Journal of Cleaner Production 506 (2025) 145459

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

A review of disassembly systems for circular product design

Giovanni Formentini [a,b,*], Joao PJ. Prioli [c], Junwon Ko [d], Buddhika Hapuwatte [e,f], Vincenzo Ferrero [e], Fazleena Badurdeen [d], Jeremy L. Rickli [g], Devarajan Ramanujan [a,h]

[a] Department of Mechanical and Production Engineering, Aarhus University, Katrinebjergvej 89 G-F, 8200, Aarhus N, Denmark
[b] Circular Momentum, Paradisæblevej 52, 2500, Copenhagen, Denmark
[c] Department of Industrial and Systems Engineering, North Carolina A&T State University, Greensboro, NC, USA
[d] Department of Mechanical and Aerospace Engineering and Institute for Sustainable Manufacturing, University of Kentucky, Lexington, KY, USA
[e] National Institute of Standards and Technology, 100 Bureau Dr., Gaithersburg, MD, USA
[f] University of Maryland, College Park, MD, USA
[g] Department of Industrial and Systems Engineering, Wayne State University, Detroit, MI, USA
[h] Department of Mechanical and Civil Engineering, Technical University of Denmark, Koppels Allé, 2800, Kgs. Lyngby, Denmark

ARTICLE INFO

Handling Editor: Dr. Sandra Eksioglu

ABSTRACT

Circular Economy (CE) is described as a means for maintaining products and materials in circulation while regenerating nature. This shift requires considering aspects at the product design phase that were not previously prioritized. One such aspect, disassembly, is a key enabler for CE. Design for Disassembly methodologies have been deployed for several years to enhance disassembly performance. However, when CE is of interest, it is essential to consider how disassembly affects the entire product life cycle system. In this regard, this paper proposes a literature review of relevant DfD methods from a system engineering perspective to evaluate their effects on Circular Economy. In this regard, we provide a framework called Disassembly Systems Engineering (DSE) to encapsulate and describe the complexity of product disassembly activities. The review is analysed with the support of System Engineering theory, where the DSE is used to classify disassembly into five system levels, highlighting how critical disassembly information and parameters affect each level. As a final result, we identified five main parameters that affect product disassembly performance within the overall DSE. The article offers a novel understanding of the complexity of disassembly systems in the context of enhanced product circularity performance.

1. Introduction

Despite the growing recognition that human activities are stressing raw material availability and the earth's biophysical limits (Rockström et al., 2023), increasing the recirculation of materials into our economy has had limited progress. A 2023 report by the Circle Economy Foundation estimates that a mere 7.2 % of material inputs are reintroduced into the global economy including all forms of recovery, while material stocks have grown by 23-fold in the 21st century (Fraser et al., 2023). The circular material uses rate (CMUR), defined as the proportion of material recycled and fed back into the economy, only increased from 10.7 % to 11.5 % in the European Union between 2010 and 2022 and was well below the 2030 target of 23.2 % (European Environment Agency, 2024). Apart from increasing the quantity of materials recirculated through increased recycling, another need is also widely recognized: to increase the efficacy of material recirculation loops by prioritizing value-preserving End-of-Life (EoL) strategies such as reuse, remanufacturing, and refurbishing (King et al., 2006), especially when such strategies can restore product use-phase efficiencies and when newer technologies do not significantly outperform secondary products (Cooper and Gutowski, 2017). However, the added complexities and costs of establishing reverse logistics, harvesting product components, and challenges in certifying secondary products (Formentini et al., 2023) tend to limit the adoption of such strategies in practice. The need for closing the loop for technical materials has grown in prominence given the increasing demand for critical raw materials and their use in green transition technologies (Eheliyagoda et al., 2025; Wang et al., 2024). The European Critical Raw Materials act requires raising domestic recycling capacity for critical raw materials to 25 % of annual consumption by 2030 (EU Regulation, 2024), and similar strategies have

---

* Corresponding author. Department of Mechanical and Production Engineering, Aarhus University, Katrinebjergvej 89 G-F, 8200, Aarhus N, Denmark.
E-mail addresses: giof@mpe.au.dk, giovanni@circularmomentum.com (G. Formentini).

https://doi.org/10.1016/j.jclepro.2025.145459
Received 10 September 2024; Received in revised form 28 March 2025; Accepted 5 April 2025

been suggested for the United States (Bauer et al., 2023). Symbiotic value preserving EoL strategies, such as remanufacturing, can potentially offset the current high costs of EoL recovery for such materials (Cong et al., 2015). Given the challenges associated with implementing high-value-preserving EoL strategies, this article focuses on exploring interdependencies between circular economy (CE) and design for material recovery. In particular, design for material recovery is studied from the perspective of Design for Disassembly (DfD), since disassembly is considering a key enabler for the CE (Formentini and Ramanujan, 2023b).

Prior research on assessing disassembly performance for CE typically focuses on specific applications, e.g., product architecture, disassembly sequencing, line balancing, and reverse logistics networks (Vanegas et al., 2018). For example, a recent study by Turkbay Romano et al., 2024 has proposed a standardized approach to assess the disassemblability of power electronic converters, which can provide insights into the design of products for disassembly and circularity. However, a systemic evaluation of the relations between DfD aspects and CE has not been undertaken in previous studies. Understanding such connections is crucial because designing products for increased value recovery requires coordinated changes across multiple systems (e.g., reverse supply chains, disassembly plans, product systems, product components) and affects various stakeholders throughout the life cycle (e.g., designers, manufacturers, consumers, logistics providers, recyclers, remanufactures).

With this perspective, this paper introduces the Disassembly Systems Engineering (DSE) framework to elucidate and analyze DfD methodologies for enhancing product circularity. The framework aims to provide a clear understanding of how DfD parameters influence the entire product life cycle within a CE framework. Recognizing the central role that disassembly plays in leveraging the CE paradigm, we review relevant literature to investigate how DfD methodologies can be explained within the DSE framework and to identify the key design parameters that drive product circularity. Additionally, we envision DSE serving as a foundation for future research to critically evaluate existing approaches, identify key limitations, and develop more holistic disassembly strategies aligned with circular economy principles. The organization of the remainder of the paper is as follows. Section 2 outlines the frameworks and strategies used to achieve circular products. Section 3 focuses on the role of disassembly in circular product design (CPD), providing a system view of product disassembly when CE is of interest. The relevant literature on DfD methodologies is reviewed and analysed from a DSE perspective. Information and parameters identified from the literature review of DfD with a system point of view are explained in Section 4. Section 5 summarizes the findings of the literature review when analysed using the DSE framework. Finally, Section 6 concludes the article.

2. Circular economy – A paradigm to address economic and environmental challenges

In this section, an overview of the CE is presented from a Product Design perspective. Additionally, an overview of standards within the CE is introduced. Finally, the pivotal role of Disassembly as an enabler of CE practices is highlighted.

2.1. Evolution from ecodesign to circular economy

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., 2022b; Opferkuch et al., 2022), led by a change in policy and regulations. For instance, the European Union Circular Economy action plan (European Commission, 2020) stresses the importance of switching from a linear economy to a circular one to boost the economy, protecting businesses from potential resource scarcity. As such, CE is seen as a broad concept that covers a variety of topics and sectors and 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). It is widely accepted that to enable the CE paradigm, product design plays an important role (Formentini and Ramanujan, 2023b). As such, product design frameworks, guidelines and methods presented in literature have evolved over the years to incorporate Sustainable and Circular Product requirements.

Ecologically focused design, Design for Environment (DfE) or ecodesign, the latter coined by Van der Ryn and Cowan (2013), is a family of approaches developed to take into account resource consumption and waste generation since the early product design phases (Bernstein et al., 2010). Inspired from concepts from different fields, such as industrial ecology (Frosch and Gallopoulos, 1989) as well as environmentally conscious buildings and architecture (Papanek and Lazarus, 2005), agriculture, and waste management (Kallipoliti, 2018), the DfE approaches offer a way to guide the development of products considering the whole life cycle, while minimizing the environmental impacts (Schäfer and Löwer, 2021).

DfE methods consist of numerous guidelines, checklists, and standards that outline relevant factors to incorporate sustainable requirements from the concept planning stage through product recovery and disposal during post-use (Brezet, 1997; Schäfer and Löwer, 2021). Standards and guidelines also incorporate requirements for ecodesign (e.g., Ecodesign Directive 2009/125/EC for energy-related products (2009/125/EC, 2009), ISO 14006 (ISO 14006 2020) and the proposed Ecodesign for Sustainable Products Regulation (ESPR)). These ecodesign guidelines emphasize the importance of incorporating a variety of requirements, such as different value recovery strategies, including effective product disassembly to enable remanufacture and recycling, minimizing resource consumption, and increasing the use of renewable resources (Ramanujan et al., 2018).

