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Design for circular disassembly: Evaluating the impacts of product end-of-life status on circularity through the parent-action-child model

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ABSTRACT

Design for disassembly approaches are crucial for supporting industrial circular economy transition. However, a significant limitation of current design for disassembly methods is their inability to model the impacts of a product's end-of-life status on the realized disassembly effort and the subsequent effects on the implemented circular design strategies. To address this gap, our work proposes a novel approach termed Design of Circular Disassembly and a corresponding design for disassembly model, called the Parent-Action-Child model, that can describe and model the impacts of a product's end-of-life status on the disassembly process in terms of disassembly effort and circularity index. The approach was tested for modelling the disassembly process of an electrical kettle. Our study highlights that failing to consider end-of-life product status can lead to sub-optimal design for disassembly recommendations from a circularity perspective.

1. Introduction

Over the recent decades, there has been increasing attention on the sustainability and circularity aspects of product development processes (dos Santos et al., 2022; Opferkuch et al., 2022; Saxena et al., 2020). The European Union Circular Economy action plan (Commission and Communication, 2020) stresses the importance of switching from a linear economy to a circular one to boost the economy and protect businesses from potential resource scarcity. Circular economy (CE) is seen as a broad concept that covers a variety of topics and sectors. It encompasses systems from the production to the consumption aspect, focusing on keeping products, components, materials, and energy in circulation for as long as possible to continue adding, sustaining, and generating value (Dias et al., 2022; Jabbour et al., 2019). Because of this broad definition, quantifying product circularity is often challenging (Blomsma and Brennan, 2017). Prior research has proposed several CE indicators that are focused on different levels of scope (e.g., global, regional, industry-level, product-level), and can be used to assess the circularity of products and processes at the design phase (Bracquené et al., 2020; Corona et al., 2019; Ghisellini et al., 2016; Moraga et al., 2019).

The conceptualization and design phase of a product are key elements for enabling the use of the circular economy paradigm in industries (Bocken et al., 2016; Chang et al., 2017). Several techniques can be applied during the product development process to account for product sustainability and circularity (Ramani et al., 2010). Among them, a broad range of Design for 'X' (DfX) methods can be used to help industries consider circularity aspects in their product development processes. DfX methods are a collection of design methods that aim to optimize the product development process towards specific goals. The 'X' is replaced with the identified goal that is to be optimised (e.g., Design for Manufacturing and Assembly - DfMA, Design for Environment - DfE, etc.). Interested readers are directed to a review by Benabdellah et al. (2019) that provides an overview of different DfX methods.

The first family of DfX methods aimed at optimising the manufacturing and assembly aspects of products were termed as Design for Manufacturing and Assembly (DfMA) methods (Formentini et al., 2022a). Design for Disassembly (DfD) and Design for End-of-Life (DfEoL) methods were subsequently developed to specifically address increasing needs for product repair, remanufacturing, and recycling. The main goal of DfD methods is the consideration of the product disassembly process during the product design stage. Initially, the aim was to reduce the cost of reparability; designing easy-to-disassemble products can enable easier repair and reducing product lifetime costs (Chen, 1994; Shetty et al., 2000). However, through the years, as environmental consciousness began to rise, DfD methods became more

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important to support the reuse and recycling of products (Vanegas Pena et al., 2016). A majority of DfD methods focused on non-destructive disassembly, where the main challenge is the representation of the disassembly sequence (De Fazio et al., 2021; Fukushige et al., 2013; Kwak et al., 2009) and the estimation of disassembly time/effort. The main drawback of current DfD methods (reviewed in Section 2.2) is their poor integration with approaches for circular product design. EoL decision-making from a circularity perspective requires considering the EoL status of the product and the impacts this status has on the disassembly process. For example, a failed component (or fastener) can preclude specific EoL fates from a component perspective (e.g., reusing, remanufacturing) as well as the product disassembly perspective. A rusted screw may make it prohibitively expensive to non-destructively disassemble, and therefore reuse specific product components.

Most current DfD approaches assume that a product is in near-perfect condition, meaning components and fasteners function as designed. While this could be a reasonable working assumption for optimising product repair, it can lead to significant discrepancies in evaluating the disassembly effort, when the goal is to improve product circularity. Consequently, most DfD methods aimed at CE optimisation are limited towards identifying efficient "as designed" disassembly pathways for maximising product recovery and product redesign for easier disassembly (Bernstein et al., 2012; Favi et al., 2012).

To address this gap, our work proposes a DfD model, called the Parent-Action-Child (PAC) model, that can describe and model the impacts of a product's EoL status on the disassembly process in terms of two indicators i) disassembly effort index (DEI) and ii) circularity index (CI). The novel contributions from this work, include i) the development of the PAC model, a novel approach to model and visualize product disassembly information based on the parent-child relationships; ii) framing the concept of DfCD which is the need to consider the real product EoL status, as early as possible in the design process, to make products easier to disassemble and improve their circularity; iii) systematically defining the concept of disassembly failures, meaning failures that have a direct impact on the disassembly process, and consequently impact product circularity.

The remainder of this article is organized as follows. Section 2 reviews state-of-the-art literature in circularity, product design, and design for disassembly methods. Section 3 describes the methodology behind the PAC model. Section 4 details the application of the PAC model to a case study analysing the DfD and CE performance of an electrical kettle. Section 5 presents results and discussions from the case study. Section 6 highlights limitations in our current work and Section 7 concludes the article.

2. Literature review

2.1. Circularity and product design

Regulatory changes coupled with material supply risks have added momentum to the idea of CE around the world (Commission and Communication, 2020; The White House, 2021). The term circularity, more generally CE, is a broad definition that collects multiple fields and topics (Blomsma and Brennan, 2017; Kirchherr et al., 2017). The overarching idea behind CE is the ability to switch from a linear economy to a circular one and create resource-efficient systems (De Pascale et al., 2021). With the goal of closing resource, material, and process loops, CE stresses a zero-waste vision. This concept has been applied in a broad range of industries, such as construction (Antwi-Afari et al., 2022; Hossain et al., 2021), automotive (Kayikci et al., 2021), machine tools (Urain et al., 2022), and robotics (Chouinard et al., 2019).

From a product design perspective, Design for CE, also termed as circular product design, aims at creating a cyclical flow of materials based on three principles: i) designing out waste and pollution, ii) keeping products and materials in use, and iii) regenerating natural systems (Ellen MacArthur Foundation, 2020; Wang et al., 2022). These principles translate into designing products to increase their rate of reuse, remanufacturing, and recycling. Due to the broad scope of CE, it is challenging to assess the degree of circularity of product systems. For instance, the definition provided by the Ellen MacArthur Foundation states that CE is *"an industrial system"* (MacArthur, 2013), while Yuan et al. (2006) states that CE is a "*system of human activities*" moving the focus from industrial systems to human activities. To this end, prior work has defined a broad range of CE indicators, including at the product-level, to measure circularity performance. Examples of CE indicators, include *recycling rate* (Graedel et al., 2011), *reusability/recyclability/recoverability (RRR)* (Ardente and Mathieux, 2014), *energy intensity (EI)* (Lokesh et al., 2020), and *recycled content (RC)* (Graedel et al., 2011). Among such indicators, the *material circularity indicator (MCI)* proposed by the Ellen MacArthur Foundation (MacArthur, 2013) is the widely used across industries and academia (Kirchherr et al., 2017). MCI studies the flow of products and provides a score ranging from 0 to 1 that indicates the circularity of the analysed system (Boix Rodríguez et al., 2021). A score of 0 represents a fully linear system while a score of 1 is a fully circular one. Even though it is widely accepted, the MCI presents some drawbacks. In particular, the MCI does not consider aspects such as product modularity, upgradability, reparability, and ease of disassembly (Saidani et al., 2017).

Although there is a growing body of research on design techniques and tools to transition from a linear economy to a CE, researchers suggest CE indicators are still in the early stages of development (Giurco et al., 2014; Kirchherr et al., 2017; Moraga et al., 2019). Most indicators focus on circularity from the perspective of material flow, while a limit number of indicators consider product characteristics like functionality or the complexity of the product architecture e.g., reconfiguration index, potential reuse index (André et al., 2019; Mesa et al., 2018). These factors are viewed as essential for enabling CE evaluation at the product design level (Mesa et al., 2018). Typically, CE indicators (De Pascale et al., 2021) do not directly consider the products disassembly complexity, therefore it is not possible to provide information upstream the design process on how to increase and improve the material or component recovery.

The product design process can be broadly divided into three phases: i) conceptual design, ii) embodiment design, and iii) detail design (Tomiyama et al., 2009). During the conceptual design phase, designers have greater freedom to make design changes, but the availability of lifecycle information to make such changes is often scarce and of low fidelity (Formentini et al., 2022a). Regarding circular product design, two formal design methodologies may be distinguished: i) design to extend product life (i.e., slowing material loops) and ii) design to provide a circular flow of material (i.e., closing material loops) (Bocken et al., 2016; Mesa et al., 2018). The former is seen as the antithesis of planned obsolescence as the objective is to extend useable life as much as possible, whilst the latter concentrates on the avoidance of waste build-up and emissions to the environment. DfD techniques can be applied at the embodiment and detailed design stages to facilitate both slowing and closing material loops.

