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Economic and environmental evaluation of design for active disassembly

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ABSTRACT

Prior research has demonstrated that a disassembly based end-of-life (EoL) treatment for electronic products is characterized by the highest recovery rates for precious metals (PMs) and non-commodity plastics, such as flame retardant plastics. Nonetheless, EoL electronic products are nowadays also commonly recycled without disassembly in different types of size-reduction based treatments or in an integrated PM smelter-refinery. This disparity of recycling processes adopted worldwide resulted in a high uncertainty on the EoL treatment processes that will be adopted for discarded electronic products. As a result, governments, original equipment manufacturers and recycling companies struggle to determine the economic and environmental value of design for disassembly. For this reason, a methodology is presented to calculate the Composite Rate of Return (CRR) on investing in design for disassembly and the resulting environmental impacts. This methodology is applied to evaluate the economic and environmental benefits of implementing three types of active fasteners for eleven electronic products which are available in both a product service system (PSS) and a traditional sales oriented business model. The performed analyses demonstrate that the preferred EoL treatment, as well as the economic and environmental benefits of implementing design for active disassembly, strongly depends on several product properties and boundary conditions. Based on the performed sensitivity analysis, the application of active pressure and temperature sensitive fasteners is expected to be only economically viable for products placed on the market in a PSS context, in which they will be separately collected with a high collection rate. Furthermore, impulse sensitive elastomer based fasteners are characterized with the highest rate of return and considered to be suited for both products sold in a traditional sales oriented business model and for products used in a PSS.

1. Introduction

Developing and emerging economies are expected to legitimately aspire to achieve the welfare of industrialized countries. This is predicted to result in a growth of the global middle class from 1.8 billion people in 2009 to 4.9 billion by 2030 (Pezzini, 2012). With today's consumption patterns this will result in a significant increase of the pressure on resources, as well as an increase in the amount of waste generated and the related environmental burdens. Therefore, a substantial increase in resource-efficiency is essential to guarantee a high quality of life for present and future generations and to achieve sustainable growth (EU Commision, 2011a, b).

For these reasons and because of financial incentives of producer responsibility organizations, customer demands for green products, personal values of managers and designers and legal obligations, original equipment manufacturers (OEMs) are striving to increase their resource efficiency (Dubois and Peeters, 2015). At the same time, new recycling processes have been developed in response to legislative developments, as well the increase in resource prices over the past decades. These developments enable to increase the recovery of, among others, PMs (Ghosh et al., 2015) and plastics (Peeters et al., 2014). However, best available recycling technologies are not consistently deployed worldwide, as a result of significant differences in labor costs, legislative requirements, volumes of waste and access to markets for recyclates (Peeters et al., 2013).

At the same time, numerous guidelines have been developed to design product to facilitate disassembly, repair, remanufacturing

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and recycling (Boothroyd, 2002; Telenko et al., 2015). Many of these guidelines have the objective of facilitating the breaking down of products into their individual components for the purpose of repair, refurbishing, remanufacturing cannibalization for component reuse, and/or recycling of the complete product or individual components, also defined as demanufacturing (Duflou et al., 2008).

In general, the efficiency of breaking down products into their individual components or demanufacturing can be increased by improving the product architecture and/or the applied fasteners (Harjula, 1996). An improved product structure facilitates most types of demanufacturing processes. However, the selection of the appropriate fasteners is more complex, since most fasteners will only improve a specific demanufacturing process and impede others. For example, the implementation fracture lines developed by Balkenende et al. (2014) facilitate the separation of PWBs from LED lamps in a shredder process, but do not facilitate a repair, refurbishing or remanufacturing process,. Accordingly, good knowledge of the demanufacturing processes that will be adopted is required to determine which of the sometimes contradicting guidelines should be implemented. However, OEMs face today high uncertainty on the demanufacturing processes that will be adopted in consequence of the disparity of recycling processes adopted worldwide. As a result, OEMs also face high uncertainty on the influence and value of the implementation of design for demanufacturing.

EoL products that were sold in industrialized countries in a traditional sales oriented business models are commonly collected by joint collection schemes. These collection schemes mostly charge a fixed contribution fee per product. Consequently, the enforcement of legislative requirements and/or the differentiation in contribution fee charged by the collection scheme are required to make producers bear the actual EoL treatment cost. In contrast, OEMs which sell products in a product-service system (PSS) business model and retain the ownership of the product over the complete product lifetime or regain ownership at the EoL stage, have direct financial incentive of implementing design for demanufacturing (Beuren et al., 2013; Reim et al., 2015; Van Ostaeyen et al., 2013).