The need to move from the standard linear economy concept (i.e., cradle-to-grave) to the CE, by adopting a closed-loop approach, is also the focus of the cradle-to-cradle (C2C) approach (McDonough and Braungart, 2010). In particular, the C2C approach emphasizes eco-effectiveness of design, focusing on enhancing the positive environmental impacts of product design while incorporating regenerative aspects.

Methods focusing on Design for Sustainability (DfS) incorporate criteria related to stakeholder wellbeing, in addition to the environmental aspects integrated in DfE strategies, to ensure societal sustainability is also considered during the design process (Corsini and Moultrie, 2021).

Most of the Design for Environment (DfE) and Design for Sustainability (DfS) methods are built upon and encompass features integrated in numerous other Design for ‘X’ (DfX)—where X refers to the targeted product feature or performance—methods. Among the earliest such methods is Design for Manufacturing and Assembly (DfMA) introduced by Boothroyd (1994) aimed at designing products considering ease of manufacturing (Design for Manufacturing – DfM) (Fabricius, 1994) and assembly (Design for Assembly – DfA) (Boothroyd and Alting, 1992), advocating a concurrent engineering approach. The focus of DfMA and other early methods on DfM and DfA was on efficiency and cost minimization. Quality improvement for reducing cost and improving efficiency and productivity is targeted through Design for Quality (DfQ) methods such as Failure Modes Effects Analysis (FMEA), Six Sigma and Design for Reliability (Chiu and Kremer, 2011). Increased interest in mitigating product environmental impacts caused due, for example, to excessive consumption of natural resources, increased wastes, and greenhouse gas emissions led to the development of various other methods that enable and/or avoid contributory total life cycle product features and manufacturing process characteristics. For example, effective product disassembly, without damage to high-value components, is a pre-requisite for component reuse and remanufacturing. Thus, Design for Disassembly (DfD) (Crowther, 2005) emerged as an important consideration for closed-loop product design for sustainability (DfD methods are discussed in further detail under section 3.2). Numerous other DfX methods, each focusing on various aspects such as end-of-life product recovery (Pozo Arcos et al., 2018), remanufacturing (Hilton and Thurston, 2019), recycling (Martínez Leal et al., 2020), target product design to incorporate features that can promote closed-loop and circular flow of resources to enhance sustainability (Chiu and Kremer, 2011; Rossi et al., 2016; Benabdellah et al., 2019).

Among the DfX methods some also embody aspects more pertinent to consumers and other stakeholders underscoring the societal aspect pertinent for DfS. Methods such as Design for emotional durability (Chapman, 2009) emphasize product design to increase customer attachment to products as means of increasing product longevity, a feature that could enhance sustainability performance (Ceschin and Gaziulusoy, 2016). Overall, DfX strategies provide a structured approach to product development by focusing on specific key performance indicators and optimizing design decisions to achieve desired outcomes, such as lower cost, improved quality, and closed-loop resource flow to enhance circularity and sustainability.

Ecodesign practices have been critiqued for the reliance on the waste hierarchy and for how the approach assumes that waste is inevitable. In other words, the notion that any product eventually leads to creating some waste is blended into the ecodesign concept (Den Hollander et al., 2017). Ecodesign has also been viewed as mostly focusing on eco-efficiency (i.e., improving the efficiency with which resources are consumed) at the expense of eco-effectiveness (McDonough and Braungart, 2010). The effect is known as *rebound effect*, meaning that to develop and produce a more eco-efficient product, it might be necessary to use more resources, thus leading to an overall higher environmental impact. CE, on the other hand, aims at focusing on both eco-efficiency and eco-effectiveness to design out waste during the product development process.

Den Hollander et al. (2017) emphasize the criticality of the Inertia Principle (Stahel, 2010) as a central feature of circular product design (CPD). The Inertia Principle focuses on ensuring that a product is designed to increase use life (i.e., longevity and durability), maintaining integrity before it is designated as having reached its EoL, and value recovery strategies such as reuse, remanufacturing, and recycling are applied. They emphasize the importance of integrating capabilities for resisting (by promoting longevity), postponing (by enhancing durability) and reversing (through value recovery et EoL) product obsolescence during the design phase. Tools such as the Circular Product Readiness (Blomsma et al., 2019) and CPD guidelines (Shahbazi and Jönbrink, 2020) can be used to assess criteria related to stakeholders, laws and regulations and evaluate the effectiveness of CPDs.

Existing approaches presented for CPD emphasize various requirements and, in some cases guidelines, for consideration. However, most fall short of recommending strategies or principles for CPD that can be used by designers during the Product Development Process (PDP) (Aher et al., 2023). As illustrated in Fig. 1, the PDP process involves a variety of steps in which key decisions (e.g., CD_1, ……, FD_y) need to be taken to reach the final design. It is imperative that the outcomes of these key decisions at each stage in the PDP be assessed for the extent to which they satisfy CPD requirements. The CPD requirements and relevance of different CE principles (e.g., using biodegradable materials) is highly product specific. As such, it is imperative that CPD requirements relevant to the product offering be chosen with consideration of specific customer needs identified during the product planning stage and in compliance with standards and regulations relevant to the offering in the target market. In addition, the existing value recovery options in place for the product as well as the economic benefits of incorporating a CPD requirement must be considered during the decision-making process. An iterative process to identify and incorporate CPD requirements that offers highest business value while enhancing circularity needs to be followed to ensure the outcome from the PDP leads to a circular product ready to be launched.

Establishing a robust measurement system is a vital step in enhancing overall performance of CPD. A multitude of product circularity assessment methods have been proposed to determine how well products align with the requirements for being considered a circular product. Recent work by Ko et al. (2024) presented an extensive review of existing product circularity assessment methods, and the aspects covered by each method, identifying common gaps. These include inconsistencies in the criteria and scale used across different methods and inadequate coverage of value recovery strategies (recover, reuse, remanufacture, and recycle). Most methods also lack engagement with practitioners in their development process, which limits their applicability and adoption in the industry.

Furthermore, the disassembly aspect is often overlooked in most existing product circularity assessment methods, despite its recognized

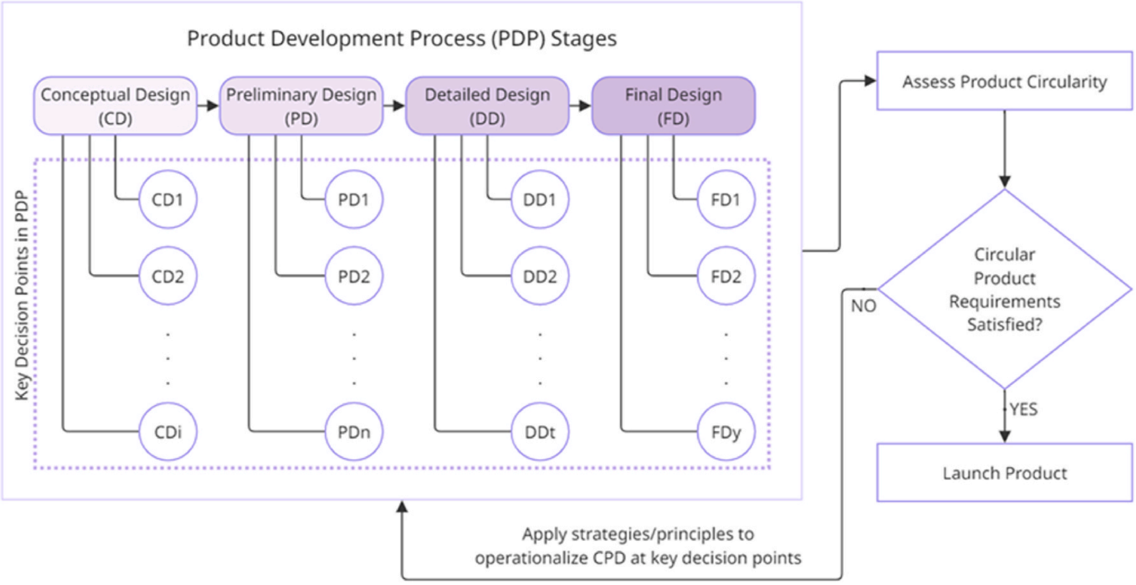


Fig. 1. Integrating Product circularity assessment and principles for CPD during PDP
(Note: CD1, CD2 …, etc., correspond to decision points during conceptual design (CD); PD1, PD2 … etc., during preliminary design (PD); DD1, DD2 …., etc., for detailed design; and FD1, FD2 …, etc.).

importance in literature focusing on CE and CPD. One of the early works by Ellen MacArthur Foundation (EMF), a cornerstone in CE discourse, highlighted the necessity of easy disassembly for facilitating CE transitions (MacArthur, 2013). Similarly (Van den Berg and Bakker, 2015), included “design for disassembly” in their product design framework for CE, describing disassembly as the initial action in most processes aimed at prolonging a product’s lifespan or repurposing its materials for a new life. More recent studies, such as the review of outcomes and benefits in CE from Nag et al. (2022), have reiterated easy disassembly as a critical element of circular products. Research by Suppipat and Hu (2022) also emphasized the importance of easy disassembly in applying value recovery strategies at the product’s EoL. However, existing product circularity assessment methods often do not explicitly incorporate the disassembly aspect. This can partly be attributed to most methods focusing only on one or a few aspects related to product circularity. For instance, the Material Circularity Indicator (MCI), introduced by the EMF, is a prominent circularity measure used across various sectors and in academic research (MacArthur, 2013; Kirchherr et al., 2017). Despite its widespread acceptance, the MCI only focuses on material utilization and does not consider the ease of disassembly, a limitation noted by Saidani et al. (2017). On the other hand, the Circularity Performance Indicator proposed by Saidani (2023) attempts to measure the ability to disassemble but falls short in addressing the environmental and economic impacts across the total product life cycle. Additionally, recent efforts to attribute EoL burdens, such as the Circular Footprint Formula (Damiani et al., 2022), primarily focus on recycling, and there is a dearth of approaches for systematically considering benefits considering disassembly during the design, e.g., by making it easier for a material to be recycled over multiple lifetimes (Pedersen and Remmen, 2022). This underscores the need for product circularity assessment methods that not only incorporate disassembly but also offer a more holistic evaluation of products’ life cycle impacts attributed to the features designed.