2.2. Design for disassembly methods and tools

The disassembly of a product can be performed in three ways: i) non-destructive disassembly, ii) destructive disassembly, and iii) semi-destructive disassembly (Zahedi et al., 2016). The first type is a reversible operation, and it is used when the product must be reused or repaired. In this case, the aim is to optimize the disassembly time, and performing actions that will not damage the product. Destructive and semi-destructive disassembly, on the other hand, are irreversible operations that could lead to alternate EoL scenarios (O'Shea et al., 1999). For instance, when a part must be refurbished a semi-destructive disassembly approach can be used, while in cases where the part is recycled or disposed, a destructive approach can be preferred (Sodhi et al., 2004; Umeda et al., 2015).

The main goal of DfD methodologies is to consider the disassembly performance of products from the beginning of the design process. DfD is considered a key aspect to enable the CE paradigm in products (Bocken et al., 2016; Mesa et al., 2018). The literature in this field is particularly broad, including several topics such as the formalization of disassembly knowledge (Favi et al., 2017; Marconi et al., 2019), and the estimation of disassembly effort and time (Boks et al., 1996; Sodhi et al., 2004; Vanegas et al., 2018).

2.2.1. Formalization of disassembly knowledge

The process of disassembly is very different from the assembly process (Kroll and Hanft, 1998). As a result, it is necessary to express and formalize disassembly knowledge. The formalization of disassembly knowledge requires the transformation of implicit knowledge into explicit knowledge that can be used to perform disassembly analysis in a scientific manner. Formal disassembly knowledge is widely used in literature to reach different goals, such as Design for Remanufacturing (Shu and Flowers, 1999; Topcu and Cullinane, 2005; Yao et al., 2014); Design for Environment and Design for Recyclability (Chen, 1994; Kim et al., 2016; Telenko et al., 2009); Design for Reparability (De Fazio et al., 2021; Shu and Flowers, 1998). To this end, a growing body of research focuses on creating models and tools to collect and use formal disassembly knowledge (Formentini et al., 2022b; He et al., 2020).

The formalization of product disassembly knowledge started with disassembly diagrams (Bourjault, 1984). Subsequently, De Fazio and Whitney (1987) introduced the concept of *liaisons* to represent product structure and architecture. Liaisons represent relationships between components of a product using a network diagram. Usually, liaisons are identified with lines connecting the network nodes. Connections among components are identified through logical (Yes/No) questions. However, the proposed structure is limited since it does not allow the representation of alternative disassembly sequences (Kwak et al., 2009). A further improvement in the representation of product structure has been proposed by De Mello and Sanderson (1990) with the AND/OR graph for representing assembly sequence. The main advantage is the possibility to consider parallel and alternative disassembly sequences within the same graph (De Fazio et al., 2021).

More recently, Fukushige et al. (2013) introduced the concept of disassembly time in a disassembly sequence graph, allowing rapid identification of bottlenecks. Building on this work, De Fazio et al. (2021) proposed the formalization of disassembly knowledge using graph structures. They created a graph, called *disassembly map*, which allows rapid analysis of assembly and disassembly properties of products architectures using standard colours and icons. While the disassembly map can be used to estimate product assembly and disassembly performance, it is rooted in the assumption that the analysed product is perfect (as designed).

2.2.2. Estimation of disassembly time

The assessment of the disassembly time is a key focus when optimising product disassembly performance in early design. Disassembly time depends on product EoL status. For example, a rusted or worn-out fastener will require additional (or different) disassembly actions, when compared to that in a near-perfect (as designed) condition.

One of the main challenges while designing a product for easy disassembly is the accurate estimation of the disassembly time. Disassembly time can be determined in two ways: i) through direct measurement, and ii) by studying the product features (Vanegas et al., 2018). The former is the most intuitive way and provides the most accurate time evaluation. However, it is strictly related to the (exact) product under study, and requires extensive effort to obtain the data, making it difficult to extend the method to other products. The latter approach involves creating models that, through the consideration of different product features, allow computing the desired disassembly time (Zandin, 2002). DfD methods which estimate disassembly time using feature-based approaches provide less accurate results compared to direct measurements (Vanegas et al., 2018). However, they allow extending DfD methods to several products, with the possibility of assessing disassembly stage behaviour before the physical production of a product.

In literature, several methods have been developed to estimate disassembly time starting from product features, extracted from CAD models and Bill of Materials (Hu et al., 2015; Kroll and Hanft, 1998; Mandolini et al., 2018). For instance, the U-effort method (Sodhi et al., 2004) estimates the disassembly time by considering the time used to disassemble each connector in the product. Connectors are rated according to the unfastening effort index (UFI) which is obtained considering different connector properties. Philips ECC (Boks et al., 1996) created an empirical database where disassembly times for commonly used connectors were collected. By inputting disassembly sequence and connector types, the authors state that it was possible to assess disassembly for different types of products, with limited errors. Other methods available to estimate disassembly time are based on time and motion (Vanegas et al., 2018). The Maynard operation sequence technique (MOST) is a well-known method to model actions according to basic operations (Zandin, 2002). The MOST technique is based on the identification of three basic motion sequences: *general move*, *controlled move*, and *tool use*. Then, a time coefficient is identified for each sequence and translated into a time value, expressed in seconds. For instance, Kroll (1996) used the MOST approach to measure disassembly times of electrical equipment while observing worker movements. The main drawback of prior works that apply the MOST technique to DfD is the assumption that disassembly is performed under ideal conditions (i.e., perfect product conditions). This assumption usually does not hold when operators need to disassemble products collected at their EoL; most products are discarded due to the presence of physical or functional faults, and such faults can impact the real-world disassembly time. As the magnitude of such impacts is a function of the product EoL status, improving current DfD methods requires the ability to model different failures that can occur at a product's EoL.

3. Methodology

In this work, we define a new DfX approach termed as Design for Circular Disassembly (DfCD) for considering the impacts of product EoL status on disassembly actions, and consequently the circularity potential of that product. We define DfCD as *"the process of (re)designing products and their components for easier partial/full disassembly at their end-of-life, with the goal of improving or preserving their circular economy potential"*. Thus, DfCD consists of assessing the circularity of a product with respect to the effort to achieve a given EoL scenario. DfCD differs from traditional DfD approaches in two aspects. First, most current DfD approaches do not account for EoL product status during the estimation of disassembly effort. Second, by integrating knowledge on product CE performance into DfD, DfCD represents a novel formalization of disassembly knowledge and enables simultaneous treatment of disassembly and circularity. It is also worth noting that metrics based on disassembly cost and time have been used in prior literature to measure CE performance (De Pascale et al., 2021). The underlying assumption in these approaches is that reducing disassembly effort improves product CE performance. Our definition of DfCD goes beyond such works due to the following. First, our definition of DfCD quantifies the importance of disassembly effort on the overall CE performance, based on the achievable EoL scenarios for a product/component. For example, reducing disassembly effort may not be a priority for products with easily separable material streams if recycling is the only achievable EoL scenario. Second, DfCD inherently considers the impact of imperfect product EoL status on CE performance. As show in the case study, applying DfD can, in certain cases, lead to sub-optimal redesign decision-making for CE, which is avoided by applying DfCD. Our proposed approach for DfCD relies on three assumptions: i) the disassembly sequence of the product is well-defined, ii) product disassembly is

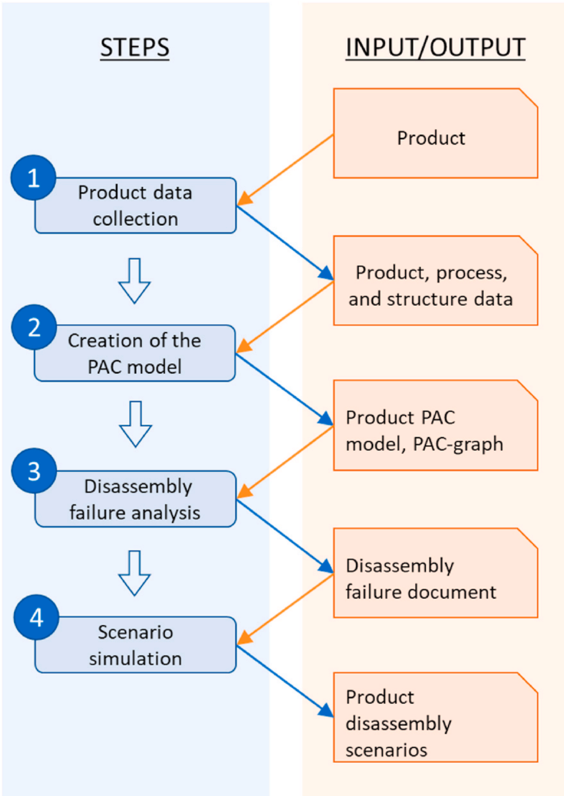


Fig. 1. DfCD method overview. 1 – Product data collection, 2 – Creation of the PAC model, 3 – Disassembly failure analysis, 4 – Scenario simulation.

performed by an experienced operator, i.e., the disassembly times can be reliably estimated from the operators' actions, and iii) the circularity potential of a product/component is quantified using a finite set of CE indicators from the available product lifecycle data. The aim of the proposed DfCD approach is to help designers obtain insights into the product structure, and to identify the potential EoL scenarios that can be achieved, with the goal of enhancing/retaining product circularity performance. The DfCD approach is based on the representation of the disassembly activities through a new model termed as the Parent-Action-Child (PAC) model. The PAC model allows considering the product EoL during the early design phase, including the effect that disassembly actions have on the product structure, and the real product EoL status. Moreover, the PAC model enables the study of different disassembly scenarios to identify desirable disassembly solutions to recover products or components with the highest EoL value from a circularity perspective.

