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EXAMINING THE ROLE AND FUTURE POTENTIAL OF DESIGN FOR DISASSEMBLY METHODS TO SUPPORT CIRCULAR PRODUCT DESIGN

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ABSTRACT

Design for disassembly (DfD) approaches are crucial in supporting the industrial circular economy transition. In literature, a great amount of DfD methodologies is available, however, it is still not clear how they can be used to improve product circularity. To address this gap, our work proposed a systematic literature review of DfD methodologies applied in the field of product design with the aim to provide an overview of the topic in the last decade (i.e., from 2012 to 2022) in terms of methods applicability (i.e., design phase), required parameters and integration capability with circularity assessment. As a result, the paper shows that DfD methods are mainly used in the later design phase to improve product sustainability performances, but a method that simultaneously considers DfD and CE is currently missing. Based on the obtained results, we outlined the requirements that a new DfX method would need to consider both DfD and CE simultaneously. Finally, we proposed a modified version of the butterfly diagram in which DfD parameters are linked to CE indicators to help visualize the connection between the two areas.

Keywords: Design for Disassembly, Circular economy, Product Design, Design for X (DfX), Design methodology

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1 INTRODUCTION

In recent years, due to regulatory changes the Circular Economy (CE) concept has begun to play a fundamental role in many businesses. CE aims to retain a products value for as long as possible by recirculating technical materials in the economy, through strategies such as designing re-usable and easy-to-recover products (Jabbour et al., 2019, Dias et al., 2022). CE is seen as a broad concept that covers a variety of topics and sectors. Several indicators have been developed to assess the circularity of products and processes. An comprehensive review of product-level CE indicators has been conducted by Jerome et al. (2022), where more than 30 indicators have been analysed. According to the indicator selected, different phases of the product lifecycle are considered. From a product design point of view, circular product design allows for a cyclical flow of materials, and it is based on three principles: i) design out waste and pollution, ii) keep products and materials in use, and iii) regenerate natural systems (Ellen MacArthur Foundation, 2020, Wang et al., 2022). These principles translate into developing products to increase their rate of reuse, remanufacturing, and recycling. Despite the increasing research effort in design methods and tools to shift from a linear economy to a CE, indicators that measure CE are still in an initial development phase (Giurco et al., 2014). Most product-level CE indicators address circularity from a material flow point of view, without considering product aspects such as functionality or complexity involved in the product architecture. These aspects are considered keys to supporting CE evaluations at a product design level (Mesa et al., 2018). From this perspective, Design for disassembly (DfD) is a crucial aspect of CE. DfD is a group of methodologies in the Design for X (DfX) family whose purpose is to improve the disassembly phase of products. DfD methods have been developed at the beginning of the '90s with the aim of enabling the easy-recover of valuable materials to reduce the overall product cost. Several DfD methods have been discussed in prior literature and a majority of these methods have been used to improve the disassembly of products to enhance sustainability performance and reduce product disposal costs. With respect to CE, DfD methodologies are considered key aspects to enable the CE paradigm in products, since they can be considered design approaches to support both the slow and close loop (Bocken et al., 2016, Mesa et al., 2018). However, it is still unclear as to which CE metrics should be used to assess and develop products that can meet circular economy needs. Prior literature reviews in DfX have treated DfD and Design for CE separately (Desai and Mital, 2003). To the best of the authors knowledge, a systematic analysis of DfD methodologies in relation with CE indicators is currently missing. Given that the design stage offers the most significant potential for improving the lifecycle sustainability and CE performance of products (Bernstein et al., 2010) (CITE), our work aims at providing a systematic literature review of DfD methods to understand how they can be used during the product design phase to create more circular products. The systematic literature review is based on four research questions -- two general questions and two focused questions. The outcome of the review is a map which presents the relationships between DfD parameters and corresponding CE indicators. The map highlights product lifecycle information that is shared among DfD methods and CE indicators and therefore helps to extend DfD methods to include CE assessments. The novelty of this paper lies in the mapping process: parameters used in DfD methods are studied in relation to CE indicators through the whole product lifecycle. Moreover, the concept of Design for Circular Disassembly is introduced as possible future research topic. The remaining part of the paper is structured as follow: Section 2 presents the method used to perform the review; Section 3 presents the results of the literature review. Section 4 discussed results obtained, and Section 5 concludes the paper.