2.2. *The role of standards in transitioning to a circular economy*

Standards supporting the transition toward a CE are in the early stages of development. However, as shown in Fig. 2, many current standards can be adapted for use in a CE. Current standards that apply to the CE often focus on sustainability, smart manufacturing, and materials.

Standards like the ISO 14000 - Environmental Management family play a paramount precursor role in the development of current CE topics and activities (Karaeva et al., 2023). ISO 14040 (2006) and ISO 14044 (ISO 14044 2006) on Life cycle Assessment (LCA) are closely aligned with the comprehensive examination of life cycle inventory (LCI) and the life cycle thinking perspective that informs CE practices and literature. Current LCA, LCI, and Life cycle Management (LCM) standards primarily consider the system boundaries, functional units, and perspectives of a single product life cycle iteration. While these standards recognize that life cycles can be cyclical and encompass multiple systems, applications to evaluate the interactions and cumulative impacts of production involving multiple systems and life cycles are not well developed (Hapuwatte et al., 2022a, 2022b).

Standards for CE that have been recently introduced represent a pivotal effort to delineate, frame, and formalize CE concepts, addressing challenges previously highlighted. To date, the British Standards Institution (BSI) has introduced BS 8001, which delineates a framework for embedding CE principles within organizational practices. The new ISO 59000 series aim to provide a comprehensive overview of the CE domain. ISO 59004 (ISO 59004 2024) introduces essential vocabulary, foundational principles, and an implementation guidance framework for CE. ISO 59010 (ISO 59010 2024) offers recommendations for transitioning business models and value networks towards CE paradigms. ISO 59020 (ISO 59020 2024) explores measuring and assessing circularity performance. These standards offer a broad perspective on CE topics and preliminary strategies for CE transitions.

Future CE standards can look to enhance the specificity of emerging, macro-level general CE standards. The shift from a linear to a circular economic model is significantly dependent on the adaptation of sector-specific frameworks, necessitating the creation of both meso (systems-specific) and micro-level (product-specific) standards. These finer-scoped standards are crucial for providing detailed and actionable

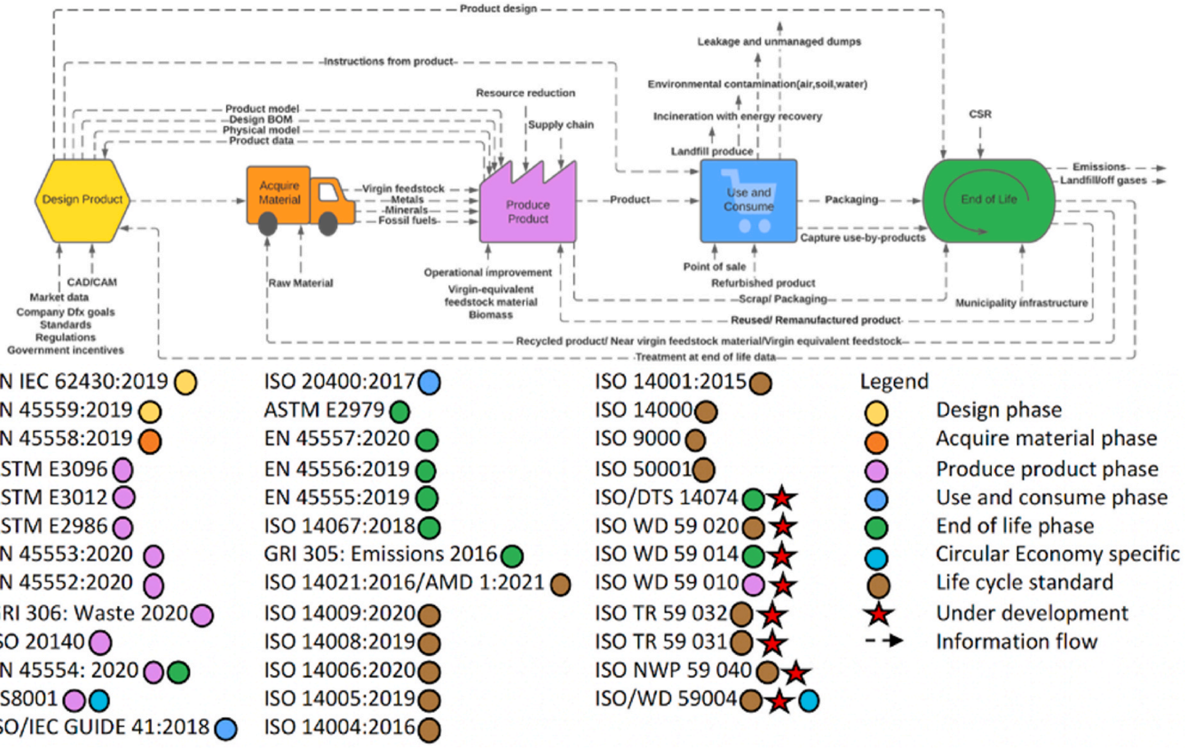


Fig. 2. – The product life cycle and standard applicable to the Circular Economy (Reslan, 2022).

guidance. Micro-level standards can address CE applications within specific sectors, while meso-level standards can explore the integration of CE practices across broader product life cycle stages, including product design.

Sustainability standards frequently serve as a benchmark to assess modifications in product design. Using current standards, it is feasible to explore product designs that incorporate circular resource flow, value recovery, disassembly, and other CE concepts. However, the comprehensive application of a CE perspective at the design stage, particularly in assessing circular impact across all life cycle stages and facilitating subsequent life cycles without dedicated CE-oriented standards for disassembly and value recovery, presents a challenge. In fact, the development of products is a multifaceted activity involving numerous tasks (Benabdellah et al., 2019). When aiming to enhance product disassembly performance, DfD methodologies are employed (Shetty et al., 2000), which are instrumental in improving product repairability, remanufacturing, recycling performance and circularity performances. However, to manage the complexity of designing circular products that are easy to disassemble, it is possible to deploy a Systems Engineering approach. In particular, the disassembly of a product can be described as a complex system in which several layers of complexity interact, each with different levels of design information granularity. In the following section, the role of disassembly in the product life cycle is analysed and explained through a systems view.

3. Disassembly Systems Engineering (DSE)

In this section, the disassembly activities are outlined from a Systems Engineering perspective. Additionally, the Disassembly Systems Engineering framework is introduced and elucidated, with respect to Circular Product Design. Finally, a review of the pertinent literature on Design for Disassembly methodologies is discussed using the DSE.

