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Ease of disassembly of products to support circular economy strategies

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ABSTRACT

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

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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.

2.2.1. U-effort

U-effort was developed by Sodhi et al. (Sodhi et al., 2004) to support product designers in implementing design for disassembly (DfD). In this method, disassembly time is calculated for every connector taking into account physical properties. U-effort computes the unfastening effort index (UFI) to account for the main attributes that influence the unfastening time for commonly used connectors, such as size or shape (Sodhi et al., 2004). U-effort computes the disassembly time per connector by an average worker in seconds (Sodhi et al., 2004). The UFI score for each connector is calculated based on the connector type and a set of weighted causal attributes. For example for a screw, these causal attributes are head shape, length, diameter and use of washers.

2.2.2. Philips ECC

Philips ECC (Boks et al., 1996), which was developed by the consumer electronics manufacturer Philips to gain insights into EoL processing costs, calculates the disassembly time using a database which contains times for unfastening commonly used connectors and for specific disassembly tasks, such as tool change or component handling. The times used in this method were determined based on time measurements during disassembly sessions. The authors state that only insignificant differences were found between the unfastening of different categories of connectors and for comparable disassembly tasks of various electronic products. Consequently, they concluded that setting up a database to calculate disassembly time is feasible (Boks et al., 1996). Once the disassembly sequence and connector type are provided, the model automatically determines the required handling, tool operations and disconnection time based on the times stored in the database.

2.2.3. Time and motion based methods

Methods to estimate standard times for manual operations date back to the beginning of the 20th century. They are based on the premise that the variations to perform the same operation are small for different workers with proper experience (Kroll, 1996). Method time measurement (MTM), developed in 1948, was the first time-motion system publicly available, and it is regarded as accurate, detailed and widely accepted. For instance, Boothroyd et al. employ MTM for validating the experimental time estimates of assembly operations in their methodology for design for manufacture and assembly (Boothroyd, 2002).

Maynard operation sequence technique (MOST) is another well-accepted work measurement technique to calculate assembly times for a wide variety of products ranging from ships to small electronics. The times modelled with MOST represent the performance of an average skilled operator, working with adequate supervision, under average conditions at a normal pace (Zandin, 2003). MOST provides a number of basic tasks already modelled which can be selected from predefined tables; the procedure to add a new task is described in (Zandin, 2003).

2.2.3.1. Kroll. Kroll developed a method to serve as a design tool to highlight opportunities to lower disassembly time (Boks et al., 1996). The disassembly time is calculated based on MOST (Kroll, 1996) and manual disassembly experiments performed with computers, keyboards, monitors and printers (Kroll and Carver, 1999; Kroll and Hanft, 1998; McGlothlin and Kroll, 1995). Kroll defined 16 basic disassembly tasks, such as unscrewing, turn and drill, and four difficulty categories: accessibility, positioning, force and one for non-standard aspects called special (Kroll and Hanft, 1998; Justel-Lozano, 2008). The method presupposes that the operator knows the disassembly sequence and that the required tools are available. Kroll has employed this approach to calculate the disassembly time for several electronic products and concluded that time estimates can be used to compare the disassemblability of different product designs in a quantitative manner, to monitor design improvements and to estimate disassembly costs (Boks et al., 1996; Kroll and Carver, 1999; Hanft and Kroll, 2012).

2.2.3.2. Desai & Mital. Desai & Mital developed a method for DfD in which disassembly time is determined taking into consideration five factors: force, material handling, tool utilisation, accessibility of components and fasteners, and tool positioning (Desai and Mital, 2003). The method is based on MTM and allows the incorporation of penalties for specialised postural requirements. Desai & Mital first define a basic disassembly task and add for all five factors additional times, which are based on detailed time studies (Desai and Mital, 2003).

2.3. Comparison of methods

An important drawback of the U-effort method is that the different causal attributes and their weights are unique per connector type. Consequently, for every new connector type, the causal attributes and weights need to be determined, hindering the ability to apply the method for a broad variety of products with different types of fasteners. In addition, the influence of different tools for disassembly cannot be taken into account with the U-effort method. Furthermore, U-effort only accounts for the disconnection time of fasteners and neglects the time needed for changing tools, identifying fasteners and product manipulation. Nonetheless, prior research demonstrates that disconnection time represents less than 50% of the total disassembly time (Duflou et al., 2008; Peeters et al., 2015a). Therefore, it is crucial to include the time of disassembly tasks other than disconnecting fasteners, which requires accounting for both connectors and product properties. In addition, Justel-Lozano reported that the calculated disconnection times with the U-effort method were overestimated for a set of analysed connectors and considered it insufficiently accurate (Justel-Lozano, 2008).

Boks et al. (Boks et al., 1996) also evaluate the methods of Kroll and Philips for CRT TVs and concluded that both approaches correspond very well to reality, that they give similar results and are equally valid. However, Boks et al. highlighted that Kroll's method is not product specific, allowing its application to other electronic products without collecting additional disassembly data, while Philips' method estimates are seen as product category specific and are likely to have lower accuracy when applied to other products. Moreover, Kroll's method offers more detail as it covers a large range of conditions for disassembly tasks, which improves accuracy; conversely, the highest degree of detail and accuracy may not always be essential in a product policy context that aims at benchmarking products. Furthermore, the estimation of difficulty rates in the Kroll method can be seen as a source of ambiguity, as these rates are assigned by the person performing the evaluation.

The main drawback of the Desai & Mital method is that it does not account the time needed for preparatory tasks, such as reaching a tool, picking it up, and putting it back. Therefore, the time estimation is seen as incomplete (Justel-Lozano, 2008). In addition, the method is based on MTM, that requires a detailed analysis and, therefore, substantial time and effort, which is in some cases considered impractical (Kroll, 1996; Zandin, 2003). The methods of Kroll and Desai & Mital have common roots, as the times calculated by Kroll's and Desai & Mital's methods come from time and motion studies of workers under real-life conditions, whereas the Philips method directly uses averages of measured times. The direct measure of time has the advantage to circumvent the systematic breaking down of tasks into basic motions as required by MTM or basic sequences as stipulated by MOST. However, time and motion analyses are product independent and offer more possibilities at the moment of deploying a generic database of standardised times, because they decompose disassembly tasks into basic motions. Table 1 presents the main characteristics of the different methods including key advantages and limitations.