2 MATERIAL AND METHODS

The methodology used to perform the systematic literature review is based on work of Formentini et al. (2022). The method consists of four phases: i) definition of research questions; ii) definition of the search process; iii) definition of criteria for article selection, iv) data classification and analysis.

2.1 Definition of the search process

Research questions concerning Design for Disassembly methods were divided into two groups, General Questions (GQs) and Focused Questions (FQs). The first group provides an overview of the research field, while the second focuses on technical aspects related to the integration of DfD methods with CE indicators. Table 1 presents the research question defined for this review.

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Table 1 - Research questions

General Questions		Area
GQ1	In which design phase(s) DfD methods have been used?	Application goal
GQ2	Which design phase(s) are the focus of DfD methods?	Design area
Focused Questions		**Area**
FQ1	How are DfD and CE related?	Method correlation
FQ2	How can DfD be used to design circular products?	Future challenges

2.2 Definition of the literature search process

The literature search was performed on the Scopus database, focusing on scientific articles (both journal and conference papers), not considering, for example, thesis, book chapters, technical reports, commercial tools, and patents. The aim of the review is to understand the development of DfD methods with respect to circularity in the last decade, thus only papers published from 2012 to 2022 were considered for evaluation. The research was limited to the engineering field, and to English papers. Five keywords were used: method*, indicator*, parameter*, model*, design for disassembly. The search was restricted to title, abstract and keywords. The query used is "TITLE (method*) OR TITLE (indicator*) OR TITLE (parameter*) OR TITLE (model*) AND TITLE-ABS-KEY (design AND for AND disassembly) AND (LIMIT-TO (SUBJAREA , "ENGI"))".

2.3 Definition of criteria for articles selection

After the initial search process, articles were skimmed to remove duplicates and non-relevant material. Exclusion was performed considering the application area (i.e., only papers with case-studies, articles related to product design, and articles related to disassembly were considered), and the publication quality (i.e., only journal with a Journal Impact Factor (JIF) quartile of 4 and 3 were considered). The publication quality checked was performed only for journal papers. All conferences papers were analysed.

2.4 Data classification and analysis

The selected articles were read, information extracted, and classified in a framework to analyse them easily. The framework presents items according to the type of research question answered. The developed framework is presented in Table 2.

Table 2 - Review framework

Item	Type
Author	Text
Title	Text
Year	Integer
Design Phase	Text (Conceptual; Detailed; Embodiment)
Optimization Goal	Text (Cost; Sustainability)
DfD Parameters	Text

3 RESULTS OF THE LITERATURE REVIEW

The analysis was performed using the created framework, including the information regarding the design phase (G1), the method optimization goal (G2), the parameters required to apply the method (F1, F2). In Table 3 the overall used framework is presented, where DfD Parameters are not presented due to space limitation.

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Table 3 - Data extraction framework

Author	Year	Design Phase	Redesign Goal
(Dagman and Söderberg, 2012)	2012	Conceptual	Sustainability
(Huang, 2013)	2013	Detailed	Sustainability
(De Fazio et al., 2021)	2021	Detailed	Sustainability
(Shetty and Xu, 2017)	2017	Detailed	Sustainability
(Zou et al., 2020)	2020	Detailed	Sustainability
(Zhang et al., 2015)	2015	Detailed	Cost
(Yao et al., 2014)	2014	Detailed	Cost
(Smith and Hung, 2015)	2015	Detailed	Sustainability
(Cong et al., 2019)	2019	Detailed	Cost
(Kim and Moon, 2020)	2020	Detailed	Cost
(Jeandin and Mascle, 2016)	2016	Detailed	Sustainability
(Kim et al., 2016)	2016	Detailed	Sustainability
(Igarashi et al., 2016)	2016	Detailed	Sustainability
(Vanegas Pena et al., 2016)	2016	Detailed	Cost
(Flipsen et al., 2020)	2020	Detailed	Sustainability
(Hu et al., 2015b)	2015	Embodiment	Sustainability
(Soh et al., 2014)	2014	Embodiment	Sustainability
(Behdad et al., 2013)	2013	Embodiment	Sustainability
(Umeda et al., 2015)	2015	Embodiment	Cost
(Rossi et al., 2022)	2022	Embodiment	Sustainability
(Favi et al., 2012)	2012	Embodiment	Cost