3.1. Disassembly overview

Disassembly activities are considered key to enable the CE paradigm (Oturu and Oluah, 2024; Formentini et al., 2024). A holistic approach is necessary to examine these activities within the CE context, as the complexity of disassembly impacts, not only the product, but all actors across its lifecycle. We therefore frame the disassembly process (es) as a complex Disassembly Systems Engineering (DSE) system, building upon the definition of an engineering system given by Sillitto et al. (2019). Specifically, DSE is defined as:

> “a complex engineering system where an elevated number of information and interactions are encountered among direct and indirect

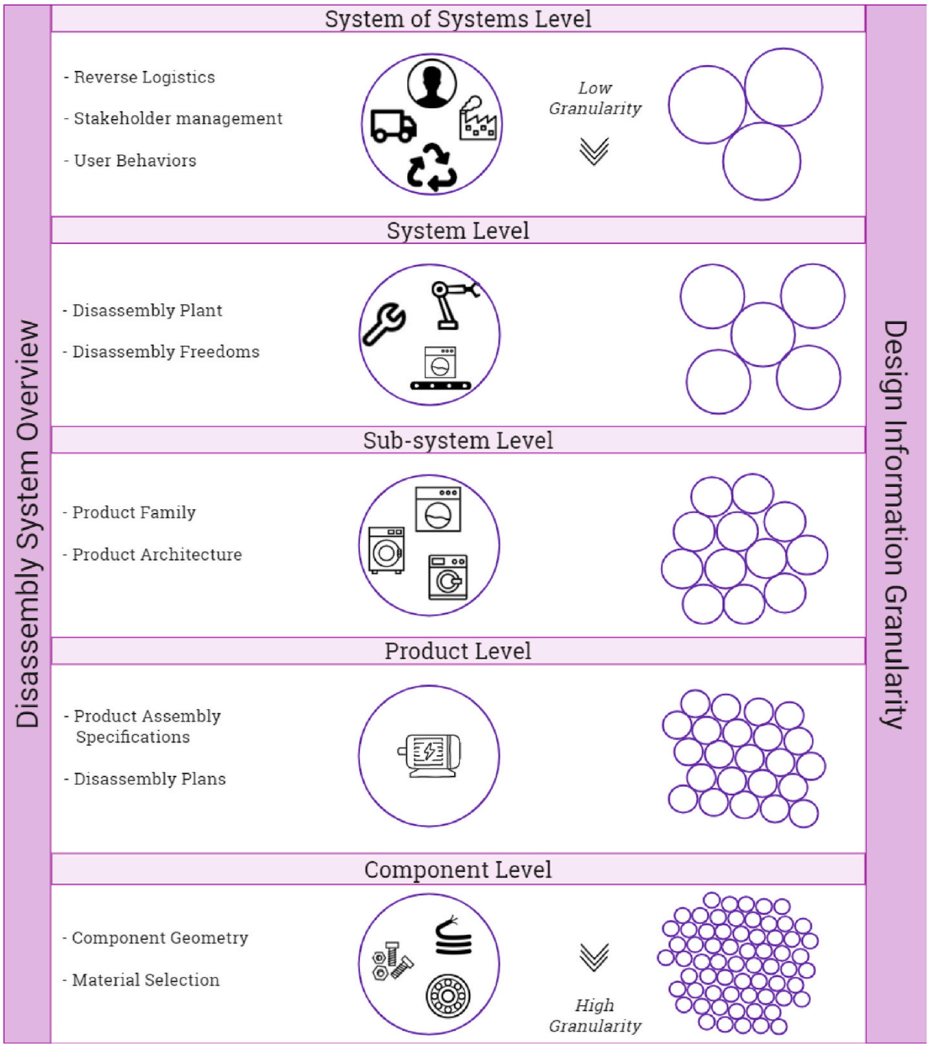


Fig. 3. – Disassembly Systems Engineering framework. It is composed of five (5) levels; moving from the System of Systems Level to the Component Level the number of actors interaction within each level decreases while the design information granularity increases (i.e., more detailed information available at component level than system of system level).

actors involved in the disassembly process of a product within its life cycle"

The provided definition emphasizes two key aspects.

- An elevated number of information interactions, with the proposition that successful disassembly relies on significant information sharing among lifecycle stakeholders.
- Direct and indirect stakeholders, which stresses the need to understand the effect that each stakeholder has on the disassembly process where DSE considers both direct stakeholders (e.g., recyclers, manufacturers performing disassembly operations) and indirect stakeholders (e.g., customers, regulatory bodies influencing product design and end-of-life management).

To analyze the complexity of a disassembly process, we adapt a hierarchical decomposition model from prior work (Formentini, 2022) based on systems engineering (Walden, 2015). We structured the DSE into five distinct, interacting levels. Each level is characterized by the type and granularity of information exchanged, and the scope of influence on design decisions, as shown in Fig. 3. These levels are.

- System of Systems (SoS) level: This is the highest level, with the lowest information granularity. It focuses on the interactions between multiple, independent systems that influence disassembly. For example, the interaction between the 'Reverse Logistics System' (how products are collected and transported) and the 'Industrial System' (where disassembly operations occur) can directly impact the feasibility and efficiency of disassembly. Other such systems include the 'User System' (influencing product condition at end-of-life) and the 'Recycling System' (determining material recovery pathways). Information at this level is strategic, focusing on broad policy and infrastructure. Design influence is indirect, setting the context for lower-level decisions.
- System level: This level focuses on a single system from the SoS level, providing more specific information. For instance, within the 'Industrial System,' this level details the specific disassembly operations: type (automatic, semi-automatic, manual), mode (destructive, non-destructive), and facility layout. Information managed here might include disassembly planning for entire product families (e.g., all washing machines from a manufacturer). The design influence becomes more direct, impacting process planning. Considering an industrial system capable of disassembling diverse product types and families, e.g., different models of ovens and refrigerators, is key to manage the complexity.
- Sub-System level: This level examines specific product families and their architectural structures within a given system. Information granularity increases further, focusing on relationships between product design and disassembly operations within a product family. For example, the presence of a common motor type across all models of a washing machine family allows for standardized disassembly procedures targeting that component. Variations in design within the family (e.g., a unique motor in a single model) necessitate a shift to the next, more granular level.
- Product level: This level focuses on individual product models. Information is highly specific, detailing the relationships between components within a single product. For example, the number and type of fasteners used in a specific washing machine model are identified here. This level allows for the identification of design patterns that either facilitate or hinder disassembly.
- Component level: This is the most granular level, focusing on individual parts and components and their interrelationships (e.g., a specific screw type and its material, the bearing used in a motor and its lubrication). This level provides the most direct information for DfD improvements, enabling targeted design changes to enhance disassembly performance (e.g., using snap-fits instead of adhesives).

The proposed view represents a top-down approach, meaning it starts with high-level systems (such as reverse logistics, stakeholder management, etc.) with low granularity, and then gradually leads to higher granularity as the levels become more specific, ultimately reaching the component level. This approach has been adopted in contrast to other bottom-up methods, where system decomposition begins at the product level (Fang et al., 2023; Joustra et al., 2021a,b). Thus, to holistically implement DfD methodologies, it is essential to consider all aspects of the DSE framework. To illustrate, a modification at the component level can have a cascade effect across all other levels, thereby impacting overall disassembly performance. In the following sections, the DSE framework is used to detail how parameters and information used in different DfD methodologies impact each DSE level and identify their shortcomings and opportunities to enable CE and sustainable solutions.

3.2. *Review of Design for disassembly methods in the Disassembly Systems Engineering*

The primary objective of DfD methods is to integrate considerations for the product disassembly processes during the initial design phase. Initially, DfD focused on reducing repair costs by designing products that are easy to disassemble, thus facilitating simpler repairs and lowering lifetime product costs. However, with increasing environmental awareness, DfD methods have gained significance in promoting product reuse and recycling (Chen et al., 1994). This shift in focus potentially benefits circularity while also enabling new systemic interactions across the product life cycle. To study the effect that DfD methods have on the whole product life cycle, we group DfD methods based on their contribution to the DSE framework, considering how the suggested design changes may impact disassembly properties in different stages.

Effective implementation of DfD methods can be a complex task necessitating a comprehensive array of information, including geometric and technological data, disassembly-related information from product design files, and an integrated information system to manage product life cycle information. Geometric and technological data include details about assembly components, such as movement interference and fastener identification and are crucial for understanding connections and interfaces between components (Cruz and Hvejsel, 2022). The impact of DfD methods can be quantified by analysing material flows during the disassembly process, incorporating the number of recovered materials in instances of destructive disassembly or number of recovered parts and components in instances of non-destructive disassembly (Popescu and Iacob, 2013). In addition, the information required for DfD may differ based on intended manual, automated, and/or semi-automated disassembly processes, highlighting the need for a robust integrated information system within the design and processes.

Literature on DfD is extensive, covering various methodologies and goals. A review of the relevant literature was conducted to understand how the DfD methods relate to SDE, depending on the methodology's focus and objectives. The review was carried out using a structured approach, specifically investigating articles indexed in the SCOPUS database. The search methodology and exclusion criteria are outlined in Fig. 6 in the Appendix. The following section detail the results from the literature review, as pertaining to different levels in the proposed DSE framework.

3.2.1. *Design for disassembly – component level*

Outlined in the DSE model, the Component Level offers the highest technological information of the product to DfD strategies. These strategies are dictated by the analysis and optimization of the product disassembly effort related to the study of functional connections and component material selection. Product disassembly is significantly influenced by design choices, particularly concerning the desired separation mechanism. In other words, the selection of materials and the design of fasteners can undergo drastic changes depending on the method used to dismantle components. By examining fasteners, component connections, and materials, shortcomings in both assembly and disassembly can be identified (Crowther, 2005).