In the following paragraphs, a detailed description of each step of the DfCD approach is presented. The DfCD method consists of four steps, as presented in Fig. 1. For each step, the task and dedicated tools used to perform the analysis are presented.

3.1. Product data collection

The first step of the proposed approach is product data collection. Relevant data can be obtained from computer-aided-design (CAD) files, or by analysing the real product if available (e.g., in the case of product redesign).

Three types of data are required to use the proposed DfCD method.

i) *Product data:*It describes information related to the product itself (Fig. 2-a). It includes information such as weight of components, part geometry, and material specifications.
ii) *Disassembly data:* It represents the data required to analyse the product disassembly process, and can be divided into two subsets:
a. *Process data:*It collects information regarding the disassembly process (Fig. 2-b). For instance, the disassembly steps and the required disassembly tools.
b. *Structure data:*It describes the structure of the product (Fig. 2-c). Information such as relation between parts, and the way in which they physically interact.

3.2. Creation of the parent-action-child model

Product disassembly is a complex process that involves several factors and actions. Disassembly can be manual, semi-automatic, or fully automatic. However, to improve the design of the product, especially in the early design phase, it is necessary to have a robust disassembly model which can consider different disassembly scenarios. Before proceeding with a description of the Parent-Action-Child (PAC) model, we introduce relevant terminology.

- *Assembly/Sub-Assembly*: It represents a group of parts that are physically interfaced using mechanical connections, i.e., adhesives, bolts, screws, etc. It can be disassembled into smaller sub-assemblies and/or parts.
- *Part*: It represents the elementary item of an assembly. A part cannot be disassembled further due to physical constraints or design choices. For instance, a screw is considered a part that cannot be further disassembled due to physical constraints, while a sub-assembly can be transformed to a part if it is not desired to disassemble it further.

The PAC model consists of three main elements.

- *Parent*: A parent is the target of the disassembly analysis. The parent is an assembly or sub-assembly which is desired to be disassembled further to generate sub-assemblies and/or part(s).
- *Action:* An action is a physical act that changes the status of the parent, transforming it into children. Thus, an action is a unit disassembly step, or collections thereof, that separate an assembly into sub-assemblies and/or parts. Actions can only be applied to parents.
- *Child:* A child results from an action performed on a parent. Children represents the output of a disassembly process.

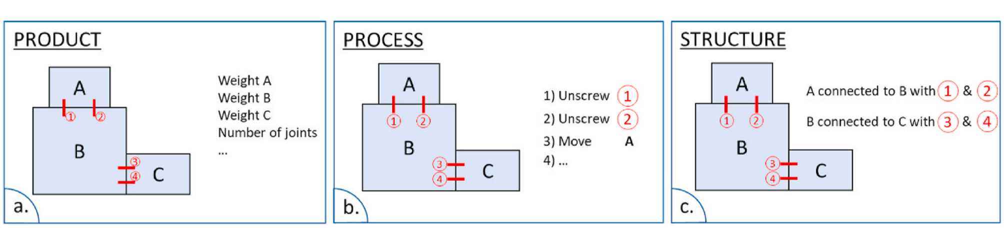


Fig. 2. Type of data to be specified: a) Product data describing information about parts; b) Process data describing the disassembly process and tools; c) Structure data describing relation among parts of a product.

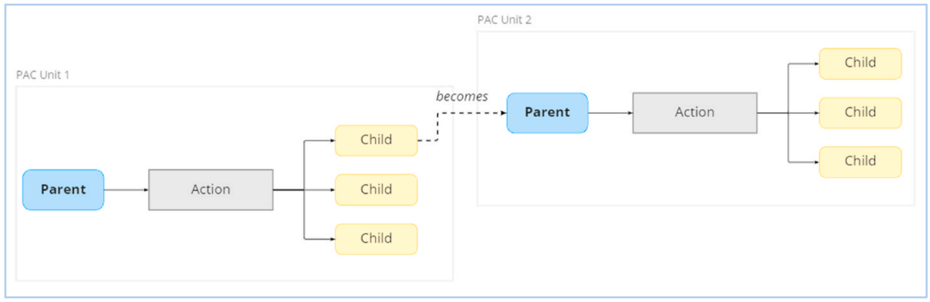


Fig. 3. Graphical template for the Parent-Action-Child (PAC) model. A set of one parent, one action and one or more children represents a PAC unit.

To create the PAC model, it is necessary to follow specific rules to define the interactions among PAC elements.

- A parent can only be subjected to one action.
- A parent subjected to an action can generate one or more children.
- A set of "Parent-Action-Child" elements create a *PAC Unit*, and represents a complete disassembly cell, in terms of disassembly action and items.
- Within a PAC Unit, children represent the final outcome. They cannot be subjected to any further disassembly action.
- When it is desired to further disassemble a child, the select child needs to be transformed into a parent and initiate a new PAC unit.
- The transformation of child into a parent is performed by expressing the will to further disassembly the selected child.

The PAC model (see Fig. 3) can be used to model product disassembly, considering both the disassembly process and the product architecture. Moreover, it enables the study of other aspects such as product circularity. From our literature analysis (Section 2.2), it emerged that disassembly time is commonly used as a proxy for measuring the ease/effort of disassembly processes. Thus, the PAC model enables the assessment of disassembly time by linking it to disassembly actions. Our literature review on circularity and product design (Section 2.1) also highlights that improving product circularity, requires its consideration during the early design phase. Thus, the PAC model enables the assessment of product circularity in early design by linking CE indicators to children. This is performed by using the available information for each child (e.g., weight, material type) and potential EoL scenarios (i.e., recycling, disposal, etc.). The PAC model does not specify the use of specific CE indicators for circularity measurement as their use can depend on contextual factors. The desired CE indicator can be selected based on two main factors: i) the goal of the CE indicator, and ii) availability of information to compute the selected CE indicator. Depending on the focus of the analysis, one or more CE indicators can be selected. CE indicators defined in prior work (De Pascale et al., 2021) can be selected for use with the PAC model to assess product circularity. Moreover, the model does not distinguish between components and mechanical fasteners (e.g., a screw can be a child, as well as a sub-assembly which is not further subjected to disassembly actions). Finally, it is important to notice that the output of disassembling permanent (irreversible) joints is only the components that have been joined together as the joining agent (e.g., adhesive) cannot be typically recovered in a reusable form.

The outcome of the Step 2 (creation of PAC model; Fig. 1) is a document in which each component of the product and each disassembly action is described and represented according to the PAC model. From the obtained document, it is possible to create the PAC-graph, as shown in Fig. 3.

The PAC-graph represents *parents*, *actions*, and *children* according to the following colour and shape code (also see Fig. 3).

- Rounded and squared boxes:
  - o Blue rounded boxes are used to represent parents
  - o Grey squared boxes are used to represent actions
  - o Yellow rounded boxes are used to represent children
- Solid arrows and dotted arrows:
  - o Solid lines are used to connect parents to actions, and actions to children. The arrow starting from the parent always points from the parent to the action. The arrow starting from the action always points to one or more children.
  - o Dotted arrows are used to represent the change of a child into a parent. Thus, it encodes the choice of further disassembling a child. In the PAC model, this can be done by updating the child into a parent (i.e., *becomes*). The dotted arrow always points from the selected child to the generated parent. The output of the dotted arrow is the same element, that can be disassembled further.

The final PAC-graph will be composed of multiple PAC units, according to the number of disassembly actions desired to perform on the analysed product.

Finally, through the PAC model, it is possible to model the disassembly of products considering both products in perfect and actual EoL status. Herein, perfect EoL status refers to products which have no failures from a disassembly point of view (e.g., no rusted screws), or from a functional point of view (i.e., no worn-out parts). Functional failures also cover aesthetic imperfections (i.e., surface scratches due to shipping). On the other hand, real EoL status refers to products that might present failures from both disassembly and functionality point of view. As discussed earlier, real EoL status is important to consider as it is reasonable to expect that products are discarded due to failures, and such failures can affect disassembly actions as well as circularity potential (e.g., a cracked aluminium panel may need to be recycled as opposed to its reuse or refurbishment). To model the disassembly of products considering their real conditions is necessary to couple the PAC model with a disassembly failure analysis (see Sec. 3.3).