Table 1
Comparison between calculation methods for disassembly time.

Method	Main Goal	Calculation Approach	Main [Advantage]/Limitations
U-effort (Sodhi et al., 2004)	Support DfD	Based on properties of connectors	[Objective: based on product properties] Only disconnection time accounted for High modelling effort for new connectors
Philips (Boks et al., 1996)	Calculation of EoL costs	Database with actual disassembly times Facilitates addition of disassembly tasks.	[Straightforward: based on direct measurements] Product specific Limited insights for DfD
Desai & Mital (Desai and Mital, 2003)	Support DfD	Factors affecting disassemblability are evaluated with MTM	[Flexible: based on time and motion analyses] Preparatory tasks not included Based on MTM which is seen as impractical
Kroll (Boks et al., 1996; Kroll and Carver, 1999; Kroll and Hanft, 1998; Justel-Lozano, 2008; Hanft and Kroll, 2012)	Support design for recycling	Base time for fasteners and difficulty scores based on MOST	[Flexible: based on time and motion analyses] Can lead to excessive detail Subjective difficulty rates

3. Proposed method: eDiM

3.1. Characteristics of a method to estimate ease of disassembly

Scientific methods that address the ease of disassembly can be useful supports for the development of international standards, including standards on material efficiency aspects of products under development according to the European mandate M/543 (European_Comission, 2015). Such standards can be helpful to evaluate the aptitude of a product towards repair, reuse or recycling, and can be useful for OEMs and recyclers. The first step towards the development of such a method is to define the required features to allow its usability within standardisation organisations, OEMs, and EoL operators.

The following characteristics (summarised in Table 2) were identified based on discussions with OEMs of electronic products, recycling companies pre-processing WEEE and findings in prior research (Mathieux et al., 2014; Dalhammar, 2016; Amezquita et al., 1995):

- Balance accuracy and detail of required information: the method should make a good trade-off to facilitate information flow among stakeholders and reduce administrative burdens.
- Ease of application: minimise labour intensity of implementation for manufacturers and market surveillance authorities, as stipulated in the Ecodesign Directive (Anon, 2009).
- Flexible: applicable to an extensive range of product categories and fasteners, and capable of evaluating partial and complete disassembly as both are commonly applied during the products' lifetime.
- Intelligible: the method rationale should be easy to understand and provide a clear link to product design aspects. Therefore, the procedure, metrics, and formulas utilised should be as straightforward as possible.
- Facilitate product information exchange between OEMs and EoL operators to improve treatment process efficiency; OEMs and market authorities for regulatory purposes.
- Verifiable: the required experience and equipment, as well as the complexity of verification procedures, should be kept to a minimum to reduce costs, allowing verification of a larger number of products.
- Reproducible and Repeatable: to be able to be replicated and retested by different stakeholders with high precision.
- Unambiguous: no room for subjective interpretation, to be applicable for product policy and to prevent "creative workarounds", which do not improve disassemblability.
- Suitable to set up regulatory requirements: quantitative information on disassembly easiness enables that market authorities can use the method for both verifying that a product achieves a certain threshold and for rewarding "best-of-class" designs. Instruments meant to be applied to product policies need to be quantifiable and measurable (Recchioni et al., 2016).
- Aligned with existing regulations to avoid redundancy and

Table 2
Relevance of the different characteristics to different purposes.

	Product Design	Policy Compliance	EoL Treatment Improvement
Good trade-off between accuracy and detail of information	●	●	●
Ease-of-application	●	●	●
Flexible	●	●	●
Intelligible	●	●	●
Facilitate product information exchange between:			
OEMs and EoL operators	●		●
OEMs and Market authorities	●	●	
Verifiable		●	
Reproducible and repeatable		●	
Unambiguous		●	
Suitable to set up regulatory requirements		●	
Align with existing regulations		●	
Enable evaluation of changes in product design	●		
Facilitate communication of product information to users	●		
Do not hinder technological innovation	●		
Allow EoL treatment cost calculation			●

contradictions and to facilitate acceptance from stakeholders.

- Enable evaluation of product design changes. Quantitatively evaluate the influence of modifications in product design to enable providing concrete feedback to designers, encouraging innovations in products.
- Facilitate communication of product information to consumers to encourage comparison of ecodesign performances between products.
- Do not hinder technological innovation and provide continuous incentives for ecodesign.
- Allow cost calculation to facilitate the evaluation of optimal disassembly depth by EoL operators.

3.2. *Working principles*

A novel method to evaluate the ease of disassembly of products is proposed. The method calculates the "ease of Disassembly Metric" (eDiM) and aims at assessing the effort needed to completely or partially disassemble a product. The method represents an estimation of the actual time necessary for disassembly tasks and is, therefore, expressed in seconds. eDiM aims at facilitating repair, reuse, remanufacturing and recycling by providing information for product design improvement, which is in line with the objectives of a circular economy.

From the literature review, it can be concluded that all calculation methods come with shortcomings. Not all of the disassembly tasks are considered in the existing methods (i.e., U-effort, Desai & Mital). Therefore, in order to assure completeness of the assessment, the proposed method first establishes a clear division of disassembly categories, which facilitates the identification of opportunities for improving product design. Existing methods are also not generalizable, to evaluate different products (i.e. Philips). The proposed method is instead applicable to a broad range of products, as the time and motion method MOST is used to model the defined disassembly tasks. MOST also offers a good trade-off between accuracy and the effort needed to determine the time for disassembly tasks disregarding the product type (Amelia et al., 2009), which reduces cumbersome modelling or excessive in-depth analysis (i.e. U-effort, MTM) for the time estimation. Furthermore, to guaranty ease of implementation and intelligibility, a calculation sheet with straightforward formulae is developed, providing a simple and verifiable calculation scheme. Moreover, existing methods are prone to subjectivity, as the evaluators determine parameters without a clear metric, e.g. Kroll. To avoid subjectivity in the evaluation of the disassembly time eDiM relies on easily verifiable geometric and physical fastener and product properties. A database with a well-defined taxonomy of fasteners with easily verifiable parameters contributes to avoid subjectiveness. Objective evaluation is a key characteristic to allow the implementation of quantifiable requirements in product policies to support circular economy strategies.