Fasteners play a crucial role in assembly and disassembly processes, significantly influencing DfD efficiency (Güngör, 2006). Designers aim to minimize the number of fasteners and connections within assemblies, opting for fasteners and connections that facilitate easy and quick disassembly (Crowther, 2005). They also strive to avoid non-removable fasteners and reduce the overall count and diversity of fasteners. In literature, numerous methods and tools are available with the objective of minimizing the number of connections and components to decrease disassembly time (Vanegas et al., 2018; Peeters et al., 2018). De Fazio et al. (2021) proposed a method to assess the disassembly performances of products, considering various parameters such as the reusability and reversibility of fasteners. Through a review of current repairability scoring methods, Dangal et al. (2022) highlight the importance of understanding the interconnections among components to achieve better disassembly performances.

Computer-Aided Design (CAD) tools and technical drawings are indispensable in analysing component disassemblability due to the high density of information granularity in geometry (Issaoui et al., 2017). By distinguishing geometric relationships between components, disassembly directions can be extracted for optimization of disassembly movements. The disassembly directions are often generated by analysing CAD mates and validated using move and test methodologies (Costa et al., 2018). Shape is another important aspect to DfD when determining disassembly tool and handling. While component symmetry may not be relevant for robotic disassembly (Daneshmand et al., 2023), geometrical adjustments in shape and dimensions become important to both manual and automated disassembly. These adjustments can factor in material properties and the characteristics of assembly and disassembly equipment to optimize interactions between components and ensure smooth disassembly operations (Daneshmand et al., 2023).

Material selection balances the requirements for the facilitation of disassembly with subsequent recovery, recycling, and remanufacturing processes. Factors such as material mass, degradation, contamination, potential recovery, and recyclability all play significant roles (Favi et al., 2019). For manual separation, emphasis is placed on using large masses of a single material, while for mechanical separation, minimizing the variety of materials in the assembly is key. Designers strive to streamline material types in each part, reduce material diversity in the overall product, enable parts for remanufacturing or reuse, and simplify material identification processes (Escoto and Muñoz, 2020).

When ease and speed of disassembly are in focus, the number of disassembly actions are minimized, while maximizing the number of components obtainable with each action (Formentini and Ramanujan, 2023b). In this regard, disassembly operations can be categorized into two main groups.

- One-to-one techniques: These methods enable the disassembly of one component by removing one fixing element, such as a screw or a bolt. A common example is the use of a power screwdriver to extract a screw, directly releasing the attached part without affecting other components.
- One-to-many techniques: This group allows for obtaining more than one component by performing a single disassembly action. For example, applying a heat source to an assembly body can activate multiple snap-fit mechanisms at once, causing several components to detach simultaneously (Willems et al., 2005).

Disassembly Embedded Design and Active Disassembly methods (Chiodo et al., 1998; Chiodo et al., 1998b; Chiodo and Jones, 2012; Sun et al., 2014) are classified as one-to-many techniques (Willems et al., 2005). Disassembly Embedded Design utilizes smart materials or structures in product design to incorporate triggers that enable the disassembly of one or multiple components. On the other hand, Active Disassembly focuses on designing products that can be disassembled by the application of a trigger.

Willems et al. (2005) differentiate embedded and active disassembly based on the trigger principle. Embedded triggers encompass mechanical force, heat-activated mechanisms, and electromagnetic triggers, while active disassembly triggers include pneumatic elements, smart materials, freezing elements, and soluble nuts. Both active and embedded disassembly techniques influence product design decisions which necessitates the incorporation of these features into the product development process to achieve system-wide efficient and economical processes. Researchers have endeavoured to integrate these considerations into their research, for example, Chiodo and Boks (2002) suggested that active disassembly is less costly than conventional disassembly methods due to reduced process times. Furthermore, products composed of plastics or precious metals may benefit the most from active disassembly.

In their evaluation of guidelines for one-to-one disassembly, active disassembly, and embedded disassembly, Willems et al. (2005) considered DfD aspects such as less disassembly work, foreseeing events, easy disassembly, easy handling, easy separation, and variability reduction. They concluded that Design for Active Disassembly results in a 50 % reduction in the number of guidelines that need to be followed compared to traditional DfD guidelines.

Peeters and Dewulf (2012) investigated the economic and ecological implications of active disassembly for flat-screen televisions and payment terminals utilizing pressure-sensitive fasteners (Peeters et al., 2015, 2016b). In their study on flat-screen televisions, Peeters et al. (2012) found that active disassembly led to an increased rate of recycling compared to direct shredding. However, they highlighted the importance of detailed product information for identifying active disassembly triggers and sorting disassembled components. Regarding payment terminals, Peeters et al. (2015) assessed that the return on investment in active disassembly is approximately 27 %. However, they noted that this return is contingent on factors such as the age distribution of products and the collection rate.

Building upon previous studies, Peeters et al. (2016a) assessed the economic and environmental impacts of active fasteners in eleven electronic products. Their assessment revealed that the economic and environmental benefits of active disassembly are contingent upon product properties and boundary conditions. Active fasteners, particularly those based on pressure and temperature, were found to be economically viable only in product-service systems (PSS) characterized by high collection rates and separate collection of products. In a more recent review, Abuzied et al. (2020) examined active disassembly methods and underscored their importance in the context DfD methods.

Their review identified that active disassembly studies have primarily concentrated on shape memory alloy clips, wires, or snap fits. These mechanisms activate disassembly processes by employing small disassembly forces and achieving large displacements. Additionally, the review emphasizes the necessity for further research into automated disassembly techniques and the economic assessment of active disassembly in large assemblies.

Table 1 summarizes the parameters utilized by DfD methods focusing on product disassembly performance at the Component Level. Not all required parameters are readily available at the component level, thus future studies to evaluate and obtain these parameters are required.

3.2.2. Design for disassembly – product level

Disassembly research is increasingly reliant on CAD due to its capacity to model and integrate geometric and technological information, as well as generate disassembly plans and assess their suitability (Issaoui et al., 2017; Imen et al., 2020). At the Product level, various pieces of product information, such as assembly, sub-assembly, and overall dimensions, are generally readily available.

Table 1
Parameters relevant for modelling disassembly performance at the Component level. Parameters are clustered into groups, according to their similarity.

Group	Parameter	Reference
Component properties	Material Compatibility Mechanical Stresses	(Favi et al., 2019, Escoto and Muñoz, 2020)
Component number	Component type Quantity	(Rodríguez and Favi, 2022; Kręt-Grześkowiak and Baborska-Narożny, 2023; Telenko et al., 2009; Vanegas et al., 2018)
Joint properties	Dimensions Shape Fasteners reusability/ reversibility Active disassembly	(Costa et al., 2018; Daneshmand et al., 2023; Dangal et al., 2022)
Join type	Temporary Reversable Non-reversable	De Fazio et al. (2021)

Table 2
Parameters relevant for modelling disassembly performance at the Product level. Parameters are clustered into groups, according to their similarity.

Group	Parameter	Reference
Assembly liaisons	Fastener connections Sequence planning Sub-assembly relations	(Anil Kumar et al., 2021; Prioli et al., 2022; Upadhyay et al., 2023)
Operation type	Disassembly actions Accessibility	(Boix Rodríguez and Favi, 2023; De Fazio et al., 2021; Formentini and Ramanujan, 2023a);
Component properties	Geometry constraints Material Overall size	(Joustra et al. (2021); Abuzied et al., 2020; Peeters et al., 2018; Joustra et al. (2021a, b))

Researchers have investigated approaches to facilitate product disassembly at the Product level. Mircheski et al. (2016) introduced a CAD-based method that evaluates all conceivable subassemblies and disassembly operations based on detachment priority, ultimately generating an optimized disassembly sequence. Anil Kumar et al. (2021) transformed Bill of Materials (BOM) and CAD models into liaison, geometric feasibility, and stability matrices, forming the basis for an optimization model applicable to recycling and remanufacturing processes. Prioli et al. (2022) proposed an automated process that extracts feasible geometrical disassembly sequences from CAD assembly files, emphasizing the direct relationship between component geometry and disassembly sequences. Upadhyay et al. (2023) leveraged 3D data from CAD assembly models to construct assembly and component graphs, employing graph-based learning to generate disassembly sequences. Furthermore, Scott et al. (2023) investigated operational and energy costs associated with disassembling components jointed with polymeric adhesives, particularly relevant to lithium-ion batteries. Joustra et al. (2021a,b) proposed a structural analysis to segment component for reuse based on geometry and material properties combined. Boix Rodríguez and Favi (2023) contributed a DfD method focused on manual disassembly, that considered parameters such as fastener types, tools, operation types, component accessibility, and task and sequence planning. Their results indicated improvements in the disassemblability ratio through iterative design modifications.

At the Product level, information is typically shared among the individuals responsible for product design to facilitate efficient disassembly practices. However, there may be occasions where missing information needs to be retrieved through estimation, direct measurement, or consultation with external stakeholders. Disassembly operations provide a typical example of this scenario. These operations are often estimated using CAD relationships (Prioli et al., 2022) or determined through direct experiments (Boix Rodríguez and Favi, 2023; Formentini and Ramanujan, 2023b).

