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Ease of disassembly of products to support circular economy strategies

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A R T I C L E I N F O

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A B S T R A C T

Circular economy strategies encourage, among others, concrete actions to extend the product lifetime. Product's repair and reuse, and component harvesting for reuse, all require the facilitated access to product components. Consequently, a reduction of the disassembly time and the related costs will increase the economic feasibility of product lifetime extension and therefore increase the viability of a circular economy in industrialised regions. Furthermore, disassembly has the potential to significantly increase the recycling yield and purity for precious metals, critical metals and plastics. For this reason, the European Commission and several ecolabels have considered to include design for disassembly requirements in legislation or voluntary environmental instruments. However, up to date, there is no standardised method to evaluate the ease of disassembly in an unambiguous manner with a good trade-off between the efforts required to apply the method and the accuracy of the determined disassembly time. The article proposes a robust method "eDiM" (ease of Disassembly Metric), to calculate the disassembly time based on the Maynard operation sequence technique (MOST). A straightforward calculation sheet is employed in eDiM to calculate the disassembly time given the sequence of actions and basic product information. This makes the results fully verifiable in an unambiguous manner, which makes eDiM suited to be used in policy measures in contrast to the results of prior developed methods One of the innovative aspects of eDiM is the categorization of disassembly tasks in six categories, which provides better insights on which disassembly tasks are the most time consuming and how the product design could be improved. The proposed method is illustrated by means of a case study of an LCD monitor. The presented case study demonstrates how the proposed method can be used in a policy context and how the calculated disassembly times per category can provide insights to manufacturers to improve the disassemblability of their products. The results also demonstrate how the proposed method can produce realistic results with only limited detail of input data.

1. Introduction

The European 2020 strategy for smart, sustainable and inclusive growth recognises as essential for the EU to move towards a circular economy (COM, 2011a), which entails boosting the material resource efficiency of products (COM, 2011b). Such a strategy has been recently re-affirmed by the European Commission in its EU action plan for the circular economy (COM, 2015) that clearly identifies product design as one of its main pillars. In general, three product design strategies are in line with the vision of a circular economy: increase material efficiency, product life extension and improve recycling efficiency (Allwood and Cullen, 2012).

The EU action plan for the circular economy also expressed the need "to develop standards on material efficiency for setting future ecodesign requirements on durability, reparability and recyclability of products" (COM, 2015). This request has been put into effect with the European mandate M/543 to the "European standardisation organisations as regards ecodesign requirements on material efficiency aspects for energy-related products" (European_Comission, 2015). The mandate M/543 also foresees the development of one or more standards concerning the "ability to access or remove certain components, consumables or assemblies from products to facilitate repair or remanufacture or reuse" (European_Comission, 2015).

Product lifetime extension strategies, such as repair, reuse and

Abbreviations: CRT, cathode ray tube; DFD, design for disassembly; EEE, electrical and electronic equipment; EoL, end of life; FPD, flat panel displays; IEEE, Institute of Electrical and Electronics Engineers; JRC, Joint Research Center; LCD, liquid crystal display; MTM, method time measurement; MOST, Maynard Operation Sequence Technique; OEMs, original equipment manufacturers; UFI, unfastening effort index; WEEE, waste of electrical and electronic equipment

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product harvesting for component reuse, all require facilitated access to product components. Therefore, it is crucial to define requirements on the ease to disassemble both the housing components to improve access to internal components for inspection, maintenance and repair and to disassemble commonly failing and valuable components to facilitate repair by replacing failed components and recovery of components for reuse or remanufacturing. Therefore, it is key to define a metric which can assess the ease of disassembly to quantify the extent that it is realistic to disassemble components without destroying the components itself for the purpose of reuse, repair and remanufacturing in line with the vision of a circular economy. Accordingly, a reduction in disassembly time significantly cuts down the efforts and the costs of these activities. Moreover, a decrease in disassembly effort can make product remanufacturing or component reuse the preferred End-of-Life (EoL) strategy over recycling or disposal (Yang et al., 2014; Yang et al., 2011; Duflou et al., 2008), which is environmentally beneficial (Diener and Tillman, 2015; Krystofik et al., 2015). Furthermore, recycling of complex products, such as electronics, is in industrialised countries predominantly based on mechanical comminution and automated material separation. This recycling scheme is characterized by high recovery rates for certain materials, such as steel and aluminium; but underperforms for the recovery of precious metals (Chancerel et al., 2009; Vanegas et al., 2014a), critical metals (Anon, 2010; European Commision, 2014) and several plastics (Peeters et al., 2014), which have high importance from an environmental and economic perspective (Widmer et al., 2005). Besides fostering product lifetime extension disassembly also has the potential to significantly increase the recovery rate of precious metals (Vanegas et al., 2014a; Wang et al., 2012), critical metals and plastics (Peeters et al., 2014; Ardente and Mathieux, 2014).