3.3. Disassembly failure analysis

To model the disassembly of products at their EoL, it is necessary to study their real EoL status. Excluding redesign scenarios for products that have been in the market for long periods, information regarding the product EoL status is not readily available during the design phase. Disassembly Failure (DF) analysis is used as a means to overcome this information problem. DF analysis consists of extrapolating the potential failures of the product at its EoL which could lead to a change in the product circularity and/or disassembly actions. In the proposed DfCD approach, three types of DFs are defined.

- *Type I DFs:*They represent DFs that alter product EoL status. Such DFs can be identified by likely failures during product use. For instance, a rusted or a loose screw (that eventually goes missing) are Type I failures. Type I failure are always related to the children in the PAC model.

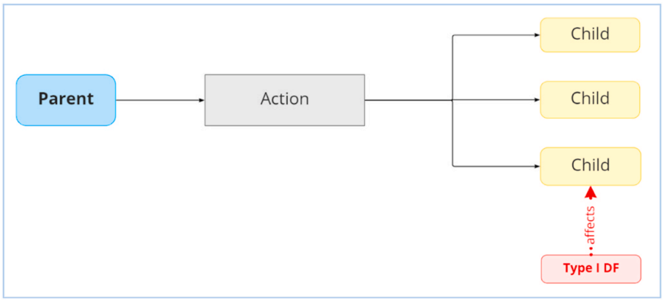


Fig. 4. Type I DF where only one child is affected.

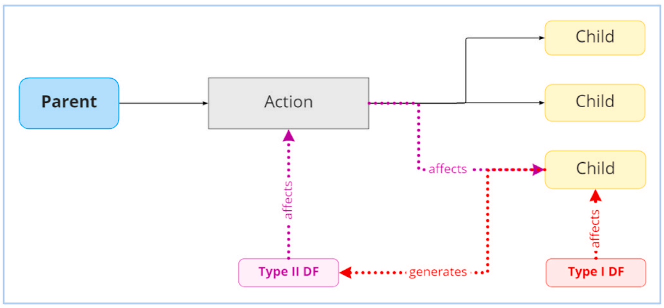


Fig. 5. Type I DF where only one child and preceding action are affected. Please note that as the preceding action is affected, this scenario also generates a Type II failure.

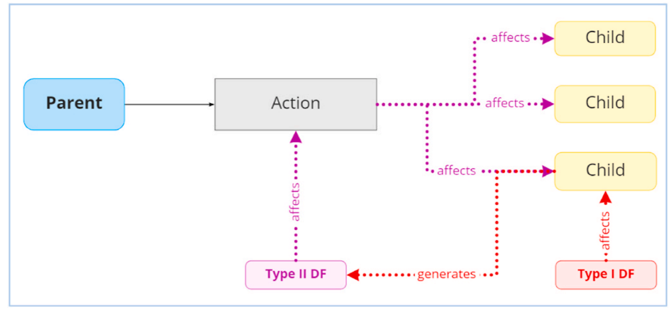


Fig. 6. Type I DF where a child, action, and other children are affected. Please note that as the preceding action is affected, this scenario also generates a Type II failure.

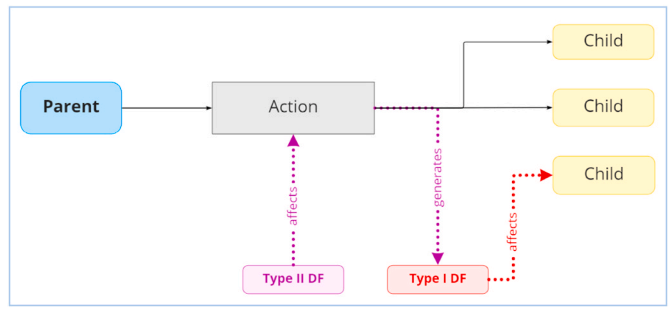


Fig. 7. Type II DF that affects an action and one child.

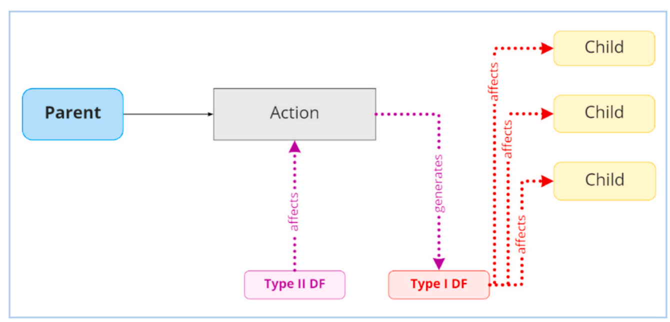


Fig. 8. Type II DF where more than one child affected.

- *Type II DFs:* They represent DFs obtained during the disassembly action. Thus, they are related to disassembly actions that further damage the children. For example, performing a destructive disassembly on a given parent (i.e., sub-assembly) might damage certain children. Type II DFs are therefore linked to actions in the PAC model.
- *Type III DFs:*They represent DFs that affect the parent, which means an action and one or more children are affected at the same time. For instance, if two plastic parts are fused together due to improper high temperature use of a product, the parent from which these two parts originate is considered to be damaged, and the original (planned) disassembly action is affected. Type III DFs are therefore linked to parents in the PAC model.

DF analyses can be performed with the help of product experts, through brainstorming sessions, and if documentation is available, through the analysis of previous product failures. Finally, understanding the resulting scenarios due to a DF is crucial, as it affects the overall disassembly process. The following scenarios can result from the identified types of DFs:

Type I DFs can generate three different scenarios.

One child is affected (OCA): It represents the simplest scenario where a Type I DF only affects (changes the EoL status of) one child, while not affecting any other children (see Fig. 4). This is the typical case for disassembly failures which assume non-functionality of specific parts. For instance, functional failure of a component (e.g., a short-circuited chip) generates this scenario. In other words, the only child affected by the DF is the short-circuited chip. Therefore, this scenario does not affect the preceding disassembly action, parent, or other children (in the same PAC unit).

One child and preceding action are affected (OCPAA): This scenario considers the situation in which a Type I DF affecting a child also generates a change in the action required to perform the disassembly (Fig. 5). For example, if the Type I DF involves a rusted screw, the action required to disassemble the rusted screw is different from the standard action. Thus, this type of scenario generates a corresponding Type II failure.

A child, action, and multiple children affected (CAMCA): The last scenario is the most complex, and is generated when a Type I DF that affects a child generates a change in both, the disassembly action, as well as multiple children in the same PAC unit (see Fig. 6). Such scenarios are typical in cases where a disassembly failure necessitates a destructive disassembly action; this leads to an altered action (Type II DF) as well as the destruction or damage of other children of the same *parent*.

Type II DFs can generate two scenarios.

Only one child affected (OCA): The Type II DF impacting the disassembly action affects one child (Fig. 7), generating a Type I DF. Such scenarios may occur due to a technical problem with the disassembly tool. For instance, if a robotic arm applies excessive torque while disassembling a flat-head screw, and consequently damages it.

More than one child affected (MCA): The Type II DF affecting a disassembly action also affects more than one child following the *action* (Fig. 8), generating a Type I DF. This scenario may occur due to improper machine settings and/or technical problems. For example, if a fully functional screw which is disassembled by an automatic disassembly tool is recognized as rusted, a destructive process could be

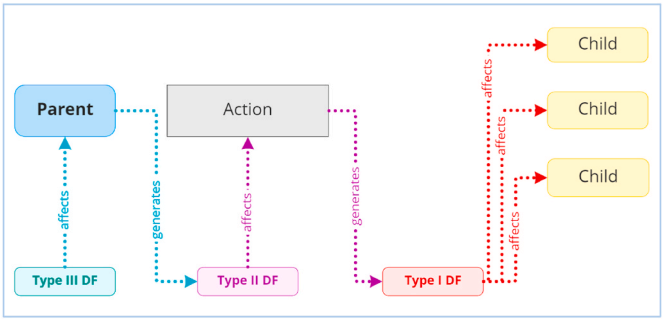


Fig. 9. Type III DF where due to a failure of the parent, Type II and Type I failures are generated (i.e., action, and children are affected).

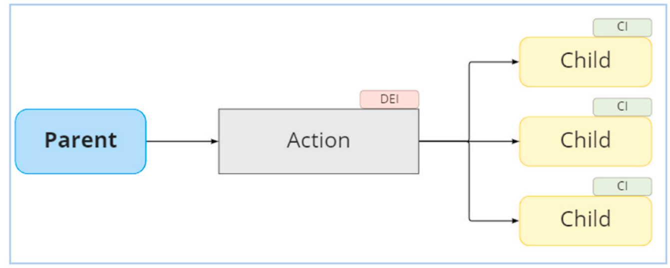


Fig. 10. PAC graph visualizing DEI and CI: DEI is linked with actions and is presented in red. CI is linked to a child and is represented in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Disassembly Failure (DF) analysis document parameters.

