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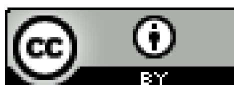

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Disassemblability Assessment of Power Electronic Converters for Improved Circularity

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Abstract: Power Electronics Converters (PEC) play a crucial role in the operation of many modern electrical systems and devices. Despite their widespread use, the lack of an efficient and cost-effective disassembly process can limit their repairability, refurbishability, remanufacturability and, ultimately, recyclability, thus hindering the circularity of products. In order to improve their circularity, it is important to assess their ease of disassembly. Therefore, this paper investigates the applicability of the "ease of Disassembly Metric" (eDiM), which is referenced in the material efficiency standards, Benelux repairability assessment method, and Repair Scoring System (RSS), to analyze the ease of disassembly of energy-related products. After identifying the limitations of the eDiM method, we refined and adapted it to make it more suitable for Printed Circuit Board (PCB)-based PEC, and thus propose a PCB-based disassemblability assessment method allowing the implementation of quantifiable requirements supporting their circularity. This standardized approach, at the PCB level, can improve the circularity of such products by facilitating design enhancements. With this approach, policymakers and designers can contribute more effectively to the transition to a circular economy in PCB electronics, particularly in the field of power electronics.

Keywords: power electronics; circular economy; disassemblability; desoldering; ease of disassembly metric; repairability; printed circuit board

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1. Introduction

Electronic waste or e-waste is one of the fastest-growing waste streams [1]. The rapid advancement of technology has also contributed to a surge in e-waste [2], with the planned obsolescence of such equipment accelerating the accumulation of WEEE in the coming years [3]. In 2019, the world generated 53.6 Mt of e-waste and the projection for 2030 is 74.7 Mt [4]. This alarming increase in e-waste highlights the urgency of sustainable practices to minimize its environmental impact. The "European Union (EU)" adopted a "Circular Economy Action Plan (CEAP)" in 2015 to support sustainable growth by reducing waste and promoting resource efficiency. The CEAP places a strong emphasis on product design as a key pillar, with strategies aimed at increasing material efficiency, extending product life, and improving recycling efficiency [1]. Legislation is increasingly focusing on extending the useful life of products to reduce e-waste generation and environmental degradation [5]. This goal can be achieved by providing multiple product life cycles by considering circularity scenarios, often referred to as R-scenarios. These scenarios cover

practices such as reuse, repair, refurbishment, and remanufacture [6]. To effectively implement such scenarios, easy access to the product casing, its subassemblies, and components for disassembly is mandatory [7].

Disassemblability refers to the ease of disassembly [8], and it varies depending on the R-scenario. This can include disassemblability for repair, refurbishment, remanufacturing, or recycling. Hence, not all devices will be equally considered regarding the R-scenario implementation. It is necessary to prioritize the parts to be disassembled and this prioritization will be different in different R-scenario contexts [9]. Before the disassemblability assessment of a product, the R-scenario shall be chosen prior to the identification of target components such as less reliable components for repair and maintenance, more reliable components for reuse, and high-value material components for recycling. Furthermore, the acceptable level of damage during the disassembly must be defined. For instance, it is important to avoid excessive thermal loading on components and interconnections (i.e., Printed Circuit Board (PCB)) if the components or the interconnections are intended to be reused. Indeed, thermal loads can shorten the lifespan of components and subassemblies. Additionally, minimizing mechanical damage is essential to ensure that components, subassemblies, and casing can be reused [10].

Numerous techniques have been proposed by researchers to assess the level of disassemblability of products, including the "Ease of Disassembly Metrics (eDiM)" developed by Vanegas et al. [1]. This project was supported by the Directorate-General for Environment of the European Commission, and the final report was published by the Joint Research Centre [11]. eDiM aims to provide information to improve product design in accordance with the principles of circular economy. eDiM focuses on electrical and electronic equipment and the scoring system is based on the number of seconds required to perform a specific operation for the required disassembly [12]. This metric has been integrated into different repair scoring systems as a reference point to evaluate the ease of assembly of products. Some of these systems are as follows:

- Material efficiency standard EN45554 [9] released under the EU's CEAP (2020) as part of efforts to promote material efficiency under the eco-design directive 2009/125/EC and the proposed Eco-design for Sustainable Products Regulation.
- The Benelux repairability assessment method, which is a semi-quantitative evaluation method based on 24 criteria that aims to quantify the ease of repair for "Energy-related Products (ErPs)" [13].
- Repair Scoring System [14] developed by the Joint Research Centre to assess the repairability, reusability, and upgradability of products.

Despite the availability of such methods, there is still a gap in the literature regarding the calculation of the disassemblability of entire electronics and PEC products, as noted by Patra (2021) [15]. Patra specifically emphasized that the general horizontal standard EN45554 has limited applications in unique energy-related products such as power electronic drives [15]. Therefore, in this study, "Power Electronics Converters (PECs)" are considered as a case problem in the given context. PECs play a crucial role in the efficient conversion and control of electrical energy in various applications, including renewable energy systems, electric vehicles, and power transmission and distribution networks [16]. A significant portion of these converters are low- to medium-power electronic systems, which are mostly assembled and interconnected through PCBs. However, PCBs represent a growing problem due to their large heterogeneity and high degree of integration, making it difficult for any circular economy initiative to succeed. This creates challenges for the realization of sustainable practices in the electronics industry.