The scope of the method within this research is focused on non-destructive operations, aiming at fostering product lifetime extension via strategies such as repair and reuse. Adaptation of the method for destructive operations, commonly known as dismantling, is deemed as possible but fall outside the scope of this article.

3.3. *Disassembly task categories*

In literature different ways of categorising disassembly tasks were found, as shown in Table 3.

Table 3
Disassembly task categories in prior research.

	Research Context	Disassembly Task Categories
Hesselbach and Kuhn (1998)	Disassembly evaluation	Handling Separation Transition Taking off
Murayama et al. (1999)	Improving recyclability by computer-aided means	Setting a tool Releasing connection Removing components Changing a tool Changing the pose of components
Kondo et al. (2003)	Reversibility and disassembly time of components	Identify connection Disjoin connection Remove component
Das et al. (2000)	Facilitate economic analysis of disassembly operations	Setup Handling Hand-on disassembly
Hwa-Cho et al. (2003)	*Disassembly time evaluation*	Tool preparation Moving between joints Disassembly joint elements Post-processing
Alonso Movilla et al. (2016)	*Disassembly evaluation for ecodesign*	Pre-dismantling (2D, 3D positioning; bit-change; observe; pick up tool; try) Dismantling (break; cut; hit; remove; unscrew), Post-dismantling (sort; test ferrous; clean, pick up component; walk)

In addition to the categories in Table 3, identifiability of connectors is regarded as a key factor influencing disassembly time (Justel-Lozano, 2008; Ghazilla et al., 2014). Based on the presented prior research and direct observation of manual disassembly operations in several large recycling facilities, six basic disassembly tasks are proposed: *Tool change* refers to picking up and/or putting back a tool including the adaptation or preparation of the tool for usage. *Identifying connectors* accounts for the time required to identify the location of connectors including the time needed to determine the type of connector and the kind of tool required for its disconnection. *Manipulation* concerns the time necessary to manipulate the product to access or identify a connector in order to disconnect it, e.g., flipping over the product. *Positioning* is the action of positioning the tool relative to the fastener prior to the actual disconnection process, for instance, placing a screwdriver on top of a screw. *Disconnection* is the time of the actual disconnection of a fastener, e.g. the unscrewing of a screw. Disconnection time commonly depends on several physical characteristics of the connector itself. *Removing* relates to the time needed for removing the unfastened components and putting them into bins.

The actions pre- and post-disassembly, such as bringing the products, placing the product on the workbench, taking the disassembled components from the table, are not included in eDiM because these are considered to be complementary actions and can mostly not be influenced by the product design. In addition, the proposed categorization does not account for inefficiencies of the disassembly process, such as time for unsuccessful disconnection attempts or unnecessary actions, since these actions are not standard, not repetitive and dependent on the operator experience and motivation. Moreover, these inefficiencies are related to the process and not the product. Therefore, to account for this, the calculated disassembly time should be multiplied by one plus the inefficiency rate, which has been documented to account for up to 30% of the actual disassembly time in large recycling facilities (Vanegas et al., 2014b).

3.4. *Database with disassembly times*

Each of the six determined disassembly tasks, Tool change, Identifying, Manipulation, Positioning, Disconnection, and Removing, are modelled using MOST to determine the time needed to perform these tasks, taking into account both product and connector properties. MOST is suited for analysing operations with slight variations in the basic motions, as it is the case for disassembly operations (Kroll, 1996). MOST models are presented in the supplementary material for the six proposed tasks.

Regarding the category Disconnection, MOST models exist for commonly used connectors and tools. However, for non-standard connectors, either the time has to be calculated by summing up the time needed for individual actions that have to be performed to unfasten a fastener or a time motion analysis needs to be conducted to model the disassembly time (Zandin, 2003). In the supplementary material, the proposed MOST sequences and disconnection times for a number of commonly used fasteners and tools are included. Since the applied disassembly tool influences the required actions to be performed, the disassembly time also depends on the adopted disassembly tool. Therefore, the tool for undoing connectors is pre-defined for every connector category, the list of tools could be based on available standards such as the ISO/TC 29/SC 10.

The category identification relates to the time needed if connectors require extra time for identification, so not automatically done within the task positioning. Ease of identification is related to the element surface, position, shape, dimensions, and colour (Justel-Lozano, 2008). Most of these characteristics are difficult to be unambiguously evaluated, so within the scope of this research only visible surface is considered for the evaluation of identifiability of screws, which all have a specific shape. Two levels of visibility are defined: visible, which means a visible surface area $> 0.05\ \text{mm}^2$, and hidden, that is a screw with a visible surface area $< 0.05\ \text{mm}^2$ when looking in the fastening direction.