In summary, product-level considerations in DfD methods are multifaceted, integrating diverse design data to optimize disassembly processes and support sustainable practices in product life cycle management. Ongoing research in the field aims to convey fundamental disassembly data from product design to enable analytical tools for disassembly assessment. Table 2 summarizes parameters used in DfD methods at the Product level.

3.2.3. Design for disassembly – Sub System level

At the Sub-system level, the focus lies on the design perspective of a product family and its architectural coherence concerning disassembly. Product family design typically follows two primary approaches. The first is scalable product family design, which involves adjusting product platform dimensions using scaling variables (Simpson et al., 2005). While this approach does not alter the product's structure or disassembly sequence, it may impact disassembly time due to variations in dimensions and positions. The second approach is module-based product family design, which generates product variants from a modular platform (Gauss et al., 2021). This approach enables the use of DfD strategies to design product modules and integrate them within the product structure, rather than focusing solely on individual components.

When assessing the disassembly implications of module design, two aspects are typically considered: Architecture Mapping and Module Assessment. Architecture Mapping involves clustering components into modules, which subsequently inform recovery decisions. Common techniques for module clustering include Design Structure Matrix (DSM) and Modular Function Deployment (MFD) (Lima and Kubota, 2021), where clustering decisions are guided by parameters such as material compatibility, connector types, or tool requirements. Once modules are delineated, Module Assessment evaluates their disassemblability performances with respect to the assembly and the disassemblability component priorities. This assessment considers factors such as disassembly depth, meaning the steps required to detach a module or target component (Anil Kumar et al., 2021), motion-based disassembly time (Formentini and Ramanujan, 2023a), and the required tool types (De Fazio et al., 2021). Additionally, the module can be designed in consideration of geometric structure reuse (Joustra et al., 2021a,b).

Designing product architectures with similar materials and lifespans is of paramount importance for sustainability (Kim et al., 2021). Modules with compatible materials present easier recovery and recycling, while grouping modules by component lifespan and material compatibility simplifies maintenance procedures (Reuter et al., 2019). Moreover, parameters such as priority components, connectors, and tool selections significantly influence DfD within product families (Boix Rodríguez and Favi, 2023). Priority Parts determine disassembly depth, profoundly impacting repairability scores, and connector types assess the reversibility of connections and module reusability across assemblies. Tool selections can also directly affect disassembly efficiency, penalizing instances requiring non-standard tools.

Although certain parameters, such as tool choices, may not be finalized early in the design process, DfD can potentially benefit from early-stage assessments such as architecture mapping of connectors and materials. These assessments can contribute to estimating disassembly depth and evaluating ease of disassembly and repair. Thus, these parameters (Table 3) can offer insights for optimizing DfD during product family development.

3.2.4. Design for disassembly – system level

At the System level, considerations typically originate from the characteristics of disassembly processes, e.g. manual, automatic, or semi-automatic. This level has limited product design freedom as no direct design actions can be performed. Therefore, a systemic behaviour

Table 3

Parameters relevant for modelling disassembly performance at the Sub-System level. Parameters are clustered into groups, according to their similarity.

Group	Parameter	Reference
Architecture mapping	Component types Sub-assembly relations	(De Fazio et al., 2021; Kim et al., 2021)
Module assessment	Module-component relationships Assembly-module relationships Disassembly-module relationships	(Kim et al., 2021; Lima and Kubota, 2021)
Material compatibility	Material properties EoL properties	Reuter et al. (2019)
Connection reversibility	Reusability of module based on connector types	(De Fazio et al., 2021; Boix Rodríguez and Favi, 2023)
Disassembly depth	Disassembly steps required to achieve a target component or module	Boix Rodríguez and Favi (2023)
Motion-based disassembly time	Time to perform disassembly considering motion	De Fazio et al. (2021)
Tool requirement	Tool type	Boix Rodríguez and Favi (2023)

comparison is necessary to understand the effects of this level on overall product disassembly performance. Li et al. (2018) proposed a framework for assessing automated robotic disassembly, considering environmental, technological, and economic performance to support recycling and recovery. They introduced a decision-support tool to compare results from different recycling scenarios based on manual and automatic disassembly. Hellmuth et al. (2021) presented an approach to assess the automation potential of disassembly steps in EV batteries, utilizing design group disassembly procedures and evaluating both automated and manual operations. Lander et al. (2023) investigated the disassembly operational cost of current EV battery models, accounting for disassembly time and costs associated with manual and/or automated operations.

The literature also reveals that design information from the product level, such as Interference Matrix and Precedence Matrix, is widely explored to establishing relationships between components and translating them into disassembly procedures. This information enables the extraction of sequences for individual disassembly outcomes, which is crucial for Disassembly Sequence Planning (DSP). Additionally, Jacomini Prioli and Rickli (2023) leveraged collaborative robot trajectories and human-robot interaction to extract disassembly sequence and task plan for automated disassembly. Beyond component relationships, disassembly planning at the System level incorporates process factors for economic assessment, including disassembly time (Laili et al., 2019), tool change time (Parsa and Saadat, 2021), disassembly direction (Liu et al., 2018), energy consumption (Hu et al., 2018), waiting time (Xing et al., 2021), disassembly method - destructive and non-destructive (Zhang et al., 2022), and robot speed (Liu et al., 2018). The variety of factors available at the System level demonstrates the complexity of disassembly, stressing the importance and the need for considering these parameters in DfD practices to reduce the cost of disassembly procedures and enhance overall sustainability and circularity performances. In Table 4, parameters collected at the System level considered in DfD methodologies are summarised.

3.2.5. *Design for disassembly – system of systems (SoS) level*

At the SoS level, understanding the dynamics of disassembly requires consideration of the perspectives of various stakeholders, particularly those involved in EoL product management. This level plays a pivotal role, especially in the context of CE practices. To understand the transition to a CE, it is necessary to study the five interconnected systems identified by Iacovidou et al. (2021), which support the shift towards a CE.

Table 4

Parameters relevant for modelling disassembly performance at the System level. Parameters are clustered into groups, according to their similarity.

Group	Parameter	Reference
Operation mode	Disassembly process Destructive/Non-destructive	(Li et al., 2018; Hellmuth et al., 2021; Lander et al., 2023, Zhang et al., 2022)
Energy	Energy consumption CO_2 emissions	Hu et al. (2018)
Time	Disassembly time Process time Tool change	(Liu et al., 2018; Laili et al., 2019; Parsa and Saadat, 2021)
Task planning	Disassembly resources Sequence planning Movements	(Hu et al., 2018; Li et al., 2018; Laili et al., 2019; Hellmuth et al., 2021; Parsa and Saadat, 2021; Zhang et al., 2022; Lander et al., 2023; Xing et al., 2021; Liu et al., 2018; Jacomini Prioli and Rickli, 2023)

- Resource Flows: Focuses on efficient material management, encompassing metrics on material usage and recycling rates.
- Governance: Establishes rules and policy enforcement regarding product management.
- Business Activities: Drive innovation and resource efficiency within economic activities.
- Infrastructure and Innovation: Relate to technological advancements and circular design practices.
- User Practices: Influence demand and resource stewardship through consumer behaviour and awareness.

Each stakeholder engaged in EoL management, including Users, Service Providers, Manufacturers, and EoL stakeholders (e.g., remanufacturers, recyclers, and reverse logistics providers), contribute unique perspectives towards DfD (Acerbi et al., 2021). Understanding the preferences and behaviours of users is vital for designing products that can be better disassembled at their EoL and encourage circularity. This understanding allows public authorities, such as environmental agencies, to better monitor lifecycle performance and related impacts on the environment.

Service of Re-X providers (i.e., recycle, remanufacturing, refurbish, repair, reuse) play a crucial role in integrating maintenance, repair, and recycling services throughout the product life cycle. They benefit from shared knowledge about disassembly guidelines and EoL activities among manufacturers and stakeholders. This includes information regarding their location, distribution model, and retail prices (Duflou et al., 2008).

Manufacturers, by considering process management aspects such as logistics and disassembly costs during the design phase, can improve the product circularity. They can also incorporate considerations like product status, failure causes, and warranty issues from other EoL sources into DfD methods (Formentini and Ramanujan, 2023a). EoL stakeholders typically rely on stored disassembly plans and maintenance information from the design phase while also providing valuable insights into product conditions, disassembly scheduling, transportation requirements, and environmental policies.

Collaboration among different life cycle stakeholders is imperative for successfully implementing closed-loop life cycles and transitioning to circular business models (Marconi and Germani, 2017). Involving stakeholders from production, distribution, use, maintenance, and EoL phases can enable devising comprehensive solutions for product life cycle management, ensuring efficient resource utilization and sustainable practices throughout the product life cycle.

Table 5 summarizes a list of the identified parameters at the System of Systems (SoS) level for DfD.

Table 5
Parameters relevant for modelling disassembly performance at the System of Systems level. Parameters are clustered into groups, according to their similarity.