This paper addresses the limitations of the eDiM and proposes a refined methodology for evaluating the disassemblability of PCB-based PECs using more suitable eDiM, with a specific focus on the repairability. Although the repair process involves product identification, fault diagnosis, disassembly, spare parts replacement, reassembly, and restoration to working conditions [17], this study concentrates only on the disassembly phases, assuming that failed components need to be disassembled in order to be replaced with functional

ones. The refined methodology allows for the establishment of measurable requirements for products that promote the circular economy. This paper is organized as follows:

- Section 1 provides an overview of the disassembly process for PCB-based PEC devices and introduces the eDiM. Moreover, we consider the difficulties of applying the eDiM to PCB-based PEC devices.
- Section 2 outlines the method for the experimental setup used in our study to fill in the eDiM table. The disassembly process of an "Uninterruptible Power Supply (UPS)" product is the focus of our experiments. The disassembly sequence and the employed tools are presented.
- Section 3 details the application of the eDiM to assess the disassemblability of the UPS casing and ECs on PCB. The successful application of the eDiM for casing disassembly, as well as the identification of the limitations of the eDiM in the context of "Electronic Components (EC)" desoldering processes are discussed, and finally, a tailored eDiM is proposed for PCB-based ECs to overcome such limitations.
- Section 4 summarizes and discusses the findings of our study. Finally, conclusions are drawn.

1.1. eDiM Approach

The eDiM method is based on the Maynard Operation Sequence Technique (MOST®), which is a predetermined time system analysis tool used by industrial engineers and practitioners to measure assembly times for a wide variety of products [1,9]. The practical application of MOST, in accordance with the guidelines outlined in reference [18], is illustrated in Table 1. The basic motions that form a standard sequence are each denoted by a letter, such as A for horizontal movement, B for vertical shift, G for obtaining control, P for placement, and L for loosening. An additional data sheet lists several indices that indicate various degrees of complexity, as well as the corresponding time frames, for these actions [18].

Table 1. Examples of MOST use according to [18].

	Get Tool	Put Tool in Place	TOOL ACTION	Put Tool Aside	Return to Position
Basic MOST tool use	ABG	ABP	L	ABP	A

The eDiM method is a quantitative assessment technique used to evaluate the time required to achieve the complete or partial disassembly of a product while attempting not to cause any damage. The tasks required to disassemble parts are listed and each task is assigned a corresponding reference time value given in the database. These values represent the amount of time effort that is required to complete each task [19]. To eliminate any subjective bias, the eDiM utilizes easily verifiable geometric and physical properties of fasteners, including a comprehensive database of fasteners with a clearly defined taxonomy and easily verifiable parameters. Table 2 shows the eDiM approach being used to compute disassembly time [1]. The first six columns provide product category information. Column 1 lists the components in a specific order to either reach the targeted components or to fully disassemble the product. Column 2 lists the sequence of connectors that must be released to extract each component. Column 3 lists the number of connectors per component, column 4 lists the number of product manipulations necessary to access to the components that need to be released, and column 5 describes the ease of identifiability of the connectors. Column 6 lists the appropriate type of tool(s) required to release each connection.

Using the information in the first 6 columns, columns (7–12) can be calculated using standard times based on reference values. Column 7 involves taking a tool and placing it in place, as well as making the necessary changes or preparations and ensuring it is ready for use. Column 8 deals with determining where the connectors are located, as well as the type

of connector and the appropriate tool needed to disconnect them. Column 9 refers to the time required to move or adjust the product to locate and disconnect a connector (i.e., turn the product over). Column 10 refers to the action of placing the tool in the correct position relative to the fastener before initiating the disconnect. For example, this might involve placing a screwdriver over a screw. Column 11 refers to the time required to physically disconnect a fastener, such as by removing a screw. Column 12 refers to the time required to remove unfixed components and place them in appropriate containers. Finally, in column 13, the total time required for disassembly is calculated from the data in (7–12). Equation (1) is given for n-component products to determine the total time required to disassemble a product [1].

$$eDiM = \sum_{i=1}^{i=n} \begin{pmatrix} ToolChange_i + Identifying_i \\ +Manipulation_i + Positioning_i \\ +Disconnection_i + \text{Removing}_i \end{pmatrix} \tag{1}$$

Table 2. eDiM worksheets-based approach to compute disassembly time [1], green indicates the input information, and yellow indicates the calculations.

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)	Manipulations (s)	Positioning (s)	Disconnections (s)	Removing (s)	eDiM (s)

1.2. Disassembling Procedure for PCB-Based PEC

A PEC generally consists of different components, including electro-mechanical blocks and "Printed Circuit Board Assembly (PCBA)" [20,21]. The electro-mechanical blocks may include heat sinks for semiconductors, the outer casing of the equipment, and large active or passive components that are not soldered on the PCB. These components are typically mechanically fastened together using screws and wiring. The PCBA is the structure that consists of a PCB and various ECs mounted on it, such as semiconductors, capacitors, magnetic elements, integrated circuits, and connectors [20,21]. The disassembly procedure for a specific EC in a PCB-based product usually encompasses the following steps within the context of a repair-oriented circularity scenario.

1. Disassembly of casing: The disassembly process starts with the removal of the outer casing, along with relevant cables and screws, to gain access to the PCBA.
2. Fixing the PCBA: This can be facilitated by using a bracket with adjustable clamps or a vice, which allows easy access to the components and avoids damage to the board as well as dust related to manipulations. To ensure the safety of sensitive ECs, the PCB attachment shall be designed to allow the board to be grounded, thereby preventing any potential electrostatic hazard. It is worth noting that the necessity of this step varies based on the operator and the type of PCB involved.
3. Releasing Solder Joints: This step involves separating the solder joints connecting the PCB and ECs, which is achieved through various methods [22,23].
4. Disassembly or Dislodging: This step is primarily executed by applying external forces strategically to extract ECs from their positions on the PCB [22,23]. Then, the targeted ECs that have settled on the PCB can be disassembled.
5. Inspection and Cleaning: Inspection and cleaning of PCB are conducted to ensure that no weld residue, debris, or other contaminants remain.