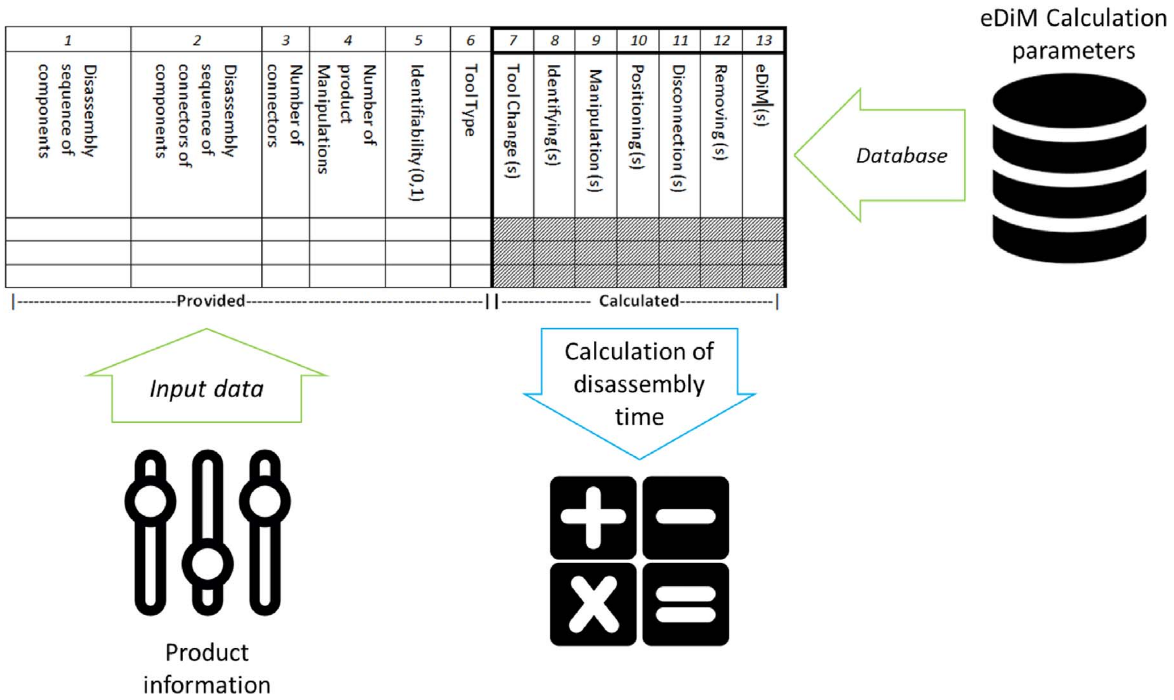
3.5. Calculation sheet

In order to calculate the disassembly time, eDiM is implemented in a spreadsheet (Table 4). The first five columns constitute the input data required for the time computation. Performed analysis has demonstrated that the disassembly sequence has an important impact on disassembly time. However, it can be argued that experienced operators would always adopt an efficient disassembly sequence. Therefore, the eDiM calculation leaves it up to the user to define the disassembly sequence and to provide it as an input to calculate the disassembly time. In the spreadsheet shown in Table 4, Column 1 lists the components in the order of disassembly. When different connectors attach a component, the component can appear multiple times in Column 1. Column 2 itemises all the connector types used in the order of disassembly. If multiple connectors of the same sort fasten the same component, the number of adopted connectors is specified in Column 3. In case product manipulation is required to undo a connector, the number of manipulations is entered in Column 4. Column 5 contains information on the ease of identifiability of connectors. Column 6 lists the type of tool required for disconnection, if no tool is needed, it is left blank. The tools are selected from a predefined list of tools.

With the information provided in the first six columns, the following seven columns can be calculated using the times modelled with MOST and stored in a database. In Column 7, the time required for tool change is calculated if the tool differs from the one utilised for the previous connector. The time required to identify connectors is calculated with the MOST estimation for this task based on the identifiability information in Column 5 and is computed in Column 8. Product manipulation needed for undoing fasteners is registered in Column 9, and it is calculated using the number of manipulations from Column 4 and the time estimation for this disassembly task. Column 10 contains the time employed for tool positioning in relation to the category of connectors used. This value is calculated by multiplying the number of connectors in Column 3 times the estimated time for tool positioning. Column 11 refers to the disconnection time of fasteners, which is calculated by multiplying the number of fasteners in Column 3 with the disconnection time of the corresponding connectors' category and tool category in the database. The time for component removal is registered in Column 12, which is accounted only once per component. Finally, the summation of times of columns 7–12 is computed in Column 13, and total time needed to disassemble the product or component is calculated with Eq. (1), for a product with n components.

$$eDiM = \sum_{i=1}^{i=n} (Tool\ Change_i + Identifiying_i + Manipulation_i + Positioning_i + Disconnection_i + Removing_i) \quad (1)$$

Table 4
Disassembly time calculation sheet.



1	2	3	4	5	6	7	8	9	10	11	12	13
Disassembly sequence of components	Disassembly sequence of connectors of components	Number of connectors	Number of product Manipulations	Identifiability (0,1)	Tool Type	Tool Change (s)	Identifying (s)	Manipulation (s)	Positioning (s)	Disconnection (s)	Removing (s)	eDiM (s)
						▨	▨	▨	▨	▨	▨	▨
						▨	▨	▨	▨	▨	▨	▨
						▨	▨	▨	▨	▨	▨	▨

4. Case study

4.1. Product characteristics

The selected product category is Flat Panel Displays (FPD), which was identified in previous research as a category that benefits from a disassembly based process (Peeters et al., 2014; Alonso Movilla et al., 2016; Peeters et al., 2013; Peeters et al., 2015c). Salhofer et al. estimate that the total mass of FPDs reaching EoL will account for 569,000 t in EU 25 by 2018, which equals 1.2 kg per capita per·year (Salhofer et al., 2011). This makes FPDs one of the fastest growing waste streams. FPDs contain a large amount of engineering plastics and precious metals, which have significant economic value, whereas, recycling processes for this waste stream are still under development (Alonso Movilla et al., 2016). Within FPDs, an LCD monitor is used as a case study as it is of average product complexity, contains a variety of fasteners and because the disassembly time for monitors is known to significantly vary.

Based on disassembly experiments in which 28 LCD monitors from the Belgian collection system were analysed, the average weight is 4.6 kg with a standard deviation (SD) of 1.5 kg, and the average size is 17.3 inches with SD 1.7 inches. From product's labels, an average age of 8 years was calculated with SD 1.8 years. Fig. 1 shows the average material composition found.

The disassembly time for the 28 monitors was also measured; the disassembly trial was performed by an experienced disassembler at a recycling facility in Belgium that processes 50 percent of all WEEE collected in the country (approx. 30,000 t). Fig. 2 shows the results for the disassembly time of different components. On average, the investigated LCD monitors require 644.11 s for complete disassembly with SD 199.2 s.

For detailed analysis, a 14″ LCD Philips monitor from 2002, which was considered to be an interesting model because it was one of the best performers regarding disassembly time, with a mass of 2618 g and a total measured disassembly time of 182 s was selected. Fig. 3, presents the measured time distribution among the different disassembly task categories, as defined in Section 3.3, for the selected monitor. Santochi et al. found similar percentages for EEE with 32% of the disassembly time for separation of connectors, 10% for tooling and 11% for sorting (Santochi et al., 2002). Ghazilla et al. also estimate that fasteners separation represents 30–40% of the total disassembly time.