To answer the research questions stated in Table 1, all 21 papers were analysed. The aim was to identify the design phase in which DfD method were used and their optimization goal. Finally, research questions to understand how to design circular products using DfD techniques were answered.

3.1 GQ1 - In which design phase(s) DfD methods have been used?

The analysis showed that 1/21 of methods were used in conceptual design, 6/21 in embodiment and 14/21 in the detail design phase. Dagman and Söderberg (2012) is the only paper that investigates the possibility of applying DfD in conceptual design phase. In particular, it proposes the use of axiomatic design to redesign the product architecture in order to improve its maintainability and reparability. However, no further development on the ideas has been found in our literature search. A majority of DfD methods have been applied in the latter phases of design, i.e., detailed and embodiment design. The primary reason for this lies in the type of information required to use DfD methods. The main attributes used in DfD methods are the product disassembly sequence and the product disassembly time. The former can be obtained through several techniques such as collision evaluation (Prioli et al., 2022), and assembly's precedents (Lambert, 2003), which are usually applicable in the embodiment design phase (using 3D computer-aided design drawings). Regarding the product disassembly time, it can be obtained through direct measurements (i.e., using stopwatches), or using methods that parametrize features or actions (i.e., MOST technique, etc.). Most of these techniques are applicable at latter phases of design.

3.2 GQ2 - With which goal DfD methods have been used?

Our analysis shows that DfD method were used mainly to achieve sustainability optimization. The term "sustainability optimization" includes methods used for improving product remanufacturing, recycling, reparability, and circularity performance. For instance, Igarashi et al. (2016) focuses on the optimization of sustainability performances of a vacuum cleaner performing a multi-objective analysis (i.e., CO2 saving, Cost, etc.) instead of bi-criteria analysis (i.e., recycling rate/cost). The outcome of the method is a better-optimized product and assembly line. Hu et al. (2015b) proposed a graph-based method and a tool for estimating the disassembly time in early design phases. The approach improves product sustainability since it considers the possibility to perform selective disassembly, meaning disassembly optimized for a particular valuable part to be recycled or remanufactured. Analysing the year of these publications, it is interesting to notice that aim of improving sustainability was studied mainly in 2013, 2015, 2015, and 2020, while the cost optimization was mainly studied in the 2015. Moreover, the interest in improving sustainability performance has been relatively constant through the last decade, while the interest in cost

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improvement has declined in the last 5 years. To obtain a deeper understanding of the correlation between DfD and product sustainability aspects (CE indices in particular), we analysed the types of lifecycle information common among DfD methods and CE indices.

3.3 FQ1 - How DfD and CE are related?

The analysis was performed by collecting all DfD parameters presented in the reviewed articles. The review showed that primary DfD parameters, i.e., the ones mandatory to perform a DfD analysis were, (i) disassembly time, (ii) definition of target components, (iii) number of components, and (iv) disassembly sequence. Some articles introduced ad-hoc parameters to consider other aspects withing DfD analysis. For instance, Umeda et al. (2015) used the extraction direction together with the disassembly steps and time, while Flipsen et al. (2020) introduced economy parameters (e.g., economic valuable parts) and accessibility-related part information (e.g., difficulty of access). To identify which DfD parameters are also used in computing product-level circularity indicators, we analysed CE indicators reviewed in Jerome et al. (2022). Jerome et al. (2022) identified different ways in which CE can be improved, which were termed as CE strategies. Among the seven CE strategies identified, only CE indicators used for the following strategies are considered in our analysis, (i) changing material composition, (ii) using more of the technical lifetime, and (iii) material recycling. The rationale for limiting our analysis to these CE strategies is the three selected strategies had a direct impact on product design, and therefore would contain CE indicators and DfD parameters useful for design decision-making. The results from our analysis are shown in Table 4, which shows the connections between DfD parameters and CE indicators.