Parameter	Description	Type
DF Type	It represents the DF type. It can be Type I, II, or III.	Categorical (Type I, Type II, Type III)
DF Scenario	It represents the DF scenario, associated with the disassembly type.	Categorical (CAMCA, MCA, OCA, OCPAA, PACA)
DF ID	It represents a unique identifier of the DF.	Alphanumeric ID
DF Description	It describes the ways in which the children can fail once the product is recovered at its end of life.	Text
Parent ID	It represents a unique identifier of the parent that is affected by the DF. Applicable only to Type III failures.	Alphanumeric ID
Action ID	It represents a unique identifier of the action that is affected by the DF. Applicable only to Type II failures.	Alphanumeric ID
Child ID	It represents a unique identifier of the child that is affected by the DF. Applicable only to Type I failures.	Alphanumeric ID
Affected Action ID	It represents a unique identifier of the action that has been affected by either a Type I, Type II or Type III DF.	Alphanumeric ID
Disassembly Action Failure	Modification of the action due to a DF. It explains the effect of the DF on the action (i.e., the disassembly process).	Text
Disassembly Action Type	It describes the disassembly type that must be performed due to the DF. It can be: i) destructive (DT), ii) semi-destructive (SDT), iii) no destructive (NDT).	Categorical (DT, SDT, NDT)
Disassembly Action Tool	It describes the tools that need to be used in order to perform the disassembly action.	Text
Affected Child (ren) ID	It represents the ID of the child (ren) that is affected by the DF.	Alphanumeric ID
Effect of failure on Children	It explains the effect of the DF on the children (i.e., parts obtained after disassembly occurred).	Text
Children EoL due to Failure	It represents the modified EoL of the children due to the DF.	Categorical (Reuse, Recycled, Disposal to landfill/incineration)

applied, with consequences on several parts.

Type III DFs only generate one scenario:

Parent, action, and children affected (PACA): The DF affects the parent which leads to a different disassembly action and affects two or more children (Fig. 9), generating a Type II DF and Type I DF. This scenario may occur due to unexpected product usage or technical problems. For instance, if the parent presents some parts that have been fused together due to improper use or maintenance, the disassembly action can change to a destructive disassembly process (e.g., shredding) that affects all children.

Please note that DFs are applied at PAC Unit level. Moreover, DFs might propagate downstream, according to the failure. For instance, if a child affected by a Type I DF becomes a parent, this parent will present a Type III failure, since the action required to further disassemble it might change.

The final output of the DF analysis is a document containing all information regarding the identified failure. The structure of the document is presented in Table 1.

3.4. Scenario simulation

Once the DF analysis is completed, it is possible to proceed with the fourth step. The scenario simulation consists of computing indices to assess the product performances respect to each identified disassembly failure. Each disassembly failure generates one scenario with associated indices. In the proposed DfCD approach, two indices are considered.

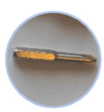
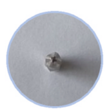
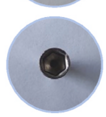
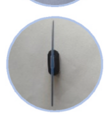
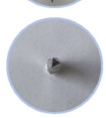
1) *Disassembly Effort Index (DEI):* The DEI represents the effort required to disassemble a component. In the PAC model, the DEI is linked to actions and is measured in seconds. Thus, it represents the time taken for completing an action in a PAC unit, or in other words, the time to disassemble a parent in a PAC unit via a corresponding action. DEI can be computed in several ways, such as from direct experimental measurements, or using methods available from prior literature (e.g., MOST technique).
2) *Circularity Index (CI):* The CI represents the circularity performance of the analysed component. In the PAC model, the CI is linked to children. This is because the end-of-life fate of materials in a PAC unit is based on the generated children. Different CE indicators available from prior literature (Haupt et al., 2017) can be used to measure CI. The selection of specific CE indicators depends on the goals of the analysis and the product data available (e.g., mass percentage of virgin materials in a component, component realized lifetime, etc.).

Each scenario has ‘*X*’ CI indices and ‘*Y*’ DEI indices, where *X* is the number of children, and *Y* is the number of actions. Finally, two general product indices: i) total DEI, and ii) total CI can be computed. The total DEI is obtained by summing up the DEI indices for each action, while the total CI is obtained from averaging the CI of across the children. The number of resulting scenarios depends on the number of identified DFs. It is possible to generate $2^n + 1$ scenario, where n is the number of Disassembly Failures identified and the extra scenario is the benchmark one (i.e., product without any disassembly failure), which is the scenario without DFs (i.e., ideal condition) which is used for comparing results of other scenarios.

The output of fourth step is a document in which computed scenarios

Fig. 11. Kettle Model Number 9001020146 produced by EPIQ (source www.foetex.dk).

Table 2
Tools required for disassembling the electric kettle analysed in the case study.

Tool	Actions	Picture – Lateral view	Picture – Front view
Hand	Separate/ Disconnect	*N/A*	*N/A*
Crosshead Screwdriver	Unscrew		
Socket Wrench	Unscrew		
Plastic Plectrum	Separate		
Tri-Wing Screwdriver	Unscrew		

are presented with their associated indices. It is possible to directly visualize this information on the PAC-graph as shown in Fig. 10.

4. Case study

The proposed DfCD method was used to analyse an electric kettle (EPIQ - Model No. 9001020146) shown in Fig. 11. The goal of the chosen case study was to identify the worse EoL scenarios for the electrical kettle with respect to DEI and CI.

As stated in the methodology, the case study assumes that the preferred disassembly sequence is provided by the manufacturer and is available to the person performing the DfCD analysis. Moreover, the disassembly process was assumed to be performed manually.

4.1. Product data collection

An existing (physical) electrical kettle was chosen to obtain the necessary product information for the case study. The tools used to disassemble the kettle are presented in Table 2. Each part was labelled to

Parent ID	Parent	Action ID	Action	Action Description	Action times	Tool	Child ID	Child	Child number
It provides a unique identifier for each parent.	*It describes the assembly from which the element is obtained.*	*It provides a unique identifier for each action.*	*It describes the action that needs to be performed.*	*It provides a detailed explanation of the disassembly action that needs to be performed.*	*It provides the number of times the action must be performed. It is applicable only for screws and/or repeated processes.*	*It describes the tool required to perform the action.*	*It provides a unique identifier for each part.*	*It describes the elements that are obtained as output of the action.*	*It describes the number of the child obtained from the disassembly action.*
0	Kettle	S1	Separate	Separate the kettle from the base	1	Hand	-	Kettle Base	1
							-	Kettle Body	1
1	Kettle Body	U1	Unscrew	Unscrew the 4 screws at the base of Kettle Base	4	Cross-Head Screwdriver	H	Crox-Head Screws	3
							I	Plastic cover kettle base	1
							-	Kettle Body w/o Base	1
2	Kettle Body w/o Base	D1	Disconnect	Disconnect the 4 electrical connectors from the Kettle Body	4	Hand	L	Metal ring kettle base	1
							-	Kettle Body w/o Metal Ring	1
3	Kettle Body w/o Metal Ring	UR1	Unscrew & Remove	Unscrew the 2 screws connecting the heating element to the kettle body and move the electronic component apart.	2	Cross-Head Screwdriver	M	Crox-Head Screws electronic connection to heater	2
							N	Rings for screws electronic connection to heater	2
							O	Electronic component	1
							-	Kettle Body w/o Electronic Component Ring	1

Fig. 12. Extract of the Kettle PAC model. Left columns (blue-light blue) describe information about parents. Middle columns (grey-white) describe information about actions. Right columns (orange-yellow) describe information about children. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

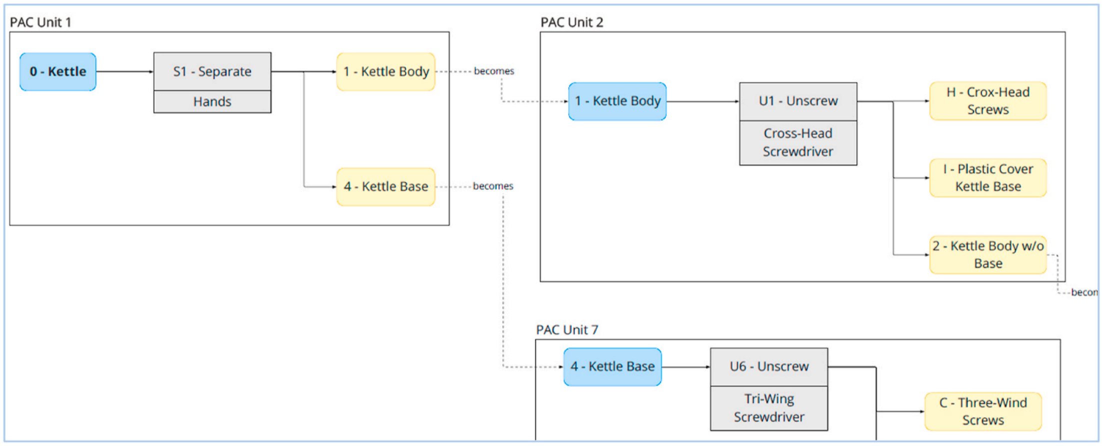


Fig. 13. Extract of the PAC-graph for the electric kettle. Blue, grey, and yellow boxes present information about a parent, an action, and children respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

make it easy to recognize during the analysis.