4.2. Application of the method

Utilising MOST, a database has been deployed for the case study, which is included in the supplementary material. The database has been built on the following assumptions:

- The product considered is a small EEE with a weight of maximum 4 kg that can be disassembled on a workbench and can be handled by one person.
- The starting position of the product is on a workbench in front of the disassembler.
- The bins for disassembled components are located within reach of the operator.
- The disassembly sequence of the product is considered to be known by the operator, so no time is accounted for deciding which task is to be performed next.
- All the required tools are available and located within reach of the operator and can be manipulated with one hand.

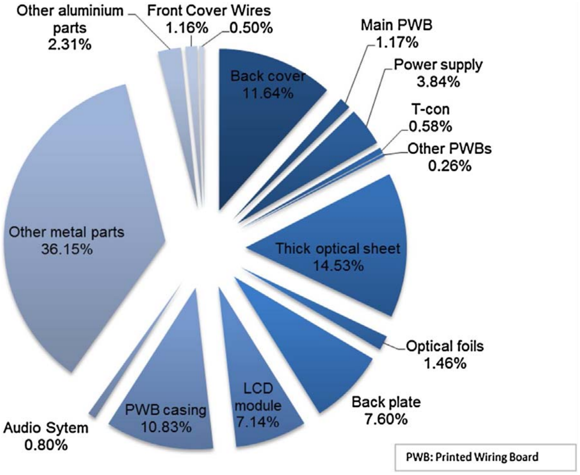


Fig. 1. Material composition of 28 LCD monitors.

The disassembly sequence was set to efficiently extract components, starting with the back of the monitor facing the operator and disassembling first the housing. Screws of the same type were disassembled in sequence to minimise tool change. Table 5 provides one complete example of the application of the method the calculation sheet for the case study product is presented in Table 5; the total calculated disassembly time is 198.2 s.

4.3. Calculated vs. actual disassembly time

To estimate the accuracy of the calculations, time measurements of the disassembly process for the case study product were performed in a plant in Belgium. The disassembler was highly experienced with disassembling small EEE. To allow familiarisation with the product first several monitors were completely disassembled during one hour, after that three monitors of the same model were fully disassembled, the times shown in Fig. 4 correspond to the last measurement. The disassembly process was filmed, and the video was analysed to measure the disassembly time. Fig. 4 depicts the comparison between the measured [M] and calculated [C] time.

5. Discussion

As shown in Fig. 4 the calculated and measured times for the LCD monitor analysed correspond very well. The difference between the total calculated and measured times is 15.6 s, whereas the largest difference is measured for the category Identifiability where the calculated time is 28.8 s, and the excess of time accounts for 10.7 s. This difference is because in this study Identifiability has only two categories which, for the case study product, overestimates the time needed for identifying connectors.

In addition, the presented time calculations for both complete and partial disassembly, as presented in the supplementary material, demonstrate the generic applicability of eDiM. This is important since complete disassembly is rarely performed at repair, remanufacturing or recycling centres. Instead, selective extraction and/or replacement of relevant components is commonly performed (Duflou et al., 2008; Ardente et al., 2014).

Furthermore, eDiM enables evaluating the contribution of each task to the total disassembly time, obtaining better insights on which aspects have a bigger influence on the improvement of disassemblability. This is one of the innovative aspects of eDiM, as it provides quantitative feedback on which type of disassembly tasks can be facilitated and on the effect of product design improvements. For example, from the calculation sheet in Table 5, it can be seen that 63% of the time is spent on positioning and disconnecting fasteners. Accordingly, most of the time can be reduced by improving these operations. The method also allows evaluating the effect of facilitating fasteners disconnection, by applying a commonly DfD guideline and reducing the number of screws. In total in the case-study, 72 connectors were identified, of which 40% (29) are screws, which account for 73% (11.2 s) of the time forTool Change, 83% (40.6 s) for Positioning and, 53% (37 s) for Disconnection. In general, a screw needs time for taking/putting back the required tool,

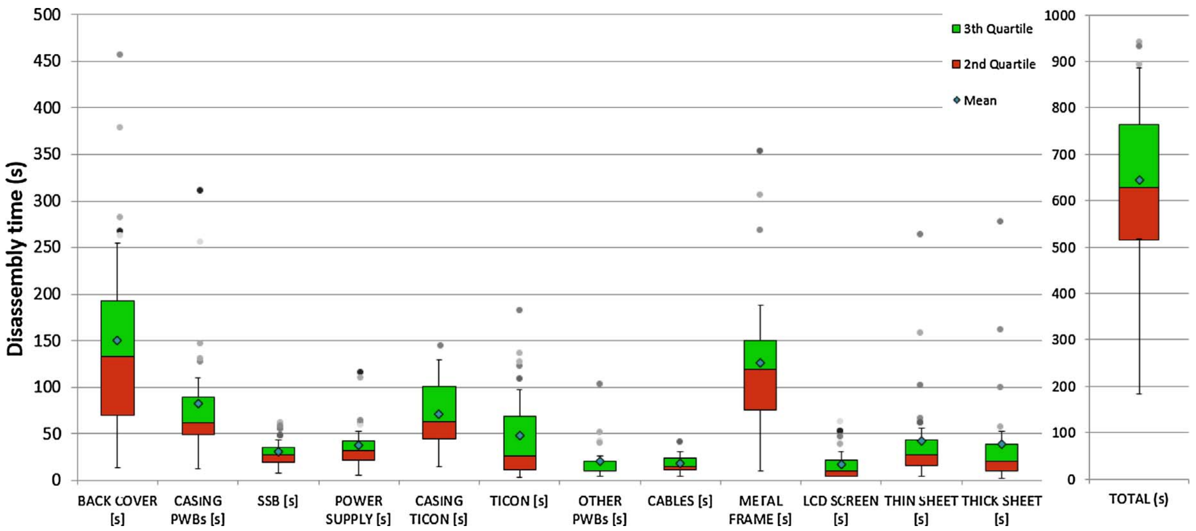


Fig. 2. Disassembly time of 28 LCD monitors.