Table 4 - Identified circularity indicators and design for disassembly parameters

Circular Economy Strategy	Circularity Indicator	Design for Disassembly Parameter	Article
Changing Material Composition	PR - Product Renewability	Part Material; Material Life; Material Environmental Performances; Material Recoverability; Material Separability; Component Number	(Hu et al., 2015a)
Changing Material Composition	RCR - Recycling Content Rate	Components number; Part Material	(Hu et al., 2015a)
Changing Material Composition	RC - Recycled Content	Material Life; Material Environmental Performances; Material Separability; Material Recoverability	(Yao et al., 2014)
Using More of Technical Lifetime	PRI-reuse - Potential Reusability Rate	Component Number; Priority Part; Joint Number; Joint Reversibility; Reusability Rate; Reuse Process Cost; Revenue Reuse Parts	(Hu et al., 2015a, Flipsen et al., 2020, Vanegas et al., 2018, De Fazio et al., 2021, Zou et al., 2020, Huang, 2013)
Using More of Technical Lifetime	Rreuse - Reusability Rate	Component Number; Priority Part; Joint Number; Joint Reversibility; Reusability Rate; Reuse Process Cost; Revenue Reuse Parts; Disassembly Depth	(Hu et al., 2015b, Vanegas Pena et al., 2016, De Fazio et al., 2021, Huang, 2013)

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Material Recycling	CR - Collection Rate	Recovery Process Cost; Material Separability; Part Material; Material Recoverability; Component Number	(Huang, 2013, Hu et al., 2015b)
Material Recycling	EoL-RR - End-of-life Recycling Rate	Disassembly Depth; Recovery Process Cost; Treatment Cost; Fixation; Part Grasping and Manipulation; Access; Force to disassemble; Revenue Material Recovery; Disassembly Damage Cost; Part Material; Risk of Damage; Extraction Direction	(De Fazio et al., 2021, Huang, 2013, Igarashi et al., 2016, Jeandin and Mascle, 2016, Kim and Moon, 2020, Behdad et al., 2013, Cong et al., 2019, Umeda et al., 2015)
Material Recycling	Rrec - Recyclability Rate	N/A	
Material Recycling	OSCR - Old Scrap Collection Rate	N/A	
Material Recycling	OSR - Old Scrap Ratio	N/A	
Material Recycling	PRI-rec - Potential Recycling Index	Part Material; Recovery Process Cost	(Huang, 2013)
Material Recycling	RR - Recycling Rate	N/A	
Material Recycling	RPER - Recycling Process Efficiency Rate	N/A	

3.4 FQ2 - How DfD can be used to design more circular products?

Our literature review identified potential information-related overlaps between DfD and CE, however current methods do not consider them simultaneously. In other words, current methods are focusing on improving disassembly performances without directly considering circularity performances. Using results from GQ1, GQ2 and FQ1 it is possible to add further context to answer FQ2. In order to design more circular products, it is necessary to create a new approach which merges DfD techniques with CE analysis, shifting the focus from a life cycle assessment point of view towards circularity. This new type of DfX method will require the integration of CE performances in DfD, enabling a novel formalisation of disassembly knowledge together with simultaneous treatment of disassembly and circularity. Finally, the new DfX method will require the consideration of EoL product status to properly estimate the disassembly effort and the understanding the product circularity potentiality. In fact, reducing disassembly effort may not be a priority for products with easily separable material streams if recycling is the only achievable EoL scenario.

4 LIMITATION

The present paper's literature analysis reveals several limitations that may affect the findings' scope and require clarification. The research process was systematically carried out, with the identification of parameters and criteria aimed at minimizing potential biases. However, the primary limitation arises from the use of a filtering process based on criteria determined by the authors. This approach may exclude articles that could be available to other users depending on the type of database and accessibility of the institution. This lack of scientific rigor and replicability could limit the generalizability of the results. Furthermore, this review exclusively focuses on scientific articles published in journals and conferences, neglecting other sources such as theses, book chapters, technical reports, commercial tools, and patents. Given that Design for Disassembly (DfD) is an

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applied science in engineering, some valuable contributions from beyond the academic community may have been omitted from this analysis.