The desoldering process is highly affected by the desoldering temperature; this affects the duration of the process, as well as possible damage to the PCB. Additionally, other factors such as the desoldering tool, the size and shape of components, and the PCB type can also affect the desoldering process. For example, using a desoldering iron with a fine-tip nozzle can facilitate precise targeting of soldered joints and minimize damage to adjacent components [24]. Therefore, it is important to consider all these factors to achieve the optimal results when performing desoldering. Moreover, functional value retention options require non-destructive disassembly. Therefore, the focus in this work will be on releasing the solder joint by heat treatment by minimizing impacts on the PCB and components.

1.3. Limits of eDiM in the EC Desoldering Process

The implementation of the eDiM approach is limited to the mechanical stages down to the PCB. The eDiM method, which is based on the MOST, faces limitations when applied to the EC desoldering process. The eDiM's scope does not extend to include the desoldering process. Notably, the eDiM method could not be applied at the PCB level [25]. Firstly, the eDiM method was originally designed for mechanical disassembly processes and did not encompass the heat-related disassembly process of desoldering. This limitation rendered it incapable of generating a metric using the existing calculations. Secondly, there is unavailability of proposed MOST sequences in eDiM database for desoldering movement actions. Furthermore, there is an absence of a database for solder connectors and connector characteristics. To assess the feasibility of employing eDiM for PCBA, this study identifies three key challenges that need to be addressed:

- Database Expansion: eDiM methodology is based on tool selection from a predefined inventory (compliant with standards such as ISO/TC 29/SC 10 [26]) covering tools for pinching, pliers, screws, and nuts [18]. However, there is a notable absence of references for desoldering tools, necessitating an expansion of the database.
- Specific Input Data Requirements: Disassembly time is affected by complex desoldering processes; however, current eDiM method does not provide detailed information on these aspects. Additional specific input data is essential to capture the nuances of these processes.
- Development of Disassembly Task List: The current disassembly task list lacks temperature-related information. Details regarding temperature considerations should be included to increase the comprehensiveness of the list.

To effectively adapt the eDiM method to measure the disassemblability of PCB-based electronics and PECs, it is imperative to integrate other relevant criteria into the desoldering process. At the same time, the MOST database needs to be expanded by incorporating comprehensive information regarding both ECs and desoldering processes, such as a time index for detailed actions related to the desoldering task.

2. Method

An experimental study was conducted to feed the eDiM table the necessary data to evaluate the disassemblability of PCB-based PECs. The study focused on determining the disassembly sequence of components and connectors, as well as the number of production manipulations, identifiability, tool types and other key input parameters required for eDiM calculations. Then, the data collected during the experimental study were used to perform the calculations using the MOST database. The MOST database provides standard times based on reference values for tool change, identification, manipulations, positioning, disconnection, and removal. By integrating the experimental data into the MOST database, this study aimed to quantitatively evaluate the time and effort required for partial disassembly of PCB-based PECs and thus contribute to the development of a standardized approach to assess the disassemblability of such products.

Consequently, disassembly tests were carried out in two stages: (i) the housing and (ii) the ECs. The experimental study focused on a UPS product to evaluate the applicability

of eDiM in PE products. By choosing a UPS product, the study aimed to capture the complexities and challenges associated with the disassembly of a PCB-based PEC representing a wider range of electronic devices.

2.1. Casing Disassembly

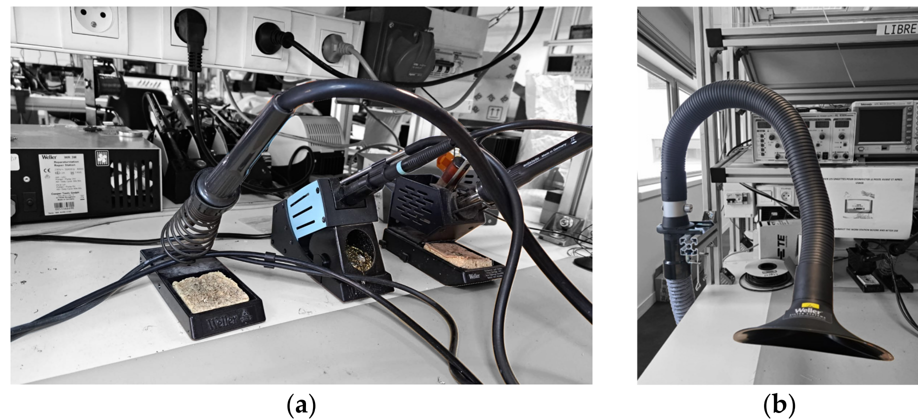
The casing disassembly involved removing the outer casing, along with the relevant cables and screws, to access the PCBA. A set of tools (screwdrivers and Torx drivers) was used for disassembly. Additionally, manual manipulation was used to release clips or connectors. The researchers documented the disassembly sequence, number of connectors, and number of product manipulations, adding input data into the eDiM calculation sheet (Table 2) of the casing components.

2.2. Electronic Components Disassembly

As part of this study, the researchers conducted tests on the desoldering of ECs. As highlighted in the introduction, eDiM is not adapted to the desoldering process. The study aimed to identify the limitations of the eDiM method and refine it to make it more suitable for PCB-based PECs. The aim is to propose a standardized approach to compare the disassembly of different PECs and to facilitate the identification of design improvements in terms of circularity. Therefore, the objectives of this experiment were as follows. (i) To complete the eDiM calculation sheet (Table 2) by providing details on the disassembly sequence of components and connectors, number of connectors and product manipulation, identifiability, and tool types. Based on the results, we aim to assess the suitability of these input data to perform the disassembly metric calculations and, if any elements are missing, identify and specify them. (ii) To identify desoldering movement actions and propose a database. (iii) To identify other relevant inputs that may affect disassembly or desoldering time, such as temperature-related information.