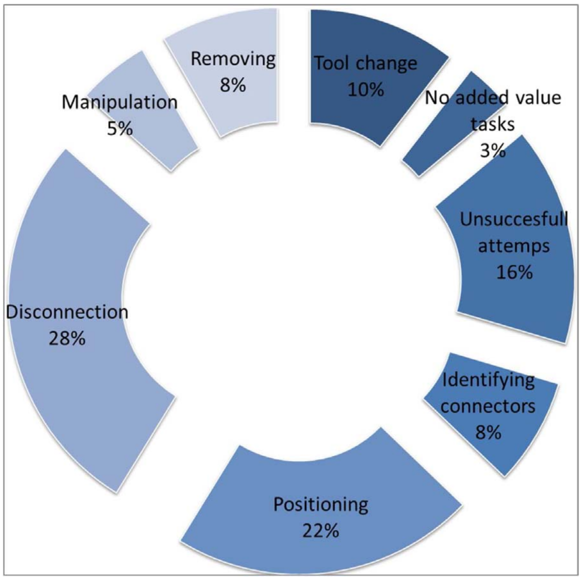


Fig. 3. % of time of the different categories of disassembly tasks for the case study product.

positioning and disconnection; for a screw type 1 these tasks add up 3.9 s (1.4 + 1.4 + 1.1), whereas a snapfit/hinge type 1 needs only 0.4 s (0 + 0 + 0.4) as no tool is required, and easy manual positioning is sufficient for disconnection. Accordingly, if 15 screws are replaced in the case study product by hinges type 1, reductions of up to 5.6 s in Tool Change, 28.8 s in Identification, 21 s in Positioning and 10.5 s in Disconnection can be achieved, which in total represents a reduction of 33.2% of the disassembly time.

Fig. 5 summarises these differences in disassembly time and the calculation sheet with these changes is presented in the supplementary material.

This simplified example demonstrates the applicability of eDiM to provide quantitative feedback on the influence of improvements in the product design. The example was theoretically build to show the potentiality of the method to support choices of designers. However, design for disassembly strategies as the one previously analysed should be carefully checked with manufacturing companies and designer in order to prove its feasibility for the considered product. Furthermore, eDiM can be used to identify other improvements, such as enhanced connector visibility, reduction in the number of components or the use of innovative fasteners, such as the ones proposed in (Peeters et al., 2015a,b). Concerning criteria for DfD, designers could set specific time thresholds for certain key components, especially those commonly replaced during the product use phase, repair and/or components that are likely valuable to be reused and/or remanufactured and/or components that should be extracted at EoL because they contain hazardous substances or critical raw materials. Such requirements could be easily verified by manufacturers and checked by third parties since the calculation is based on geometrical and physical information on components and fasteners that can be directly verified on the product.

The information on disassembly time organised in categories is relevant for disassembly optimisation efforts, automation of disassembly tasks and development of disassembly tools (Peeters et al., 2016). An additional benefit of the presented categorization is the possibility to exclude one or several categories for disassembly time estimation when this facilitates the verification process and implementation in legislation. Moreover, for specific cases, some categories can be omitted, for instance, Identification in case that the same product is expected to be disassembled a significant number of times by the same operator.

Ultimately, the amount of input data required for the calculation and the effort to provide the required information to evaluate ease of disassembly is deemed as acceptable. Leading manufacturers like HP and DELL already provide on their website detailed disassembly instructions, including disassembly sequence, location of connectors and required tools for some products, for example (HP, 2016; DELL, 2017). However, there is no common data format for sharing this information, utilising the presented calculation sheet can provide a standardised way for providing disassembly data assuring that all the required information is supplied. The accuracy obtained for time estimations with the proposed method is judged, based on the case study, as sufficiently high for the adoption of the method in a policy framework. Furthermore, the disassembly time estimation can be utilised as input for Eol treatment improvement, for example by EoL operators interested in determining the optimal disassembly depth of products.

Some limitations of the method have been identified. The eDiM does not account for penalties due to factors influencing ease of disassembly in specific product designs. For instance, in the developed database for the case study, extra force required to undo a fastener or limited accessibility in a specific product design are not accounted for. Accounting for these factors would result in a significantly larger database of fasteners and more complex taxonomy. Another issue of accounting additional parameters is that it is not evident to determine measurable parameters for all disassembly categories, which requires a compromise between accuracy and workability. For example, in the case study product, only surface visibility of screws is accounted for the

Table 5
Calculation sheet for the LCD monitor.