5 DISCUSSION

Results from our review show that DfD methods are not yet fully integrated with CE analysis. The accurate estimation of the disassembly sequence and disassembly time in early design are key limitations. These two parameters are central in DfD analysis to understand the product disassembly performance. To support this, the research question G1 showed that most methods are applied at late design phase which is indeed where it is possible to gather this date. This limits the applicability of the DfD methods, since they need to be used as redesign methods, leading to difficulty to apply CE thinking in the initial product design (Sabaghi et al., 2016). The predominant application of DfD at the latter design phases shows also that product disassembly performance has mainly being considered at the end of the product design phase, thus DfD approaches have been used as reactive solution (i.e., to solve problem already present) and not as proactive solution. This is confirmed by the fact that, since in the last decade the topic of sustainability became a core discussion in academia and industry, DfD methods have been used mainly to improve product sustainability. This result is in line with the shift that researchers and society have had in the last decade. In fact, lately there has been a sharp rise in the interest in sustainability and circularity across a variety of industries (dos Santos et al., 2022, Hapuwatte et al., 2022). However, only recently the distinction between CE and sustainability has been in focus (European Commission, 2020) and more papers are stressing the fact that sustainability does not imply CE and vice versa (Wang et al., 2022). This may justify that nowadays, many methods available in literature provide improvement in terms of material reduction and eco-design approach which however do not consider aspects typical of circularity analysis, such as the product end-of-life, the reusability potential, etc. (Den Hollander et al., 2017). These create a weak coupling between DfD and Circularity. The focused question F1 showed that, there are several lifecycle information overlaps between circularity analysis and DfD methods, at different stages of the product life, and within different CE strategies. This suggests the possibility to extend DfD methods to enable the consideration of product-level CE performance. For example, CE indicators such as Product Renewability (PR), Recycling Content Rate (RCR), Collection Rate (CR), etc. might be used to couple CE and DfD, since they share much information. The integration of these indicators will allow to overcome the current definition of DfD methods, leading to the creation of new DfX methods to design more circular product. As suggested by the focused research question F2, this family of methods should focus on integrating disassembly product performances with estimation of real product end-of-life conditions, which is strictly related with the idea of Circular Economy since it will allow a better reuse and recycle of the whole product. This new method will allow the creation of a completely new field of study, allowing the investigation of innovative materials (e.g., metamaterials) to produce products easy to disassemble and reused, new business models (e.g., product-as-a-service) to enable the re-use of target components, and make fully use of the advantages given by the industry 4.0 through enchanted product sensor. In Figure 1, the butterfly diagram proposed by MCAllert (Ellen MacArthur Foundation, 2017) has been readapted to consider DfD methods. On the right side, each phase of the butterfly diagram has been linked to a CE indicator, while on the left side each CE indicator is linked with relevant DfD parameters identified during the literature review.