These tests involved a systematic assessment of the disassembly process for various ECs mounted on the PCB. Following the eDiM framework, which suggests a disassembly process that can be either completed or partially completed without causing harm to the components [12], this study opted for partial disassembly rather than disassembling all ECs. In the context of partial disassembly, a prioritization of components was undertaken. Given that the primary goal of eDiM is to contribute to the repairability score of PE products, the emphasis was given to identifying weak ECs. Capacitors, transistors, and rectifier diodes were given priority for disassembly, as these components are reported in the literature to be the least reliable in power electronic applications [27–30]. Therefore, these components have been chosen for disassembly.

The experimental setup for EC desoldering is illustrated in Figure 1. A set of tools is necessary for the desoldering process, such as desoldering iron, soldering iron, hot air guns, tweezers, soldering tweezers, external pumps, and solder wick, among others. In this experiment, only a desoldering iron, tweezers, a magnifying lamp, and fume extractor were used. First, a desoldering iron with an internal pump was used to melt the solder and extract the molten solder from the joint and the leads of ECs. Such a tool is available in different nozzle sizes to fit different EC lead diameters. Second, tweezers were employed to extract components with precision and accuracy while protecting the operator from the component's elevated temperature, which was caused by the desoldering iron. Furthermore, a fume extractor was used to protect the operator from the hazardous effects of solder fumes. In addition, an adjustable magnifying lamp was used to provide adequate lighting; however, high magnification was deemed unnecessary, as component identification does not pose challenges similar to those encountered in microelectronics. As a safety precaution, operators were advised to wear special bracelets and shoes to prevent the accumulation of electrostatic currents in the operator, as it can lead to unintended electrostatic discharge and potential damage to sensitive ECs.



(**a**) (**b**)

Figure 1. (**a**) desoldering station, (**b**) fume extractor.

3. Results

This section is organized in four parts: (i) firstly, eDiM results related to the casing disassembly are presented; (ii) secondly, desoldering motion actions using the MOST database are proposed for the predefined eDiM databases; (iii) thirdly, enhancements to eDiM are proposed with the aim of increasing its effectiveness in assessing the disassemblability of ECs. (iv) Finally, attention is drawn to the desoldering tests performed in this study. Desoldering test results were presented, with particular emphasis on desoldering time for capacitors, transistors, and diodes.

3.1. eDiM of UPS Casing

Figure 2 visually illustrates the disassembly sequence of UPS casings and less reliable ECs. The figure shows the sequential disassembly steps, highlights the cases where the eDiM table was successfully completed, and indicates the areas where difficulties were faced. The analysis demonstrates the suitability of the eDiM approach for casing disassembly, while facing the challenges in its application to ECs. The defined boundaries of eDiM are shown in the left box, while the elements outside the scope of eDiM are shown in the right box.

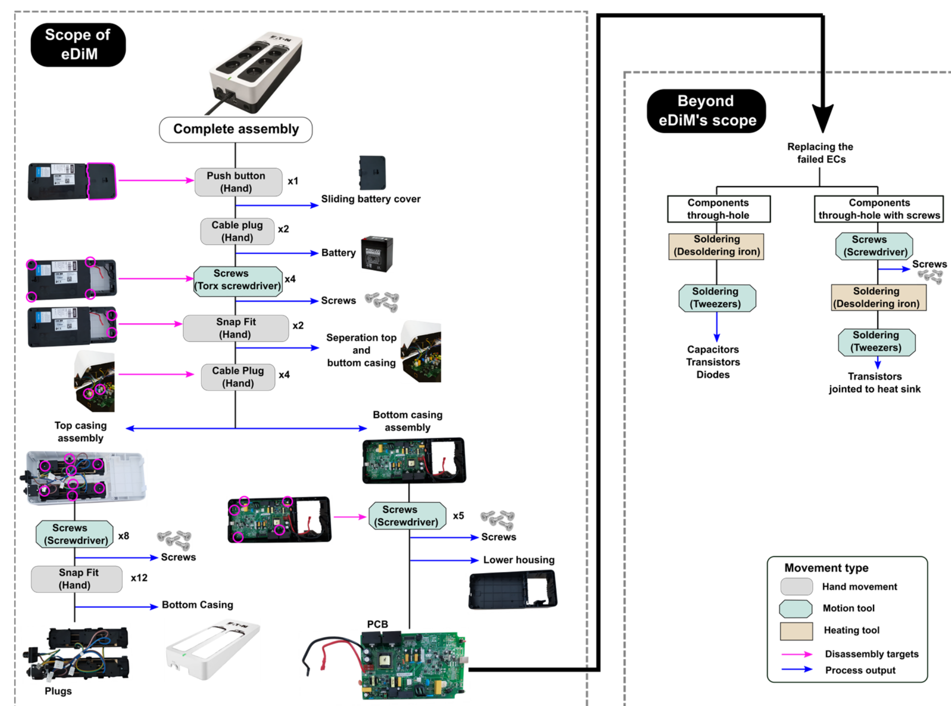


Figure 2. UPS casing and ECs disassembly sequence with eDiM scope.

Table 3 provides an overview of the eDiM procedure for disassembling the PCBA from the UPS casing. In the table, the disassembly sequence of components has been chosen to optimize the path to reach the PCB in the most efficient way possible. This approach ensures that the metric yields objective results, specifically reflecting the effort directed towards the PCBA. As a result, the top casing disassembly sequence is intentionally excluded from Table 3.

The eDiM in Table 3 is computed by the summation of the timing of identification, manipulation, positioning, disconnection, and removal of each component. The duration of each step is presented in a different column. For example, for the sliding battery cover, the eDiM is the total of the positioning (|A1B0P3|), disconnection (|L3|), and removal times (|A1B0G1| + |A1B0P1|). This results in an index sum of 11, which, when multiplied by 0.36, equals 3.96 s.