The kettle was completely disassembled, and the dismantling process was recorded in a spreadsheet to construct the PAC model.

4.2. Creation of the PAC model

After the product data were collected, the PAC model was created. The model consisted of 14 parents, 28 children, 14 actions, and 14 PAC units. An extract of the obtained PAC model is presented in Fig. 12. Interested readers can refer to Annex I for a detailed presentation of the PAC model.

To make the model easy to visualize the corresponding PAC-graph was created. In the graph, basic information such as parents, parent IDs, actions, action IDs, children, and children IDs are presented. Finally, the tools used to perform various actions are presented below each action block. An extract of the obtained PAC-graph is presented in Fig. 13.

4.3. Disassembly failure analysis

The DF analysis was performed on each child to identify Type I, II, & III DFs for the electric kettle. To identify these DFs three meetings were organized with 3 Ph.D. students with experience in sustainable and circular product design. All meetings were performed physically. The first meeting was used to introduce the overall method and present the PAC model together with the methods for DF analysis. The second meeting consisted of a 1-h brainstorming session, where the analysed product (i.e., electrical kettle) was presented. The PAC model and the PAC-graph (see Figs. 12 and 13) was also provided to the participants. Based on these data, each participant was asked to individually identify potential DFs for the electric kettle. After the second meeting, participants' results were collected by the authors and repeated DFs were deleted. Finally, in the third meeting the obtained results were presented to participants, and the list of DFs were refined based on their feedback. An extract of the output from this process is presented in Fig. 14. Due to space limitations, detailed results are available in Annex I.

4.4. Scenario simulation

As stated in the methodology, the DEI was quantified in terms of disassembly time. A benchmark disassembly time for the electric kettle was estimated using the MOST technique (Kroll and Carver, 1999), assuming the kettle to be in perfect EoL condition, i.e., presence of no failures. Thereafter, the MOST technique was used to assess the disassembly time for the identified DF scenarios. The MOST approach was chosen because it is straightforward, accurate, and may be used for manual tasks that are not clearly specified (Kroll, 1996). Actions required to be performed when DFs are present were validated using interviews with an industry expert in the recycling sector. The interview lasted 1-h and was conducted as an online meeting. After a short introduction of the DF analysis, the DF spreadsheet was presented and each DF was analysed in detailed to review: i) the proposed modification to the disassembly action due to the presence of the DF, and ii) the proposed EoL for children affected by the DF.

CI was quantified using a combination of two CE indicators, the recycling rate (RR) and the reuse rate (RE) as defined by Haupt et al. (2017). RR is defined as the ratio $M_{rec}/M_{coll.eol}$ where M_{rec} represents material that is recycled at a product's EoL and $M_{coll.\ eol}$ represents the total product mass that enters the EoL phase. RE is defined as the ratio $M_{res}/M_{coll.eol}$ where M_{res} is the mass of reusable product mass at the product's EoL. RR and RE were chosen to demonstrate the DfCD method since their computation required easy-to-assess parameters when compared to other prevalent resource-based CE indicators assessing material circularity. As discussed in the methodology, practitioners can choose other CE indicators based on contextual factors such as available product information and computational complexity. RE and RR take on the values given in Table 3, as per the specified EoL scenarios. CI is defined as the maximum of RE and RR values and encodes the maximum fraction of material that can be retained in the technical loop once the product reaches its EoL.

As per the proposed methodology, DEI was computed for each action, while the CI was computed for each child. Finally, the total DEI (Eq. (1)) was computed by summing up all DEI indices for all actions, and the total CI (Eq. (2)) was computed by summing all children CIs and dividing it for total number of children.

Eq. (1): Formula for computing total DEI

$$Total\ DEI = \sum_{i=1}^{\#actions} DEI_i \tag{1}$$

Eq. (2): Formula for computing total CI

$$Total\ CI = \frac{1}{\#\ children} \sum_{j=1}^{\#\ children} CI_j \tag{2}$$

Fig. 15 presents the total DEI and total CI values obtained from the above analyses. For the benchmark case (i.e., perfect EoL product status), it was assumed that the entire electric kettle can be entirely reused (e.g., as spare parts).

5. Results and discussions

The DF analysis identified 17 different failures that can affect the electric kettle at its EoL. All failures, except the failure DF3, are

Disassembly Failure (DF) Type	Disassembly Failure (DF) Scenario	Disassembly Failure (DF) ID	Disassembly Failure (DF) Description	Parent ID	Action ID	Child ID
It represents the DF type. It can be first-type; second-type or third-type.	*It represents the DF scenario, associated with the Disassembly Type*	*It represents a unique identifier of the Disassembly Failure*	*It describes the way in which the Child(ren) can fail once the product is recovered at its end of life*	*It represents a unique identifier of the Parent(s) that is affected by the failure. Applicable only to Third-Type failures.*	*It represents a unique identifier of the action(s) that is affected by the failure. Applicable only to Second-Type failures.*	*It represents a unique identifier of the children that is affected by the failure. Applicable only to Type I failures.*
Type I	Only child and preceding action are affected (OCPAA)	DF1	Screws blunt or worn out.			H
Type II	Only one child affected (OCA)	DF2	Cable broke while removing during disassembly.		U7	
Type III	Parent, action, and children affected (PACA)	DF3	Parts fused due to electrical malfunction.	0		

Affected Action ID	Disassembly Action Failure	Disassembly Action Type	Disassembly Action Tool	Affected Children ID	Effect of failure on Children	Children EoL due to failure
It represents a unique identifier of the action that has been affected by the DF.	*It explains the effect of the DF on the action (i.e., the disassembly process).*	*It describes the disassembly type that must be performed due to the DF. It can be: i) destructive, ii) semi-destructive, iii) no destructive*	*It describes the tool that needs to be used in order to perform the disassembly action*	*It represents the ID of the children that is affected by the DF.*	*It explains the effect of the DF on the children (i.e., parts obtained after disassembly occurred).*	*It represents the EoL of the children due to the DF.*
U1	Cannot unscrew. Drill the screw out.	Semi-destructive	Drill	H	No effect on siblings.	Recycle
	Too much force applied during the unscrewing action. The cable is broken.	Destructive	Hand	G; D	Cable cannot be reused.	Disposal to landfill
S1	Effort to disassemble too much. The whole product is thrown away	Destructive	Cutter	ALL	Parts cannot be reused. They need to be disposed.	Disposal to landfill

Fig. 14. Extract of the DF analysis for the electric kettle. Four sections are presented in this figure, divided by dark grey rows. The top-left section (orange cells) presents information on the DFs. The top-right section presents information on DFs applied to parents (blue cells), actions (grey-white cells), and children (yellow cells); The bottom-left section presents information on actions resulting from the DFs. The bottom-right section presents information on child(ren) affected due to the action necessitated by a DF. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
RE, RR, and CI values for the EoL scenarios analysed in the case study.

EoL scenario	EoL scenario description	RE	RR	CI
Reuse	A product/component can be completely reused without any material loss.	1,0	0,0	1,0
Disposal to landfill	The product/component is discarded to a landfill and materials cannot be recovered by any means.	0,0	0,0	0,0
Recycling	Product/component is completely recycled with an average material loss of 9%. This assumption is based on the average mass loss statistics in recycling small household appliance, as specified by the interviewed waste management from ERION COMPLIANCE ORGANIZATION S.C.A R.L (R.L, 2021)	0,0	0,91	0,91

DF	Total DEI	Total CI
No Failures (Benchmark)	210	1,00
DF1	243	0,99
DF2	197	0,96
DF3	0	0,00
DF4	210	0,96
DF5	210	0,96
DF6	280	0,89
DF7	210	0,96
DF8	206	0,96
DF9	232	1,00
DF10	210	0,99
DF11	210	0,99
DF12	273	0,96
DF13	203	0,96
DF14	210	0,96
DF15	210	0,96
DF16	210	1,00
DF17	302	0,96

Fig. 15. –Total DEI and Total CI results for the electric kettle. For each DF, the Total DEI (left) and Total CI (right) are presented. The total CI is 1,0 in the benchmark configuration because, if no failures are applied, the kettle can be reused completely. DF3 presents the case in which the kettle is discarded to landfill without starting the disassembly process.

Table 4
DFs considered in the analysis and discussion of the results.