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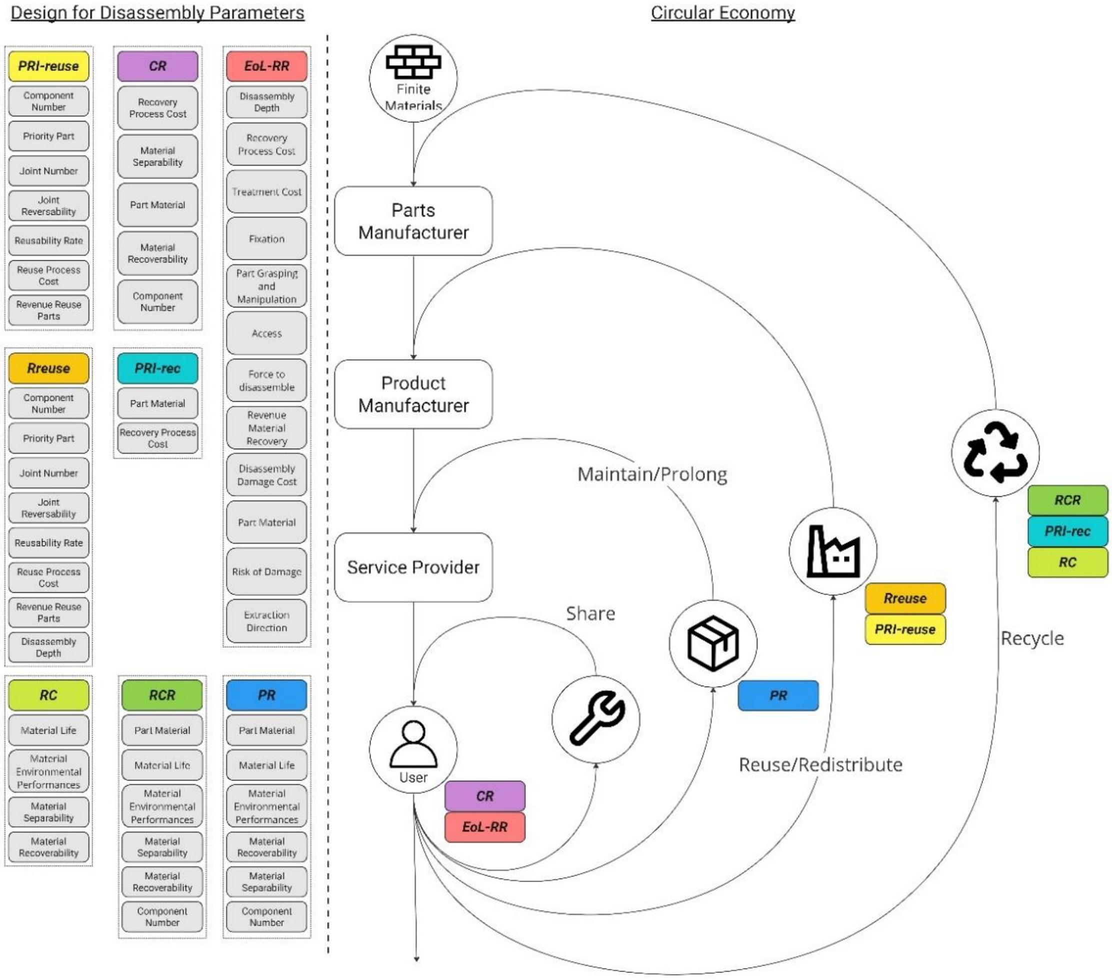

Figure 1 - Design for disassembly and circular economy. On the right - circular economy indices are identified with respect to the CE phases; On the left - DfD parameters that can be used to compute CE indices are presented.

The map shows that, even though the main DfD parameters are not directly linked with circularity assessment (i.e., product disassembly time and product disassembly sequence), there is still significant overlap of product lifecycle information among the two areas. Thus, we argue that a promising direction for further research is developing stronger linkages between DfD and CE assessments. This will help position DfD methods as enablers for designing more circular products.

6 CONCLUSION

This paper presented a systematic literature review of Design for Disassembly (DfD) methods in relation to Circular Economy (CE) indicators. DfD methods are widely used in industry and academia, to design products easier to be disassembled to reduce disposal cost or improve product sustainability. Even though DfD approaches are considered enablers for obtaining circular products, nowadays no clear understanding of how DfD methods and CE indicators are linked. This review aimed at answering four questions, two general questions which provide a general overview of DfD methods, and two focused questions to understand the link between CE and DfD methods, to provide insight in possible future research topics. Results show that DfD methods were mainly used in latter phases of design with the goal of improving the product performance in terms of sustainability. However, a coherent Design for X (DfX) methodology that simultaneously considers DfD and CE performance is currently lacking. Our review showed that an overlaps between DfD and CE methods are present, in terms of the lifecycle information required to perform such assessments. Thus, future research should focus on the exploiting this overlap, and aim at creating novel DfX methods which couple DfD and CE assessment.

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