The disassembly process involves tool change, identification, manipulations, positioning, disconnections and removing. Components such as the sliding battery cover and the battery exhibit a relatively straightforward disassembly process, receiving an eDiM of 3.96 s and 5.04 s, respectively. Both components involve minimal manipulations, which are mainly performed by hand. The lower casing offers a relatively longer scenario. The screws on the bottom casing require a Torx T10 screwdriver. This, along with the presence of clips and cables, slightly lengthens the disassembly process, resulting in an eDiM of 46.08 s, indicating a longer disassembly procedure. Additionally, PCBA disassembly requires a PH2 screwdriver, contributing to an eDiM of 42.84 s. While certain components exhibit a shorter disassembly time, the overall eDiM is influenced by the extra time introduced by tool changes and multiple manipulations, particularly in the case of the bottom casing and PCBA. The total metric required to disassemble the PCBA from the casing is 98.52 s, using the predetermined time estimation provided by MOST. It is important to note that this precise disassembly time does not represent the actual time it might take a person to perform this task. Instead, eDiM serves as a metric designed for benchmarking, offering insights into the disassemblability of various components. The comparative eDiMs of various components are visually shown in Figure 3. Each eDiM represents the index that initiates from the undisassembled casing each time. This metric serves as an analytical tool for evaluating and comparing the efficiency of disassembling different components within the UPS product.

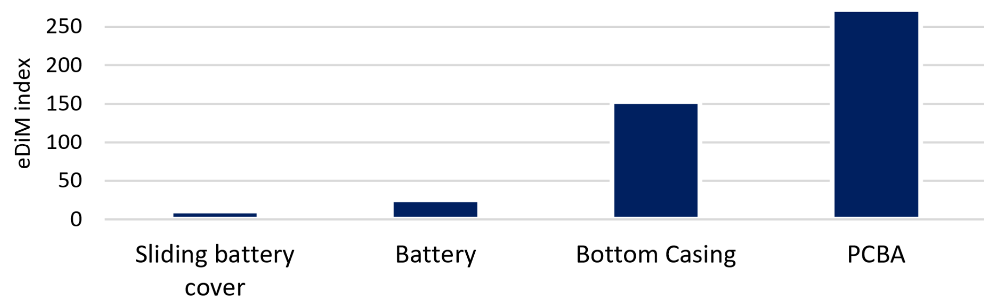


Figure 3. Comparative eDiM among different UPS components.

Table 3. eDiM worksheets-based methodology for calculating disassembly metric up to PCBA.

1	2	3	4	5	6	7	8	9	10	11	12	Index	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)**	**Manipulations (s)**	**Positioning (s)**	**Disconnections (s)**	**Removing (s)**		**eDiM (s)**
Sliding battery cover	Snapfit	1	0	0	Hand	0	0	0	∣A1B0P3∣	∣L3∣	∣A1B0G1∣ + ∣A1B0P1∣	11	3.96
Battery	Cable plug	2	0	0	Hand	0	0	0	∣A1B0P3∣	∣L3∣	∣A1B0G1∣ + ∣A1B0P1∣	14	5.04
Bottom Casing	Screws	4	0	0	Torx T10 screwdriver	∣A1B0G1∣ + ∣A1B0P1∣	0	0	∣A1B0P3∣	5 × ∣L3∣	∣A1B0G1∣ + ∣A1B0P1∣	96	34.56
Bottom Casing	Clips	2	0	0	Hand	0	0	0	∣A1B0P3∣	∣L3∣	0	10	3.6
Bottom Casing	Cables	4	1	0	Hand	0	0	∣L3∣	∣A1B0P3∣	∣L3∣	∣A1B0G1∣ + ∣A1B0P1∣	22	7.92
PCBA	Screws	5	0	0	PH2 Screwdriver	∣A1B0G1∣ + ∣A1B0P1∣	0	0	∣A1B0P3∣	5 × ∣L3∣	∣A1B0G1∣ + ∣A1B0P1∣	119	42.84

3.2. Contribution to eDiM Database with Desoldering Movement Actions

In eDiM database, disassembly actions provided with a series of sub-actions. The identified desoldering movement actions have been listed in Table 4 to contribute to this database.

Table 4. Proposed MOST desoldering movement actions.

Action	MOST Sequence	Index	eDiM Value (s)
Desoldering Iron Change by Fetching and Putting it Back	∣A1B0G1∣ + ∣A1B0P1∣	4	1.4
Nozzle change of the desoldering iron for different sizes of diameter of leads of components • Grasp the desoldering iron ∣A1B0G1∣ • Grasp the replacement kit ∣A1B0G1∣ • Put desoldering iron in place ∣A1B0P1∣ • Put replacement kit in place ∣A1B0P1∣ • Use the replacement kit to unfasten the nozzle by turning the wrist ∣L3∣ • Place replacement kit on the workbench ∣A1B0P1∣ • Grasp pliers ∣A1B0G1∣ • Pick up the hot nozzle using pliers and leave it on the workbench ∣A1B0P1∣ + ∣A1B0G1∣ + ∣A1B0P1∣ • Leave the pliers on the workbench ∣A1B0P1∣ • Grasp replacement kit and place it ∣A1B0G1∣+∣A1B0P1∣ • Pick up a new nozzle and place it on the replacement kit ∣A1B0G1∣+∣A1B0P1∣ • Fasten the new nozzle with replacement kit by turning wrist ∣F3∣ • Leave the replacement kit on the table ∣A1B0P1∣	∣A1B0G1∣ + ∣A1B0G1∣ + ∣A1B0P1∣ + ∣A1B0P1∣ + ∣L3∣ + ∣A1B0P1∣ + ∣A1B0G1∣ + ∣A1B0P1∣+ ∣A1B0G1∣ + ∣A1B0P1∣ + ∣A1B0P1∣ + ∣A1B0G1∣ + ∣A1B0P1∣ + ∣A1B0G1∣ + ∣A1B0P1∣ + ∣F3∣ + ∣A1B0P1∣	36	12.96
Dislodging the EC	∣A1B0G1∣ + ∣A1B0P1∣	4	1.4
Cleaning the remained solder with solder wick • Grasp solder wick ∣A1B0G1∣ • Place it on the remaining solder ∣A1B0P1∣ • Grasp soldering iron ∣A1B0G1∣ • Place it on the solder wick ∣A1B0P1∣ • Put solder wick aside ∣A1B0P1∣ • Put solder iron aside ∣A1B0P1∣	∣A1B0G1∣ + ∣A1B0P1∣ + ∣A1B0G1∣ + ∣A1B0P1∣ + ∣A1B0P1∣ + ∣A1B0P1∣	12	4.32