DF Type	DF Scenario	DF ID	DF	DF Action	EoL DF Scenario
Type I	Only child and preceding action are affected (OCPAA)	DF1	Screws blunt or worn out.	Cannot unscrew. Drill the screw out.	Recycle (screws only)
Type II	Only one child affected (OCA)	DF2	Cable broke while removing during disassembly.	Too much force applied during the unscrewing action. The cable is broken.	Disposal to landfill (cable only)
Type III	Parent, action, and children affected (PACA)	DF3	Parts fused due to electrical malfunction.	Effort to disassemble too high. The whole product is thrown away	Disposal to landfill (whole kettle)

independent. In other words, they can occur independently from each other. Due to the computational complexity of analysing all possible DF combinations (i.e., $>2^{16}$ DF scenarios), our analyses and results consider the impacts resulting from separate occurrences of DFs. Due to space limitations, only three DFs (Table 4) scenarios are presented in this article. Interested readers are directed to Annex I in the supplementary materials, that contains information on the remaining DFs.

DF1 represents a common failure type, where the screw is blunt or worn out and it requires a different action to be removed. Feedback from the interviewed experts suggests worn or blunt screws in small appliances are generally drilled out using an electric drill. The application of DF1 leads to an increase of the disassembly time due to the further actions required to perform the disassembly process. The circularity indicator also decreases because, differently from the benchmark scenario, the screw cannot be reused and needs to be recycled. DF1 is a Type I DF that generates a OCPAA scenario, thus it generates an impact both on the actions (i.e., Disassembly Effort Index) and child (i.e., Circularity Index).

DF2 affects the disassembly action as it is a Type II DF. The failure happens when the disassembly action is performed incorrectly, and too much force is applied while removing the cable. This causes a break in the cable, and it is therefore discarded. In this scenario, the disassembly time is reduced since the aforementioned disassembly action is switched from a non-destructive one to a destructive one, leading to a reduction of the disassembly effort. However, the CI of the element is significantly affected because the end-of-life changes to *disposal to landfill*, leading to a score of 0,0 for the cable.

DF3 affects the kettle at the beginning of the disassembly process. It is a Type III DF, where the base of the kettle and the body are fused due to an electrical malfunction. In this scenario, the kettle disassembly process is not started because the effort required to separate the base from the body is too high from the point of view of the disassembler. This leads to a total DEI of 0,0 and a total CI of 0,0. This scenario represents the highest drop in both CI and DEI when compared to the benchmark scenario. Fig. 16 summarizes results from the three DF scenarios in comparison to the benchmark.

This same process was repeated to analyse scenarios generated by all the DFs (listed in Fig. 15). Please, refer to Annex I for a detailed results for each DF (DF1–DF17). All possible scenarios were computed assuming that they occur individually. Results from these analyses are visualized by comparing the total DEI and total CI values, as shown in Fig. 17. Please note that results are plotted with respect to the change in values from the ideal condition (i.e., benchmark scenario). DF3 was excluded from the graph since it presents the case in which disassembly does not occur. Since the MOST technique was used to derive disassembly times for DFs, an error of ±4% on the results obtained for the DEI were considered. For estimating the error magnitude, the disassembly time of the kettle derived using the MOST technique was compared with the real disassembly time obtained through direct measurement for the benchmark configuration. Results showed a 4% error between the overall product real disassembly time and the one obtained with the MOST technique, which is in line with the literature (Zandin, 2002).

Fig. 17 shows that DF9 is the worst scenario if only the change in total DEI is considered. DF9 leads to an increase in total DEI of 22 s with respect to the ideal scenario; the circularity is not affected. For further analysis, the DFs are divided in three clusters. DFs in cluster 1 worsen product circularity (total CI) without significantly affecting the total DEI. An interesting scenario is seen in the case of DF2, which worsens product circularity while improving (reducing) the disassembly effort. This results from the fact that DF2 represents a scenario where a change in disassembly action from a non-destructive (i.e., *unscrew elements*) type to a destructive type (i.e., *cable broken due to high disassembly force*) prevents subsequent disassembly and negatively impacts the product's EoL scenario. DFs in cluster 2 significantly affect the disassembly time, while the ones in cluster 3 significantly affect disassembly time as well as circularity performance. Analysing them in detail, DF6 and DF17 perform poorly relative to the other DFs as they increase the total DEI and reduce the total CI. More specifically, DF6 assumes the heating element of the kettle and associated screws are bent. Thus, it is necessary to proceed with a semi-destructive disassembly action, using a drilling

Child ID	Child	Circularity Index (CI)			
		Benchmark	*DF1*	*DF2*	*DF3*
H	Crox-Head Screws	1,00	0,91	1,00	0,00
I	Plastic cover kettle base	1,00	1,00	1,00	0,00
L	Metal ring kettle base	1,00	1,00	1,00	0,00
M	Crox-Head Screws electronic connection to heater	1,00	1,00	1,00	0,00
N	Rings for screws electronic connection to heater	1,00	1,00	1,00	0,00
O	Electronic component	1,00	1,00	1,00	0,00
P	Bolts	1,00	1,00	1,00	0,00
S	Metal Heating Part	1,00	1,00	1,00	0,00
Q	Crox-Head Screws connecting plastic part to metallic one	1,00	1,00	1,00	0,00
R	Plastic Heating Part	1,00	1,00	1,00	0,00
T	Plastic cover handle kettle	1,00	1,00	1,00	0,00
U	Kettle button	1,00	1,00	1,00	0,00
V	Cross-Head Screw for PCB card	1,00	1,00	1,00	0,00
Z	PCB card	1,00	1,00	1,00	0,00
AA	Led	1,00	1,00	1,00	0,00
BB	Cross-Head Screw Handle	1,00	1,00	1,00	0,00
CC	Handle	1,00	1,00	1,00	0,00
DD	Lid	1,00	1,00	1,00	0,00
EE	Probe Faston	1,00	1,00	1,00	0,00
FF	Probe	1,00	1,00	1,00	0,00
GG	Kettle body naked	1,00	1,00	1,00	0,00
C	Tri-Wing Screw	1,00	1,00	1,00	0,00
B	Base Part Cable cover	1,00	1,00	1,00	0,00
A	Top Part Cable cover	1,00	1,00	1,00	0,00
E	Plastic Cap	1,00	1,00	1,00	0,00
D	Small screws copper connections	1,00	1,00	1,00	0,00
F	Plastic structure connector	1,00	1,00	1,00	0,00
G	Cable	1,00	1,00	0,00	0,00

Action ID	Action	Disassembly Effort Index (DEI)			
		Benchmark	*DF1*	*DF2*	*DF3*
S1	Separate	1,08	1,08	1,08	0,0
U1	Unscrew	24,48	57,60	24,48	0,0
D1	Disconnect	12,96	12,96	12,96	0,0
UR1	Unscrew & Remove	17,28	17,28	17,28	0,0
U2	Unscrew	20,52	20,52	20,52	0,0
U3	Unscrew	19,44	19,44	19,44	0,0
R1	Remove	21,60	21,60	21,60	0,0
D2	Disconnect	19,44	19,44	19,44	0,0
U4	Unscrew	6,48	6,48	6,48	0,0
U5	Unscrew	15,84	15,84	15,84	0,0
R2	Remove	3,96	3,96	3,96	0,0
U6	Unscrew	30,24	30,24	30,24	0,0
R3	Remove	3,96	3,96	3,96	0,0
U7	Unscrew	12,96	12,96	0,00	0,0

Total Disassembly Effort (Total DEI)			
Benchmark	*DF1*	*DF2*	*DF3*
210 sec	243 sec	197 sec	0 sec

Total Circularity Index (Total CI)			
Benchmark	*DF1*	*DF2*	*DF3*
1,00	0,99	0,96	0,00

Fig. 16. DEI and CEI results for the DF1, DF2, and DF3. Cells with the yellow background indicate values that differ from benchmark values. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

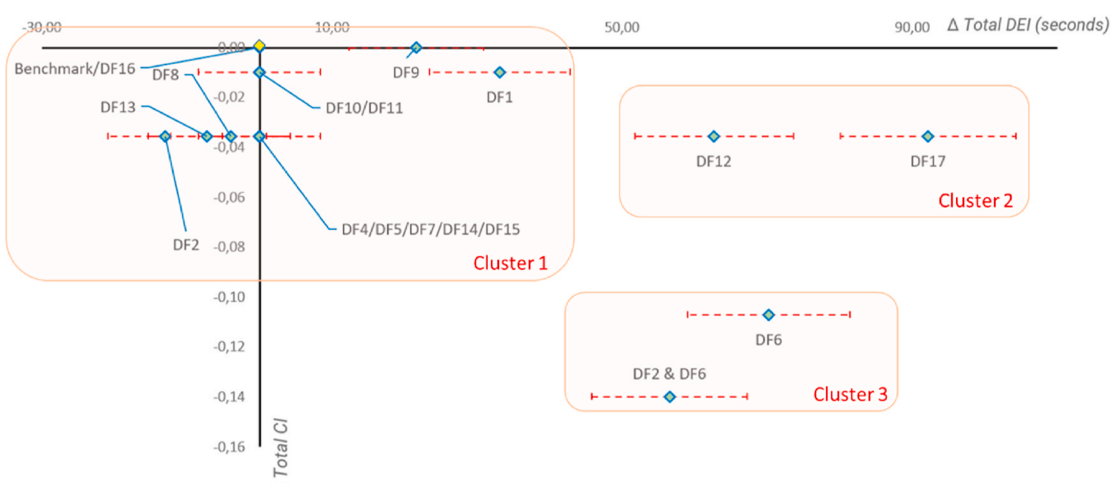


Fig. 17. Total DEI and total CI scores for the analysed DFs. Please note that results are shown as the change in these values with respect to the benchmark scenario (total DEI = 210 s, total CI = 1,0). The benchmark scenario is represented with a yellow diamond. DFs are collected in three clusters based on the change in DEI and CI values. Dotted lines represent error bars of ±4% resulting from uncertainties in estimating disassembly time using the MOST method. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

operation. The drilling operation increases total DEI and destroys the associated components, leading to a decrease in total CI. DF17 assumes that the screws connecting the base and body of the kettle are rusted. Thus, the disassembly process requires drilling out these screws, which decreases total CI and increases total DEI.