1 Disassembly sequence of components	2 Disassembly sequence of connectors of components	3 Number of connectors	4 Number of product manipulations	5 Identifiability (0,1)	6 Tool type	7 Tool Change (s)	8 Identifying (s)	9 Manipulation (s)	10 Positioning (s)	11 Disconnection (s)	12 Removing (s)	13 Total (s)
Front Cover	Screw Type1	1			PH2	1.4		0.0	1.4	1.1	1.4	5.3
Front Cover	Snapfit Type1	2	1			0.0		1.8	0.0	0.8	0.0	2.6
Front Cover	Hinge Type2	6				0.0		0.0	0.0	6.6	0.0	6.6
Buttons PWB	Screw Type1	1	1		PH2	1.4		1.8	1.4	1.1	1.4	7.1
Back Cover	Snapfit Type2	2			Slot	1.4		0.0	2.8	2.2	1.4	7.8
Back Cover	Hinge Type1	2				0.0		0.0	0.0	0.8	0.0	0.8
Metal Backcover	Screw Type1	6			PH2	1.4		0.0	8.4	6.6	1.4	17.8
Main PWB	Screw Type3	2	1		Hex No 5	1.4		1.8	2.8	7.2	1.4	14.6
Metal Backcover	Hinge Type1	4				0.0		0.0	0.0	1.6	0.0	1.6
Main PWB	Screw Type1	3			PH2	1.4		0.0	4.2	3.3	0.0	8.9
Power Suply	Screw Type1	2			PH2	0.0		0.0	2.8	2.2	1.4	6.4
Small PWB	Screw Type1	2			PH2	0.0		0.0	2.8	2.2	1.4	6.4
Power Suply	Hinge Type1	2				0.0		0.0	0.0	0.8	0.0	0.8
Power Suply	Cable plug Type1	1				0.0		0.0	0.0	0.4	0.0	0.4
Main PWB	Hinge Type1	3			Slot	1.4		0.0	0.0	1.2	0.0	2.6
Main PWB	Cable plug Type3	1				0.0		0.0	0.0	2.2	0.0	2.2
Main PWB	Cable plug Type2	1				0.0		0.0	0.0	1.1	0.0	1.1
Metal Plate	Screw Type1	2	1		PH2	1.4		1.8	2.8	2.2	1.4	9.6
Metal Plate	Screw Type1	2	1		PH2	0.0		1.8	2.8	2.2	0.0	6.8
Metal Plate	Clamp Type2	2				0.0		0.0	0.0	2.2	0.0	2.2
Metal Plate	Cable plug Type2	1				0.0		0.0	0.0	1.1	0.0	1.1
Buttons PWB	Cable plug Type2	1				0.0		0.0	0.0	1.1	0.0	1.1
LCD PWB	Screw Type1	4		3	PH00	1.4	14.4	0.0	5.6	4.4	1.4	27.2
LCD PWB	Cable plug Type1	2				0.0		0.0	0.0	0.8	0.0	0.8
LCD Small PWB	Tape Type2	1	1			0.0		1.8	0.0	1.1	1.4	4.3
Metal Frame	Snapfit Type2	3				0.0		0.0	4.2	3.3	1.4	8.9
Metal Frame	Hinge Type1	3	1			0.0		1.8	0.0	1.2	0.0	3.0
LCD	Clamp Type3	1				0.0		0.0	1.4	2.2	1.4	5.0
Plastic Frame	Screw Type1	4		3	PH000	1.4	14.4	0.0	5.6	4.4	1.4	27.2
Plastic Frame	Snapfit Type1	1	1		Slot	1.4		1.8	0.0	0.4	0.0	3.6
Plastic Frame	Hinge Type1	4				0.0		0.0		1.6	0.0	1.6
Metal Back Cover LCD						0.0		0.0			1.4	1.4
Foils (4 thin + 1 thick)						0.0		0.0			1.4	1.4
		72			Total (s)	15.4	28.8	14.4	49.0	69.6	21.0	198.2

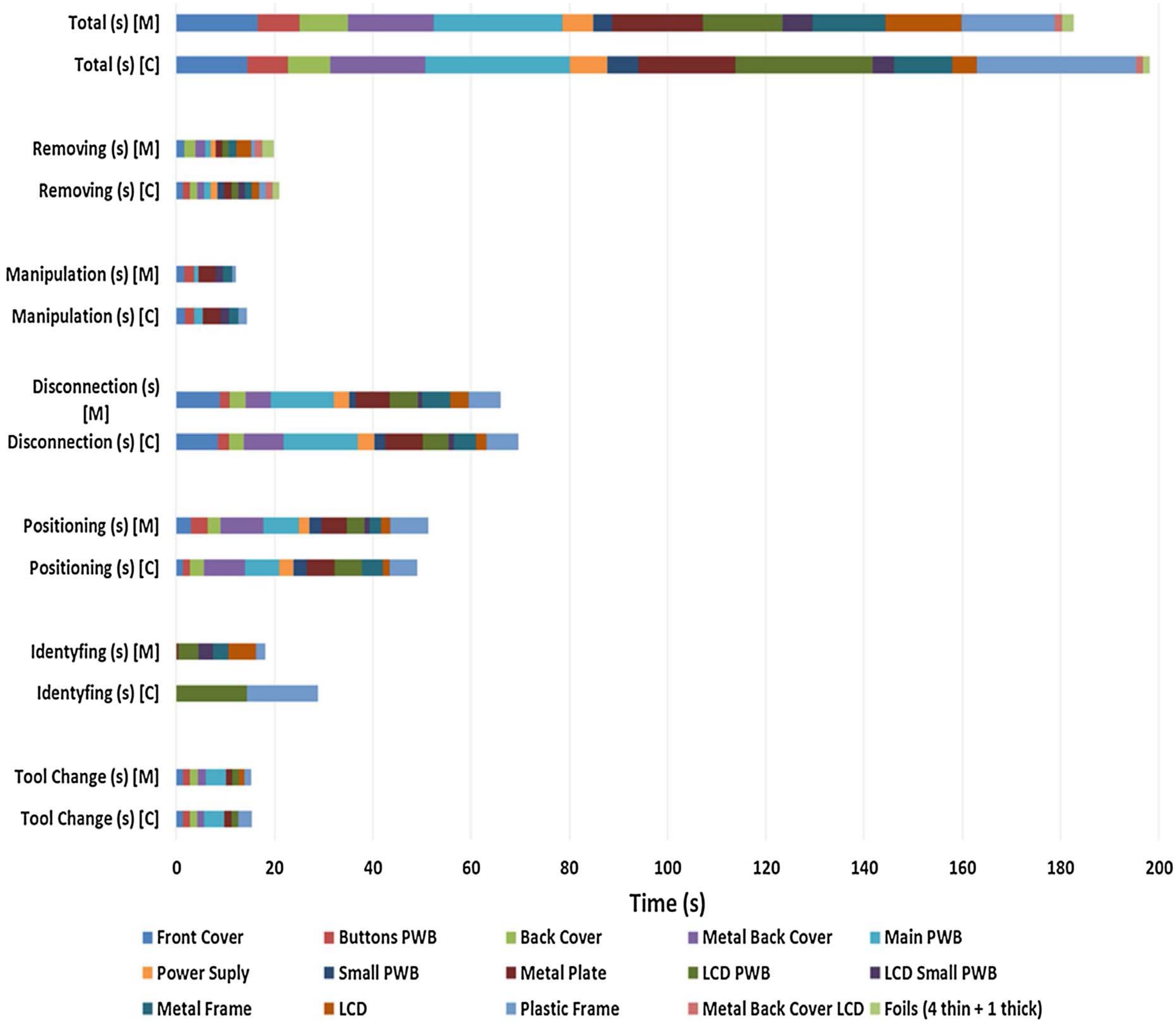
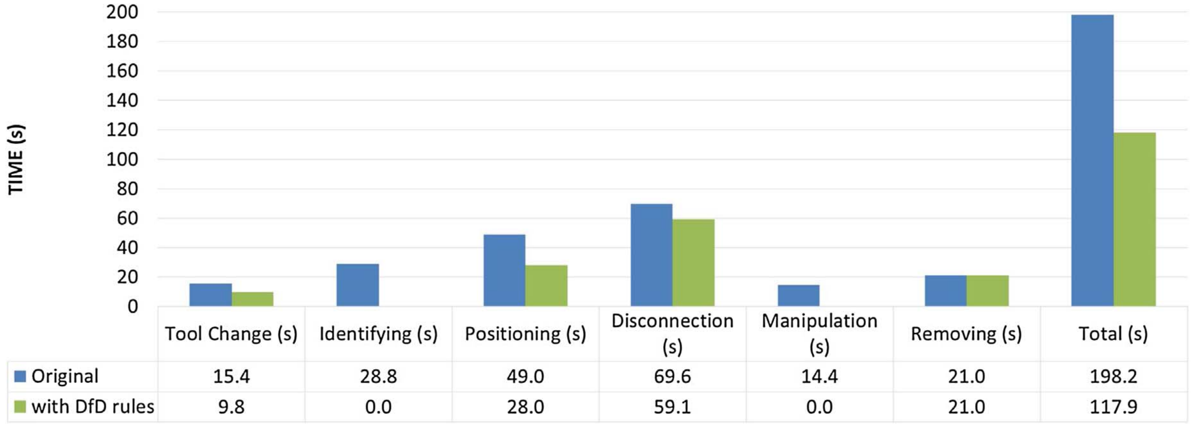