However, clear economic and/or environmental benefits are a prerequisite for both OEMs to invest in Design for demanufacturing and for governments to include design for demanufacturing targets in their legislation or to make the differentiation in contribution fees to collection schemes mandatory. Several methodologies have been presented in recent research to evaluate different recycling processes (Ravi, 2012) and disassembly options (Cheung et al., 2015; Go et al., 2011), as well the economic, environmental and/or social benefits of design for disassembly (Ma and Okudan Kremer, 2015; Sabaghi et al., 2016; Ziout et al., 2014). However, these methodologies do not take into account that a broad variety of distinct EoL treatments can nowadays be used for electronic products. In addition, these methodologies cannot be used to determine the Rate-of-Return (ROR) of investing in design for demanufacturing. Therefore, a methodology is presented to determine the environmental and economic performances of a variety of commonly adopted EoL treatment options for WEEE and to determine the ROR of investing in design for demanufacturing, such as active disassembly. To apply this methodology, the product's material composition is first analyzed. Thereafter, the efficiency of commonly adopted recycling processes, as well as the efficiency increase that can be obtained by the implementation of design for demanufacturing is assessed.

The proposed methodology is demonstrated by means of a case study for eleven electronic products, in which the economic and environmental benefits of design for active disassembly for these products is evaluated. Design for active disassembly requires the implementation of active fasteners which can be simultaneously unfastened without direct, individual, physical contact between a disassembly tool and every individual fastener (Duflou et al., 2008). The presented case study focus on the evaluation of active fasteners, since prior research predicted that active disassembly has the potential to shift an EoL treatment with systematic disassembly from a cost factor to a profit generating activity (Duflou et al., 2006; Willems et al., 2005).

2. Materials

The following electronic products, which are available both in a sales oriented business model and in PSSs, were selected for the presented case study because of their distinct material compositions, product structures and lifetime distributions to allow the investigation of the influence of these product parameters on the economic viability and environmental benefits of implementing design for active disassembly: a Worldline Yomani payment terminal, a Philips 42 inch Econova LED TV (LCD with sided LEDs, model number 42PFL6805H), a Barco Coronis Fusion 10 MP medical monitor (MDCG-10130), an Asus Nexus 7 tablet (2012), an Apple IPad 2 tablet (2011), a Sagem B-Box 2 modem and a Scientific Atlanta V3 setup-box (IPP 430 MC). In addition, an average laptop, LCD monitor and LCD TV is determined in this research by the analysis of a broad range of representative products. In total, 153 EoL LCD TVs with Cold Cathode Fluorescent Lamps (CCFLs) were analyzed in 2011 with an average weight of 13.54 kg (σ: 6.5 kg), an average screen size of 30.72 inch (σ: 6.3 inch) and an average production year of 2005 (σ: 2.2 year), 51 EoL LCD monitors with CCFLs were analyzed in 2014 with an average weight of 4,56 kg (σ: 1.46 kg), an average screen size of 17.34 inch (σ: 1.68 inch) and an average production year of 2006 (σ: 1.8 year) and 32 EoL laptops analyzed in 2015 with an average weight of 2.65 kg (σ: 582 g) and an average production year of 2005 (σ: 3.3 year).

All these caste study products were dismantled in this research and both the weight and material type were registered for the dismantled components. Results of these material composition analyses are shown in Fig. 1. Previous studies have pointed out that plastics are often mismarked (Xiuli et al., 2006). Therefore, the plastic and flame retardants (FRs) were identified in this research by means of a combination of density measurements, sliding-spark spectroscopy, laser-induced breakdown spectrometry (LIBS) and/or Fourier transform infrared (FTIR) analysis.

In addition, both the easily accessible high grade printed wiring boards (PWBs) that can be separated in a partial disassembly process and the high grade PWBs that can only be separated in an in-depth disassembly process, later on referred to as first level and second level PWBs, were gathered from the case study products. Of these PWBs the PMs and copper concentrations were analyzed by inductively coupled plasma and spark optical emission spectroscopy. To determine the PM concentration for an average LCD TV 18 kg of main board and 3 kg of the PWBs of the LCD module were analyzed from TVs produced between 2004 and 2007. For the PM concentration of an average LCD monitor the results obtained for one Sony SDM-S73a LCD monitor from 2004 were used as representative values. The PM concentration of an average laptop is based on the analysis of the RAM PWB, main PWB with CPU and hard disk PWB of a Dell Inspiron of 2003 and the DVD PWB of a Fujitsu Primergy Server (RX300 S3). To assess the variation in PM concentration between similar laptops of different years, also the main board of an older Dell Latitude from 1998 was analyzed. Since a significantly higher PM concentration was found for the older laptop, two average case study products were used which only differ in the PM concentration of the main board. Net values for the high grade PWBs were provided by an integrated PM smelter-

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