Group	Parameter	Reference
Maintenance guidelines	Guidance on disassembly tasks and sequences to be made	Acerbi et al. (2021)
Distribution model	Collection and distribution strategy of EoL products	Duflou et al. (2008)
EoL activities	Collection and EoL services locations Service activities after use phase	(Duflou et al., 2008; Marconi and Germani, 2017; Iacovidou et al., 2021)
Product status	Quality of product, maintenance history,	(Duflou et al., 2008; Formentini and Ramanujan, 2023b)
Failure causes	Cause of failure and warranty injuries	(Duflou et al., 2008; Formentini and Ramanujan, 2023b)
Environmental policies	Regulation mechanisms concerning environmental issues	Iacovidou et al. (2021)
User preferences	Consumer behaviour and preferences that ensure circular use	(Acerbi et al., 2021; Iacovidou et al., 2021)

3.2.6. *Disassembly system engineering – the role of standards*

The complexity of analysing the product disassembly performance increases when the entire product life cycle is considered, especially when (re)designing a product to achieve better circularity performances. The DSE model can offer a comprehensive overview of the complexity inherent in disassembly systems, identifying levels and parameters critical for applying DfD methodologies. It is noteworthy that some identified parameters may not be readily available for sharing among stakeholders due to a lack of established information sharing infrastructure or agreements, confidentiality and intellectual property concerns, and absence of common understanding of what information to collect or technical compatibility. For example, information about a product's EoL outcomes may be available at recycling facilities, but the absence of common definitions and information flows limit accessibility to that information by product designers. Standards to enable the collection and analysis of this information would enable insight at the product design phase to improve practicable product disassembly properties. As indicated by the DSE model, the sharing of information (including DfD information useable during later stages) across different levels is essential for achieving superior product disassembly performances.

Disassembly and DfD implementations have significant implications for product use and EoL stages, involving a broad spectrum of stakeholders, often without formal business links between them. For instance, third-party product value recovery agents, unrelated to the product's manufacturer, must effectively disassemble products to maximize value recovery. This independent service underscores the importance of standards and standardization for facilitating effective communication and operations among diverse industry stakeholders. A recent study by Arduin et al. (2019) emphasizes that clearly defining the scope of standards, particularly in recycling rate calculations, improves the accuracy of assessing recycling outcomes and informs better decision-making. This principle extends to disassembly and design standards, where well-defined scopes, guided by international and regional standards, promote consistency, efficiency, and waste reduction, ultimately supporting strategic and regulatory planning through standardized terms and practices.

A noteworthy contribution to the standards landscape is the British Standard series BS 8887, known as "*Design for manufacture, assembly, disassembly and End-of-Life processing (MADE)*" (BSI 8887, 2010) which particularly emphasizes DfD approaches. Initially published in 2006, this series focuses on developing standards for sustainable product design with a life cycle perspective, incorporating considerations of disassembly. The BS 8887 series (BSI 8887, 2018) define important terms related to EoL processing, thereby aiding communication within the industry. Notably, this series serves as the basis for the companion ISO standard series ISO 8887 (2017). Currently, parts 1 and 2 of BS 8887 have been published as ISO standards, and part 3 is in development at ISO. Additionally, parts 211, 220, and 240 of BS 8887 delve into processes related to various EoL strategies within specific industry sectors. This comprehensive series provides valuable guidance and standards for sustainable product design and EoL processing practices.

Another closely related standard is the EU standard CSN EN 45554: *General methods for the assessment of the ability to repair, reuse, and upgrade energy-related products* (CSN EN 45554, 2020). This standard also discusses how easy it is to remove specific parts of a product to perform repair, reuse, and upgrades.

These existing standards primarily focus on the Component and Product levels of the DSE model. The BS 8887 sets a framework for the technical documentation, including realizing the disassembly of products. For energy-related products, the EN 45554 standard contains useful quantification of disassembly at the Component and Product levels, including the disassemblability index, time taken for disassembly of parts, and disassembly depth–defined as the number of steps in the removal of parts from a product.

Though these current standards implicitly aid the Sub System, System, and SoS levels of DSE model, more standards are needed to explicitly address the unique disassembly needs at these higher levels. For example, the above-mentioned Component and Product levels focused standards' guidance on technical documentation and defining of terminology implicitly aid the communication needs of broader levels of DSE model. However, standards are lacking to explicitly support Sub System level needs (e.g., quantify disassembly performance impacts due to scalable or module-based product family design), or System level (incorporate design considerations due to available methods of disassembly—manual, semi-automated, and automated), or SoS level (established frameworks and/or data sharing systems to enable stakeholder collaboration for effective disassembly).

While not a standard, the European Commission recently reached an agreement on the 2023 proposal "*on common rules to promote the repair of goods for consumers*" (European Commission, 2024). Although the primary focus is not disassembly, the rule will have implications for facilitating disassembly at both the Product and System levels by providing guidelines on national online repair platforms and setting spare parts availability requirements (European Commission and Parliament, 2020). Since disassembly is a fundamental aspect of extended producer responsibility (EPR), certain EPR standards and regulations have System-level repercussions related to disassembly. For instance, the waste electrical and electronic equipment (WEEE) Directive (2012/19, 2012) or end of life (ELV) Directive (2000/53, 2000) do not explicitly outline disassembly requirements. However, manufacturers must consider disassembly (or "dismantling" as termed by the directives) and provide disassembly information for their products to comply with those directives, indirectly establishing disassembly guidance at the System and SoS levels. Nonetheless, a significant gap in explicit standards on broader DSE levels' disassembly remains and could be filled with enhanced guidance for manufacturers and designers.

4. Disassembly Systems Engineering – parameters and information connections

DfD methods and frameworks available in literature differ in terms of the disassembly data needed and how information can be retrieved. This complexity is encapsulated and described with the DSE model. Analysing DfD methods and tools available in literature resulted in identification of different parameters that were clustered into levels. It is interesting to note that DfD methods require the use of several parameters at different levels to efficiently design products for disassembly.

The optimization of products for disassembly can serve three primary goals: improving product circularity, recyclability, and reparability. While these goals are interconnected, the specific design parameters that need to be tuned may vary depending on the aim. For example, optimizing the disassembly performance of a product to enhance reparability would necessitate different redesign actions compared to those required to improve the product's circularity performance (Formentini and Ramanujan, 2023a).

Different parameters within the DSE may be of interest depending on the goal of the disassembly process. Based on the literature, parameters used in various DfD methodologies are clustered according to.

- System Level: This indicates the level where data related to the parameters are available.
- Parameter Group: This identifies the name of the group of parameters considered.
- Symbol: This provides a unique identifier associated with the parameter group.
- DfD Aim: This describes which DfD methodology the parameter is considered in. It can aim to
  - o Improve product circularity, meaning the ability of reusing the product at its maximum value, where the product EoL stage is of interest.
  - oImprove product recyclability, where the ability to recover product materials is of interest.
  - oImprove product reparability, where the ability to recover product functionality before reaching the EoL stage is of interest.
- Design Effect: This describes the effect that the parameter group has on the product design.
- Ascertainability: This discusses whether the parameter group is available within original equipment manufacturers (OEMs) when applying DfD methodologies. Possible values are
  - oHigh: It can be obtained within the company.
  - oMedium: It can be estimated using different techniques.
  - oLow: It is not currently available.
- Standards Coverage: This indicates whether the parameter is presented in a standard. Possible values are
  - oYes: relevant standards are listed.
  - oNo: no relevant standards are available.
- Affected Parameters: This presents the parameters that are related to and affected by the considered parameter.

The ascertainability has been assumed based on the authors' best knowledge and experience; however, it may not be generally applicable to all industries and companies.

The interconnectedness of parameters across different levels highlights the complexity and holistic nature of DfD methodologies. Changes made at one level can have cascading effects on other levels, influencing various aspects of the product life cycle. For example, alterations at the component level, such as changes in material composition or joining mechanisms, can impact disassembly operations at the system level. A shift to different materials may affect how components are disassembled and recycled, while modifications to joining mechanisms could require adjustments in disassembly processes. Similarly, changes at higher levels, such as system or system-of-systems levels, can also influence lower-level parameters. For instance, decisions made regarding take-back practices at the system-of-systems level may dictate requirements for component-level material properties or disassembly procedures. This interconnectedness underscores the importance of considering multiple levels and parameters simultaneously in DfD methodologies. By understanding how changes at one level ripple through the entire system, designers and engineers can make informed decisions that optimize product disassembly, recyclability, and reparability across the entire product life cycle.

To explore this complexity, the identified parameters have been compiled in Table 6 and organized according to the divisions proposed earlier.

Not all identified parameters may be available with OEMs (judged based on their level of ascertainably). Particularly, information regarding the Distribution Model, Energy, and Operation Mode might be challenging to collect, as there is no direct link between the OEM and the stakeholders owning this information. To address these information gaps, several projects are currently underway, particularly within the European Union. Among these, the Digital Product Passport (Adisorn et al., 2021) is anticipated to be a mandatory innovation enabling data sharing among stakeholders within the DSE level. Certain information can be estimated internally using various resources such as reports or methods and tools. For example, information regarding product status and failure cases can be estimated using failure analysis (Formentini and Ramanujan, 2023b).