The DfCD approach also makes it possible to analyse the outcome of multiple simultaneous DFs. The analysis of multiple DFs is performed considering the effect that each DF has on the DEI and CI of the analysed product. Assuming that two DFs affect the DEI and CI of two different components, then the total CI and total DEI of the product will change. For instance, if DF6 and DF2 occur at the same time, then the total CI will be severely affected, decreasing it to 0,86. On the other hand, the total DEI will improve, because of the change of the disassembly action from a non-destructive to a destructive one (i.e., DF6 – *from unscrewing to drilling;* DF2 – *from unscrewing to break cable*) (Fig. 17).

The obtained results indicate potential modifications to the product in order to increase its circularity while also considering disassembly effort. Assuming DFs occur independently, the kettle should be redesigned to avoid DF6, DF12 and DF17, as these failures add a significant penalty to disassembly effort and circularity. Moreover, if it is desired to further enhance product circularity, parts affected by DF in cluster 1 can be redesigned.

Another interesting insight is obtained by comparing the DEI of the benchmark with the values obtained for DF1 (see Fig. 18).

Considering the kettle in a perfect EoL status (i.e., no failures), the action U6 appears to be the critical action from a disassembly effort point of view. However, if DF1 occurs, the critical action becomes U1. Thus, to improve the design of the kettle in terms of disassembly effort, the focus should be on part H (i.e., screws at kettle base). Redesigning child C (i.e., tri-wing screws connection) would lead only to a partial

Action ID	Action	DEI	
		Benchmark	DF1
S1	Separate	1,08	1,08
U1	Unscrew	24,48	57,60
D1	Disconnect	12,96	12,96
UR1	Unscrew & Remove	17,28	17,28
U2	Unscrew	20,52	20,52
U3	Unscrew	19,44	19,44
R1	Remove	21,60	21,60
D2	Disconnect	19,44	19,44
U4	Unscrew	6,48	6,48
U5	Unscrew	15,84	15,84
R2	Remove	3,96	3,96
U6	Unscrew	30,24	30,24
R3	Remove	3,96	3,96
U7	Unscrew	12,96	12,96

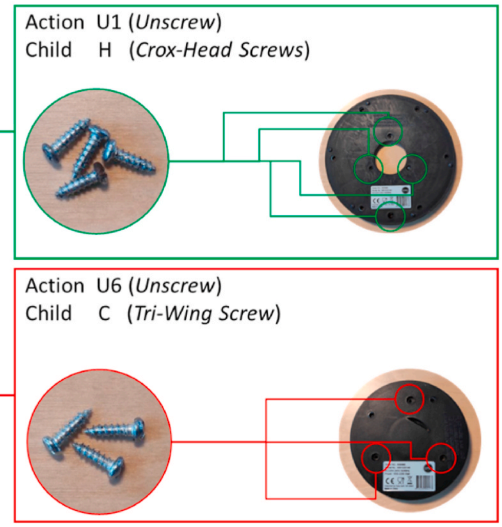


Fig. 18. Results comparing DEI for the benchmark case and DF1. The lower box (i.e., red-box) presents critical elements if no DF occurs; the upper box (green-box) represents the critical element in case of DF1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

improvement as it does not consider the real status of the kettle at its EoL. The same analysis can be repeated for all elements and actions, in the PAC model for all identified DFs. Thus, the proposed DfCD methodology enables a deeper understanding of the product architecture by considering DFs and enables improving (redesigning) products based on their actual EoL status. The proposed method overcomes limitations in current DfD approaches that only consider disassembly effort (and potential circularity implications) for an ideal EoL product status. (i.e., no EoL failures).

6. Limitations

Our evaluation process of the DfCD required making the assumptions/simplifications listed below, due to the inaccessibility of real-world product data.

- We assumed that all the components were reused if the electric kettle was in perfect EoL condition. In practice, the reuse percentage will depend on the demand for used products.
- The disassembly sequence of the kettle was formulated by the authors after physically disassembling the kettle. The assumed disassembly sequence was considered to be representative of operations that would occur in a recycling facility.
- The MOST approach was used to calculate the disassembly time from actions performed during the physical disassembly of a real electrical kettle without any failure modes. When a specific DF necessitated additional actions (such as drilling a rusted screw), disassembly time was calculated by adding the time for performing additional steps, as specified by the MOST method.

Please note that the listed limitations are strictly linked to data availability and not to the DfCD method itself. If the necessary data are available from the manufacturer and/or repairer (i.e., EoL for each item, expected lifetime, disassembly sequence, etc.) it would be possible to use alternate CE indicators (e.g., material circularity indicator) to better support redesign decision-making, and compute the disassembly effort with lesser uncertainties. It is also possible that different or additional DFs are highlighted from these data. The proposed DfCD approach and the PAC model can be potentially improved by validating them with more complex products. Our future work will focus on exploring alternate approaches that limit the accuracy of estimating disassembly effort and CE indicators, when limited lifecycle information is available; this is particularly important when applying our methods to more complex products, where obtaining such data can be time- and cost-intensive.

7. Conclusions and future work

Design for Disassembly methods can be used for reducing disassembly effort at a product's end-of-life (EoL). However, such methods do not account for any EoL failures in a product that can affect disassembly actions, and consequently the computed disassembly effort. This limits the application of such methods towards improving the product circularity, as the feasibility of specific circularity strategies (e.g., reuse, remanufacturing, recycling) depend on both the EoL product status and the corresponding disassembly effort. The Design for Circular Disassembly (DfCD) methodology proposed in this study addresses these limitations and can be used to evaluate the disassembly efficiency of products in terms of the disassembly effort index and circularity index. The DfCD approach makes use of a new disassembly formalization, termed as the Parent-Action-Child (PAC) model. The PAC model describes products in terms of disassembly actions required to transform an assembly/sub-assembly (parent) into smaller sub-assemblies/components (children). The product disassembly structure can be represented as a PAC graph to better understand the implications of each action in terms of disassembly effort and circularity. After the product is described according to the PAC model, the DfCD methodology can be applied for performing disassembly failure analyses and then computing the disassembly effort index and the circularity index for the specified failure scenarios. The DfCD approach was evaluated on a case study on a commercial electric kettle. Results show the DfCD approach can enable a deeper understanding of the product structure, and help designers spot critical failure modes, disassembly actions, and components that affect product circularity. In summary, The DfCD approach contributes to the field of Design for X methodologies by: i) developing a novel disassembly formalization that links disassembly models to end-of-life product status, ii) integrating information on potential EoL product failures with disassembly and circularity assessment, iii) providing a systematic approach that helps designers understand the effect of their design choices in terms of circularity.

The proposed DfCD approach is general and can be potentially applied to different products, if the necessary information is available. For instance, if larger and more complex products such automobiles were to be analysed, the proposed approach would still be applicable, albeit with the need for a greater amount of data; a higher number of disassembly failures and components, are needed to be collected and analysed. Further research is required to evaluate the increase in effort for applying the proposed approach with increase in product complexity. It is also interesting to note that the proposed approach can be used for developing decision-support tools for redesign, e.g., by considering the Pareto optimalities of DFs. This requires additional information about the product behaviour and the goals of the disassembly analysis. For example, the likelihood of occurrence of DFs will be an important consideration in recommending redesign suggestions. The sensitivity of the DFs to the chosen CI and DEI indices should also be evaluated in future research. Finally, in the current formulation of the DfCD approach, specific redesign recommendations are not provided to the designer. Our future work will focus on overcoming these limitations and integrating the DfCD methodology with existing product lifecycle management tools, to ease data collection and management. Finally, we will explore the potential for coupling the DfCD methodology with similarity-based and generative design recommendation tools, to identify feasible (and potentially optimal) redesign actions that can reduce simultaneously reduce disassembly effort while increasing the circularity performance.

CRediT authorship contribution statement

Giovanni Formentini: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Devarajan Ramanujan:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.137009.

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