3.3. Tailoring eDiM to Be Suitable for Disassemblability Assessment of EC

The eDiM calculation sheet (Table 2) does not provide a solution for desoldering process, making it unable to generate metrics using the existing database and sequence. Therefore, there is a need to update the eDiM, which was originally designed for mechanical disassembly processes, to include the heat-related desoldering process. To address this issue, the following steps have been taken:

- Identification of the desoldering disassembly steps to update the eDiM table.
- Reconsidering the input data required to calculate the time metric of disassembly steps.

The updated eDiM method for PCBA is presented in Table 5. The first section describes the input data required for the time calculation, while the second section presents a list of disassembly tasks for which the time metric will be calculated. Two assumptions are made in the proposal:

(i) The method excludes pre- and post-disassembly activities such as product handling, bench placement, PCB fixing, and removal of disassembled components from the table. While these activities are important for overall repair efficiency, they are typically outside the scope of PCB design. The purpose of updating eDiM is to propose the nec-

essary additions to enable its implementation in the context of PCB desoldering while maintaining its original framework. This refinement aims to provide standardized metrics that facilitate comparisons between various products and prioritize relative efficiency over absolute disassembly assembly time values.

(ii) The skill level of the operator performing the disassembly is not taken into account. This includes the ability to identify and access targeted components, use tools safely, and manage risks to the product, environment, and operators. Skill levels can vary (with levels including layman, generalist, specialist, expert, manufacturer, or authorized expert) [9], but were deliberately not chosen to maintain overall objectivity in the eDiM and MOST methods and to avoid bias due to operators' subjectivity. The assumption is that operators will have average skills, enabling objective product disassemblability comparisons by following the original approach, aiming for standardized metrics to facilitate comparisons between different products rather than providing absolute disassembly time values.

Table 5. Tailored eDiM for PCBA.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Disassembly sequence of ECs	Disassembly sequence of connectors of ECs	Number of manipulations	Identifiability (0,1)	Mechanical connection type	Packaging type	Number of leads and pins of EC	Tool type	Temperature of desoldering tool	Melting point of the solder	Tool Change (s)	Identifying (s)	Manipulations (s)	Positioning (s)	Desoldering and dislodging (s)	Removing (s)	Cleaning (s)	eDiM (s)

The explanatory points for each column of Table 5 are elaborated as follows:

1. *Disassembly Sequence of ECs:* Considering that this eDiM will be used for repairability assessment purposes, this column refers to the priority sequence for disassembling of frequently failed ECs.
2. *Disassembly Sequence of Connectors of ECs:* Connectors refer to the various mechanical options that can be used to create an assembly between components and subparts. In such a way, a solder joint is considered to be a connector. The disassembly sequence of connectors is important due to potential additional connections. This could involve unfastening screws or disconnecting other elements before initiating the desoldering process. For instance, transistors connected to heat sinks may require preliminary unfastening of screws from the heat sinks.
3. *Number of Product Manipulations:* This column quantifies the operations necessary for EC disassembly. It encompasses actions such as manipulating a PCB gripper to facilitate removal of ECs from the PCB. For instance, for through-hole components, it is necessary to turn the PCB at least once.
4. *Identifiability*: This refers to the ease with which connectors can be identified. This concept is defined in [12], which states that (i) connectors with a visible area greater than 0.05 mm^2 are considered easily identifiable, while (ii) connectors with hidden areas or where only less than 0.05 mm^2 is visible are considered difficult to identify. This is, for example, the case for power device packages with thermal pads soldered on their PCB or Ball Grid Array (BGA) packages.
5. *Mechanical Connection Type:* ECs exhibit various mechanical connections, such as Surface Mount Technology (SMT), Through-Hole Technology (THT), and riveted,

screwed, and socket pedestals [21], as illustrated in Figure 4. Distinct disassembly tools are required for different connections, influencing tool selection (Column 7).

6. *Packaging Type:* Identifying the best disassembly tool for a given EC requires considering the type of packaging it has. Packaging types include dual and multiple through-hole leads, single in-line, dual in-line, small outline, transistor outline, quad flat line, lead chip carrier, ball grid array, gull wing, leadless, J-Lead, etc. (Figure 5) [31]. In some cases, specialized desoldering/disassembly tools may be necessary for certain packaging types. On the other hand, in certain cases, specialized desoldering/disassembly tools may be necessary for certain packaging types, in which case the number of leads would not affect the disassembly time, since the tool permits simultaneous disassembly.
7. *Number of leads and pins of EC:* The number of leads and pins must also be taken into account as it significantly influences the time required for desoldering and dislodging the EC.
8. *Tool Type:* This includes specific desoldering tools (see Figure 6) such as a desoldering iron, desoldering pump, solder wick, soldering iron, hot air guns (especially for SMT), tweezers, solder tweezers, screw drivers, etc. While there are alternative techniques for dismantling ECs, the tools listed here are best suited to targeting individual components. For the reassembly of the ECs, the necessary tools are a soldering iron, solder wire, and solder flux. Solder flux is a chemical substance that is used to clean and prepare the surfaces to be soldered by removing oxides and impurities. After soldering, there will be solder remains on the soldering iron tip and it should be cleaned by brass wool, cleaning paste, etc. Moreover, in order to ensure that the PCB is free from any debris or contamination, it should be cleaned using a chemical, a brush, and pressured air. It is crucial to acknowledge that the desoldering iron may retain heat during the nozzle replacement procedure, necessitating the usage of pliers to change the nozzle. Alternatively, the use of specific heat-resistant gloves may be warranted to facilitate handling during the nozzle replacement, accompanied by the respective actions and time required to don and doff the gloves.
9. *Temperature of desoldering Tool:* Tool temperature affects the duration and quality of the desoldering. For instance, if the temperature is too low, the solder may not melt properly, causing an increase in desoldering time. On the other hand, if the temperature is too high, the heat could damage the surrounding components and PCB, making it less suitable for a successful repair.
10. *Melting point of the solder:* The desoldering iron temperature (9) and melting point of the solder (10) can be used to help estimate the time until the solder reflows. See Table 6 for melting temperatures of different solder alloys to help estimate the desoldering time.

