. color, density, texture) of metals and polymers, and magnetic detection for ferrous metals. The material composition was divided into three material categories: Ferrous (iron and steel), Non-ferrous (copper and aluminum) and Polymers (plastic and rubber). Components made of more than one materials (e.g. electromotors, wires, and connectors) were dismantled further to reach to the composition at material level. However, other components with much more complex material composition (e.g. PCBs and battery) were not dismantled further.

2.2. EoL assessment

The fate of EoL RVCs was measured by following the material flows in the WEEE recycling chain by combining an experimental run in a preprocessing plant and a comprehensive material flow analysis. A total of 125 (349 kg) EoL RVCs was treated at a conventional preprocessing plant in Denmark. This sample size was chosen to provide enough feed for a minimum of 15-minute run in the preprocessing plant with a capacity of one metric ton per hour. The batteries (63 kg) were removed manually from the RVCs before feeding them into the plant for the trial. Therefore, the batteries are not part of the EoL assessment.

Fig. 3 shows the process flow of the plant together with the material flows. In the plant, WEEE first goes through a manual dismantling and pre-sorting stage, where selected components (containing hazardous substances and/or valuable materials) are removed. Then a conveyor belt carries the WEEE to the chain shredder, which is equipped with a multi-cyclone system for the cleaning of the exhaust air, resulting three residue fractions (F_1, F_2 and F_3). The material outflow from the shredder travels through an overbelt magnetic separator, where the ferrous fraction (F_4) is partially picked by the magnet.

The flow then enters a size-sorting unit with cut-off size 10 cm × 10 cm, splitting the input into two streams with different particle sizes. The stream with smaller particle size passes through another overbelt magnet, followed by a drum magnet, where the remaining ferrous metals are separated more effectively, resulting in fractions F_5 and F_6 respectively. The remaining fraction is then sent to an eddy-current separator, where the non-metal (F_7) and non-ferrous metal (F_8) fractions are separated. The stream with larger particle size also follows a similar route with an overbelt magnet, resulting in another ferrous fraction (F_9) and the second eddy-current separator at the end of the process resulting in fractions F_{10} and F_{11}.

All 11 output fractions from the plant were collected and characterized. Each of the output fractions from the experimental run was sorted manually in the lab and their composition was determined. In case of non-liberated components, it was estimated based