Fig. 4. Comparison between calculated and measured time.

disassembly task ‘Identifiability’. This simplification ignores other factors that influence identification, such as colour contrast. Therefore, the time estimation for this category can be improved. However, a trade-off needs to be made between accuracy and the amount of product information required, as well as the ambiguity of the evaluation.

The results obtained are still linked to the case-study product analysed and need to be tested on more products. In order to make eDiM applicable to an extensive variety of products, the deployment of a database with a well-defined taxonomy of fasteners and the corresponding disassembly time is required. For this database it is crucial to define every type of fasteners with easily verifiable parameters as well as the ranges of these parameters used to classify them, a compromise needs to be made between accuracy and efforts required. In addition, a procedure needs to be developed to enable manufacturers to propose the addition of new types of fasteners to the database to assure the applicability of eDiM for both today’s and future product designs.



	Tool Change (s)	Identifying (s)	Positioning (s)	Disconnection (s)	Manipulation (s)	Removing (s)	Total (s)
Original	15.4	28.8	49.0	69.6	14.4	21.0	198.2
with DfD rules	9.8	0.0	28.0	59.1	0.0	21.0	117.9

Fig. 5. Original Disassembly Time vs. Disassembly Time after DfD guidelines.

6. Conclusions and perspectives

This article describes the development of a method to determine ease of disassembly of products to support the circular economy. The proposed method provides a scientific background to organisations developing standards on material efficiency aspects that include the disassemblability of products and supports OEMs and EoL operators by providing a method to assess DfD for repair, reuse and recycle.

Following a literature review of existing methods and practical experiments to determine the main factors influencing disassembly operations, a calculation method is developed using a database with disassembly times determined based on the work measurement system theory MOST and a straightforward calculation sheet. A case study of an LCD monitor is used to demonstrate the applicability of the proposed method. The presented analysis shows how the output of the method can be utilised for evaluating ecodesign improvements regarding disassemblability. One of the key features of eDiM is that it is transparent and easy to use thanks to the basic formulae employed for the time calculation, facilitating its implementation and verification by manufacturers, market surveillance authorities and EoL operators. The method is regarded as reproducible and repeatable as it builds on a widely applied methodology for work measurements, in which the accuracy of time estimations is statistically grounded. Since MOST focuses on basic motions, eDiM could be applied to all product groups and the time needed to remove a specific component by all kinds of manual disassembly tasks could be calculated.

In addition, eDiM can be used to model the disassembly time for novel connectors with different types of tools, providing the required flexibility to serve as a generic method for policy measures and to incorporate an extensive range of products and fasteners. Because the classification of fasteners and disassembly tasks is done on the basis of easily verifiable geometric and physical properties, such as dimensions or force, subjectivity in the assessment is minimised. Furthermore, eDiM provides the required flexibility to be applied for complete and partial disassembly. Moreover, the proposed categorization of disassembly tasks provides effective quantitative feedback on the influence of product design adaptations, while the amount of input data remains acceptable. Besides, the required product information utilised as input can be complemented with data on, for example, material content to evaluate the performance of other ecodesign criteria. Therefore, further research should focus on the development of a single input data sheet which enables to simultaneously assess multiple ecodesign performances, such as reparability, remanufacturability, and recyclability. At the same time, robust information systems should be developed to make product information provided by OEMs available to research institutes and companies to anticipate evolutions in waste streams to be able to optimise their EoL processes.

This analysis contributes to improve the assessment of disassemblability of products and could also enhance the enforcement of quantifiable requirements within existing product policies. In fact, eDiM was selected as one of the key scientific inputs for the development of the on-going European standardisation activities for the implementation of the Commission's action plan on the Circular Economy (European_Comission, 2015). In case the method is standardised, there will be the need to evaluate for which products disassemblability should be assessed. Specific thresholds of the eDiM could be set for certain key components, especially those commonly replaced for repair, or components that should be extracted at the EoL because they contain hazardous substances or critical raw materials that are valuable to recover. Such requirements could be easily used by manufacturers as design objectives and checked by third parties (e.g. market surveillance authorities) since the calculation is based on information about the product’s composition and fastening that can be directly verified on the product. The calculation of the eDiM is also unambiguous, and this would avoid any subjectivity during the verification by third parties.

Overall, quantifiable requirements in product policies supported by such standardised method should allow manufacturers to implement product lifetime strategies for a more circular economy.

Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2017.06.022.

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