Waste electrical and electronic equipment (WEEE) is one of the fastest growing waste streams (Huisman et al., 2012; Bakker et al., 2014). WEEE contains more than 1000 different materials (Widmer et al., 2005), of which many are hazardous, and other have considerable market value (COM, 2015). Improving material recovery of this waste stream has the potential to reduce the environmental burdens of mining, production, and disposal of the materials used in electrical and electronic equipment (EEE) (COD, 2011). In an EU context, Original Equipment Manufacturers (OEMs) of business to consumer products often do not recycle their own products and, therefore, the link between product design and EoL treatment is broken. As a result, there is no economic stimulus for OEMs to implement design for disassembly, even when this is profitable from a global perspective. This is most likely also the reason why the majority of the OEMs of the EEE industry in the United Kingdom indicated in a large-scale survey that legislative pressure is a better incentive for design for recycling than cost reductions in the EoL treatment (Cheung et al., 2015).

To stimulate product life extension and improve recycling efficiency of EEE, the Joint European Research Centre (JRC) of the European Commission has discussed the inclusion of maximum thresholds for disassembly times of key components of electronic displays in European product policies (Mathieux et al., 2014). However, at present, there is no standardised method available to measure or quantify the disassembly time of EEE (Mathieux et al., 2014). The lack of instruments to prove compliance with ecodesign requirements is known to be one of the key causes for the limited implementation of design practices regarding resources efficiency in industry (Dalhammar, 2016). Furthermore, in the current policies to foster circular economy strategies, there has been identified a lack of indicators at a micro-level (products, companies) (Huysman et al., 2017). Therefore, the European Commission has mandated a request to develop standards to prove compliance for material efficiency aspects in late 2015 to stimulate ecodesign implementation by industry (Anon, 2015).

The present article aims at enhancing circular economy through the development of a method to assess the ease of disassembly of products. The method is intended to be the scientific ground for the development of standards dealing with material efficiency aspects of products and related to the design for disassembly for lifetime extension (repair and reuse) and recycling. The method is intended to be unambiguous and verifiable by a third party subject (e.g. a market surveillance authority).

The proposed method is demonstrated through a case study for an LCD monitor for which the disassembly time is calculated with the presented method, and opportunities to improve product design are analysed. The lessons learned from the application of the method, as well as its limitations, and opportunities for the adoption of the presented methodology in policy are discussed.

2. Literature review

2.1. Ease of disassembly evaluation

Metrics to evaluate the (degree of) easiness of disassembly or disassemblability can be classified into 1) absolute metrics such as time, energy or entropy and 2) relative metrics such as design effectiveness (Afrinaldi and Mat Saman, 2008). Data needed to calculate absolute metrics are easier to obtain and define (Go et al., 2011). Among absolute metrics time has been acknowledged as a valid indicator of disassemblability, while other measures of work, such as energy, are deemed as difficult to obtain and comprehend (Kroll, 1995; Kroll, 1996). Furthermore, time has been used as a valid metric for disassembly modelling (Boks et al., 1996), to measure ease of disassembly to compare alternative product designs (Go et al., 2011), and as a performance indicator to measure recoverability (Alonso Movilla et al., 2016). Moreover, disassembly time has already been used in environmental product labelling by the EU Ecolabel (Anon, 2011) and the IEEE (Anon, 2012) to evaluate ease of disassembly. In recent publications by the JRC on the integration of resource efficiency criteria in European product policies “extraction time” has also been identified as a good proxy to evaluate the easiness of disassembly (Ardente et al., 2014). Therefore, a standard method to determine the disassembly time to extract components represents the basis for evaluating easiness of disassembly for ecodesign to support the enforcement of product requirements that facilitate lifetime extension strategies and improve EoL treatment.

2.2. Methods to calculate disassembly time

Two alternatives were identified to determine the partial or complete disassembly time: (1) direct measurement and (2) calculation based on product parameters. The most straight forward method is to perform direct measurement of disassembly times of products of the same category by several operators with varying experience. This approach is labour intensive, non-reproducible and influenced by several human factors. In addition, this method does not allow to easily quantifying the effect of product design changes without performing new measurements. Furthermore, a dedicated setup that mimics an average disassembly setup is needed to make the measurement reproducible and verifiable (Recchioni et al., 2016). Therefore, it is opted to develop a method in which the required disassembly time is calculated with a standardizable formula, using as input geometrical and physical product parameters verifiable on the product itself. Such a method could be applicable within a policy framework, enabling the categorization of products with respect to their ease of disassembly.

In literature two approaches are identified to calculate the disassembly time: 1) based on properties of the product and connectors and, 2) based on basic motions of disassembly tasks. An example of a method of the first type is the U-effort described in Section 2.2.1. The most prominent methods of the second type in literature are 1) Philips ECC (Boks et al., 1996), 2) Kroll (Kroll and Carver, 1999; Kroll and Hanft, 1998; McGlothlin and Kroll, 1995) and 3) Desai & Mital (Desai and Mital, 2003), which are described in Sections 2.2.2, 2.2.3.1 and 2.2.3.2.