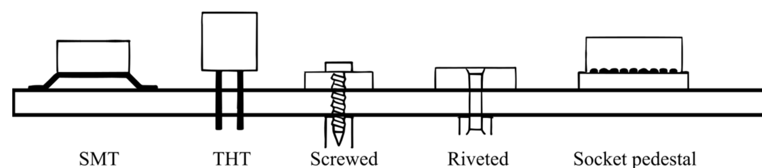


Figure 4. Different connection technologies [21].

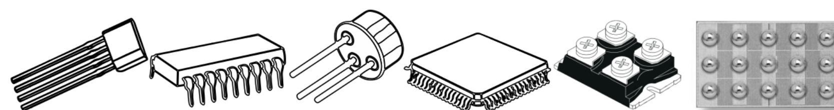


Figure 5. Examples of packaging types [31–33].

Figure 6. Different desoldering tool technologies.

Table 6. Melting temperatures of various solder alloys used in electronics [34].

Solder Type	63Sn/37Pb	42Sn/59Bi5	Sn/10Bi/5Zn	77.2Sn/20In/2.8Ag	99.3Sn/0.7Cu
Melting Temperature (°C)	183	183	138	179–189	227

In the disassembly time calculation section of Table 5, explanatory points for each column are detailed as follows:

11. *Tool change (s) = f* (8)*:* The calculations are based on the changes in tool change time (8), i.e., the time required to change the tools or nozzles of the desoldering soldering iron.
12. *Identifying (s) = f* (4)*:* Determination of the time required to identify the relevant leads or pins of the ECs. Calculations will be based on the availability of identification information (4).
13. *Manipulations (s) = f* (3)*:* This refers to the time required to relocate, adjust, or flip the PCB to facilitate access to and disconnection from the connector. Calculations are performed using the information provided (3).
14. *Positioning (s) = f* (7)*:* This is the time it takes to adjust the position of a tool relative to the solder; for example, to position the desoldering soldering iron precisely on the EC lead and also to position the tweezers on the ECs. This can occur before or simultaneously to the positioning of the desoldering soldering iron, allowing the tweezers to quickly dislodge the ECs as the solder melts.
15. *Desoldering and dislodging (s) = f* (5,6,7,8,9,10)*:* This metric represents the time required for the solder to melt, leading to the disconnection between the ECs and the PCB. The melting point of the solder indicates when the connection is broken. The variables in columns 8, 9, and 10 play an important role in determining the desoldering time. Furthermore, this metric includes the time required to remove ECs from the PCB using tools such as tweezers, hands, or specialized tools. Calculations for this aspect are performed based on the information provided in columns 5, 6, 7.
16. *Removing (s) = f* (1)*:* This indicates the time required to remove the dislodged components and carefully place them in their designated containers.
17. *Cleaning (s) = f* (7)*:* After desoldering, the PCB must be cleaned of any solder and flux residue before another EC is soldered. Any residue left behind can lead to complications in the subsequent soldering process, such as preventing the appropriate fitting of leads of a new component in case solder residues in the through-hole. Using a desoldering iron with a pump is advised to achieve a clean PCB because it cleans through-holes whilst performing the desoldering. Another method is to use an external desoldering pump to extract the molten solder. Moreover, using a solder wick for remaining solder or using a cleaning solution, such as isopropyl alcohol, for any lingering flux, is effective in this cleanup procedure.
18. *eDiM (s):* For eDiM calculation, the values corresponding to (11–17) are summed. After any faulty EC has been removed for repair purposes, a working EC must be assembled to the PCB in its place. These stages are not detailed in this study.

3.4. Strategies for Establishing an Extended Database in Tailored eDiM Implementation

To create a database on EC desoldering, we populated Table 5 with the findings from our case study, which are detailed in Table 7. The aim is to demonstrate our approach for expanding this database, intended to be used by manufacturers, researchers, and product suppliers.

Table 7. Tailored eDiM for PCBA, total eDiM = 326.88 s.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Disassembly Sequence of ECs	Disassembly Sequence of Connectors of ECs	Number of Manipulations	Identifiability (0, 1)	Mechanical Connection Type	Packaging Type	Number of Leads and Pins of EC	Tool Type	Temperature of Desoldering Tool	Melting Point of the Solder	Tool Change (s)	Identifying (s)	Manipulations (s)	Positioning (s)	Desoldering and Dislodging (s)	Removing (s)	Cleaning (s)	eDiM (s)
Electrolytic cap	Electrolytic cap	1	1	TH	Radial	2	Desoldering pump + Tweezers	450	unknown	|A1B0G1| + |A1B0P1|	0	|L3|	|A1B0P3| × 2	40	|A1B0G1| + |A1B0P1|	0	19 × (0.36 s) + (40 s)
Ceramic cap	Ceramic cap	1	1	TH	Radial	2	Desoldering pump + Tweezers	450	unknown	0	0	|L3|	|A1B0P3| × 2	23	|A1B0G1| + |A1B0P1|	0	15 × (0.36 s) + (23 s)
Film cap	Film cap	1	1	TH	Radial	2	Desoldering pump + Tweezers	450	unknown	0	0	|L3|	|A1B0P3| × 2	67	|A1B0G1| + |A1B0P1|	0	15 × (0.36 s) + (67 s)
Mosfet	Mosfet	1	1	TH	TO220	3	Desoldering pump	450	unknown	0	0	|L3|	|A1B0P3| × 3	68	|A1B0G1| + |A1B0P1|	0	19 × (0.36 s) + (68 s)
Diode	Diode	1	1	TH	Axial	2	Desoldering pump + Tweezers	450	unknown	0	0	|L3|	|A1B0P3| × 2	99	|A1B0G1| + |A1B0P1|	0	15 × (0.36 s) + (99 s)

Table 7 lists the EC disassembly sequence (electrolytic capacitor—nine pieces; ceramic capacitor—six pieces; film capacitor—seven pieces; mosfet—four pieces; diode—four pieces). Desoldering and dislodging times (column 15) were calculated as the average of the experimental tests. Each component was only desoldered from the PCB once, without repetitive tests. This decision was taken due to the non-negligible difference between the manufacturer's original soldering characteristics and the new soldering characteristics after the ECs were re-soldered on the same PCB in the laboratory. Table 7 provides a detailed comparison of the desoldering and dislodging times on different ECs and shows the differences influenced by factors such as the packaging type, type of mechanical connection, and number of leads. The detailed breakdown will grant us an improved understanding of the complexities involved. Cleaning (column 17) is marked as 0 because the desoldering tool used allowed molten solder to be absorbed simultaneously during column 15, and therefore cleaning had no impact on the total desoldering time.

4. Discussion and Conclusions

The eDiM method was found to be highly effective at the level of casing disassembly. Figure 3 provides a graphical depiction of the relationships between eDiM results and the disassemblability of casing components. By analyzing Figure 3, stakeholders can gain valuable insights into the disassembly characteristics of each component. This information can be used to identify casing design spots where improvements can be made, ultimately contributing to the overall maintainability and repairability of the product.

On the other hand, the limits of the eDiM method at the desoldering level were identified. The desoldering process is more technical and complex than disassembly with a screwdriver, pliers, or hand motions. Moreover, the temperature of the process significantly affects the desoldering time. The proposed update to eDiM provides a theoretical framework to evaluate the disassemblability of PCB-based PEC. The adapted eDiM method faces challenges in its measurement due to the lack of a standardized benchmark. There is a need for standardized benchmarks and time measurements to estimate disassemblability, including factors such as the properties of ECs, tools, and heat treatments. This underlines the importance of the proposal. In doing so, our approach is in line with the principles of circular and sustainable product management and emphasizes collaboration to improve knowledge and practices related to the disassembly of ECs in PECs. The creation of such a database should be addressed in future efforts.

The eDiM method can also be used to identify hotspots in the PCB-based PEC design that hinder disassembly, and design modifications can be proposed to enhance disassemblability. Theoretically, desoldering and removal time is influenced by factors represented as a function of =f (5,6,7,8,9,10) and the interaction between these factors needs to be investigated. Considering dependencies such as copper trace designs, heat-transfer contact surfaces, the presence of voids in the solder, re-soldering, and pin bending, standardizing the soldering and desoldering time turns out to be a challenging task. However, it is crucial to underline the need for standardized metrics to understand the disassembly of ECs. The methodology is not limited to PCB-based PEC devices alone. It can also be adopted by other PCB-based products in various industries, as the methodology incorporates a standardized approach to evaluate the characteristics of ECs, its connection with PCB, desoldering tools temperature, and desoldering material to provide a metric for EC disassembly.

This study presents preliminary results, but future research should focus on extensive testing to establish a robust database followed by a detailed analysis of correlations between key variables. This will enable a more accurate comparison, including a detailed consideration of integrating modular design factors.

Besides the technical aspects, the key variables identified in this study also provide a foundation for evaluating and comparing the environmental impacts of disassembly procedures, which should be further developed in future research. To this end, an inventory database of the input and output energy and material flows associated with each disassembly step should be constructed. The relationship between these energy and material flows and disassembly variables, such as desoldering temperature, desoldering time, and the use of tools and materials, should be modeled.

One important recommendation emerged from the technical analysis conducted in this research: a call for manufacturers, researchers, and product suppliers to actively participate in the creation of a comprehensive database dedicated to the disassemblability of ECs. The envisaged initiative aims to create a comprehensive repository by adopting a systematic approach similar to the successful development of the MOST database.

In addition, compared to assembly processes, which are mainly carried out in factories, repair processes can take place in different locations: at the user's home, in a repair café, or in a maintenance center managed by an eco-organization. This leads to diversity in operators' skill levels influencing the disassembling time. However, this variable has not yet been addressed in the MOST database. Although the EN45554 standard provides qualifications for different skill levels of operators, their influence on the disassembly time index has not been evaluated. Therefore, further research is needed in this area to better understand how different contextual factors may affect the disassembly time.

Consequently, the proposed methodology provides a theoretical framework to comprehensively evaluate the disassembly potential of electronic systems. Using this methodology can promote eco-design improvements of PCB-based PECs by facilitating disassembly during product development; this could contribute to more effective circularity scenarios and improve the circularity of such products in the short and medium term. The findings may be useful to stakeholders in the PE industry who are working to achieve circularity and sustainability goals when developing new PECs and are aiming to provide a framework for European policies for such products.

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