Currently, the coverage of standards in the context of DSE is opposite to that of the general coverage of CE standards. CE and CE-adjacent standards are at the macro-level, often covering topics such as terminology, general concepts, indicators, and business models. However, within the scope of DSE, many of the available standards are within the component, product, and sub-system levels. We observe the need for micro and meso-level standards to build highly granular standards that can be used to inform system-level standards in the scope of not only DSE but other complex CE systems.

It is important to note that high-level standards in DSE are still needed to set scope, boundaries, and commonalities. As shown in Table 6, standards coverage for maintenance guidelines exists within the systems-of-systems area of DSE. Standards coverage in other SoS parameter groups, such as user preference, EoL activities, and distribution models, can help characterize the relationships between DSE and EoL activities. Using high-level standards for domain mapping remains an opportunity to inform requirements of more granular system-level standards.

The relationships among parameters groups have been plotted in Fig. 4 based on information in Table 6. To further analyze the relationships visualized in Fig. 4, and to quantify the influence of the identified DfD parameters, we have calculated centrality metrics (Borgatti, 2005) for the parameter network. Table 7 in Appendix summarizes the Degree, Betweenness, and Closeness centrality metrics for each parameter, evaluated across the overall DSE framework as well as specifically for networks focused on Circularity, Reparability, and Recyclability. These centrality metrics provide a data-driven perspective on parameter importance within the DSE framework. In our DSE context, Degree centrality reflects the number of other disassembly parameters directly influenced, revealing a parameter's broad impact. Betweenness centrality identifies crucial intermediary parameters that act as bridges, significantly affecting how influence propagates throughout the disassembly system. Finally, Closeness centrality indicates a parameter's central integration and efficient connectivity within the entire network of DfD considerations, highlighting its fundamental role.

Analysis of Table 7, available in Appendix, reveals several key insights. Across both the overall DSE framework and the network focused on Circularity, SB7 (Tool requirement) emerges as particularly critical, exhibiting high centrality values and highlighting the fundamental role of tool considerations in diverse disassembly contexts. Furthermore, parameters that dictate the disassembly process, namely C4 (Joining type), S1 (Operation mode), and S4 (Task planning), consistently demonstrate high betweenness and degree centrality, underscoring their central influence in shaping effective disassembly. Several parameters act as important 'runners' influencing disassembly processes, including SB2 (Architecture mapping), SB4 (Connection reversibility), S3 (Time), and SS4 (Product status), suggesting their significant, though slightly less central, role. When focusing specifically on Reparability, C4 (Joining type) becomes even more central, alongside SB2 (Architecture

Table 6

DfD parameters are divided into DSE levels. The table summarizes information obtained from the literature review, clustering DfD methods according to their System Level, Aim, Effect on product design, and Ascertainability. It also indicates whether standards are available covering the identified parameter groups and which parameters are linked to each other.

DSE level	Parameter Group	Symbol	DfD Aim	Design effect	Explanation	Ascertainability	Standard Coverage	Affected parameters
Component	Material	C1	Circularity Reparability Recyclability	Creates material selection	Selection of different material can impact the circularity of the product, reducing the number of times it can be reused; the recyclability modifying the process required to recycle it and reparability, since brittle materials may be not suitable to be repaired	High	IEC TS 6342, IEC 82474-1, ASTM E3027	SB2, SB3, P3, C4
	Geometry shape	C2	Circularity Reparability Recyclability	Constrain access and handling	The geometry shape may affect the recovery and reparability process of components	High	Not Available	C3, C4, C5, SB7, S4, P3, S2
	Parametric dimensions	C3	Circularity Reparability	Constrain access and tool requirements	Component dimensions may affect the recovery and reparability process of the component	High	Not Available	P3, SB1, SB4, SB6, SB7, S3
	Joining type	C4	Circularity Reparability Recyclability	Create component relationship, dictates the reversibility	Different joining may affect the recovery and recyclability process, increasing/decreasing the easiness of removing specific components	High	Not Available	C5, P1, P2, SB1, SB2, SB4, SB6, S3, SS1, SS5, SS4
	Component number	C5	Circularity Reparability	Dictates the assembly complexity	The number of components affects the product complexity, increase/decrease the number of required actions to recover components.	High	Not Available	P1, SB1, SB2, SB5, S3, S4, SS1, SS2, SS7
Product	Assembly liaisons	P1	Circularity Reparability Recyclability	Influence disassembly directions and operations sequence	It affects the relation among components, influencing assembly and disassembly operations constraining directions and sequences.	High	EN 45554, BS 8887	C5, P2, SB1, SB2, SB5, S1, S3, S4, SS1
	Operation type	P2	Circularity Reparability Recyclability	Prescribes design-based process	Product designed with specific disassembly operations may influence the possibility to perform disassembly with other means (e.g., manual disassembly products can be hard to be fully automatic disassembled)	High	EN 45554, BS 8887	C2, C3, C4, SB1, SB2, SB4, SB5, SB6, SB7, S1, S2, S3, S4, SS4
	Component properties	P3	Circularity Reparability Recyclability	Constrains movement and tool access	Different components properties may constraint the disassembly process to be done with specific tool	High	EN 45554	C2, SB2, SB4
Sub-system	Module assessment	SB1	Circularity Reparability	Dictates assembly and subassembly decomposition	Modules affect the collection of target components and the business model behind the reparability and circularity	High	Not Available	C5, P1, SB2, SB4, SB5, S1, SS1, SS2, SS3
	Architecture mapping	SB2	Circularity Reparability	Dictates module reversability and material destination	Modules affect the collection of target components and the business model behind the reparability and circularity	High	Not Available	C4, P1, SB4, SS6, S4
	Material compatibility	SB3	Circularity Reparability Recyclability	Influences EoL recovery process	Affects EoL recovery processes	High	Not Available	C1, C4, SB7, S1, S3, S4, SS3, SS5, SS6
	Connection reversibility	SB4	Circularity Reparability Recyclability	Influences disassembly method	Affects the reuse and reparability properties of products, enabling consideration regarding module reusability and reversibility	High	EN 45554, BS 8887	C3, SB6, SB7, S4, S3, SS5, SS7
	Disassembly depth	SB5	Circularity Reparability	Influences serviceability and recovery of component and repurposing of modules	Affects the ability to recover and repair key components.	High	Not Available	C5, P1, SB2, SB6, S1, S3, S4, SS1, SS3, SS7
	Motion-based disassembly time	SB6	Circularity Reparability Recyclability	Influences task and trajectory planning	Assessment of disassembly time through motion-based techniques consider aspects related to the overall product architecture	Medium	Not Available	C2, C3, C5, SB2, SB4, SB7, S3, S4, SS4, SS5

(continued on next page)

Table 6 (*continued*)

DSE level	Parameter Group	Symbol	DfD Aim	Design effect	Explanation	Ascertainability	Standard Coverage	Affected parameters
	Tool requirement	SB7	Circularity Reparability	Prescribes toolset	Tools affect the ability to disassemble products efficiently	High	Not Available	C2, C3, C4, P2, SB4, SB6, S1, S3, SS1, SS3, SS4, SS5; SS6, SS7
System	Operation mode	S1	Circularity Reparability Recyclability	Adjusts shapes to process	The choice of disassembly operation affects the product design. Automatic, Semi-Automatic and Manual techniques have different effect on the product design	Low	Not Available	P1, P2, SB2, SB4, SB7, SS1, SS3, SS4
	Energy	S2	Circularity	Adjusts component properties	The use of different energy sources can impact the overall circularity of the product	Low	Not Available	P2, SB7, S1, SS4, SS7
	Time	S3	Circularity Reparability	Adjusts component number and joining type	Time heavily affects circularity and reparability performances	Medium	Not Available	C4, C5, P2, SB2, SB5, S1, SS3
	Task planning	S4	Circularity Reparability	Dictates the disassembly sequence	Planning disassembly procedures considering disassembly sequence and resources needed can affect product architecture and product design	High	Not Available	P1, P2, SB2, SB5, SS1, SS2, SS3, SS4, SS7
System of systems	Maintenance guidelines	SS1	Reparability	Influence reparability aspects	Information about maintenance of the whole system affects the reparability practices	High	ISO 55000, ISO 13374	P3, SB4, SB5, SB7, S1
	Distribution model	SS2	Circularity Recyclability	Influence product dimensions, materials and task planning	The logistic linked to product recollection at EoL and when it breaks down, affect the product CE business model	Low	Not Available	C1, C3, P3, SB3, S1, S4, SS3, SS4, SS6, SS7
	EoL activities	SS3	Circularity Recyclability	Adjust material selection and operation mode	Activities performed at product EoL affects the disassembly performances of the product	Low	Not Available	C1, SB7, S1, SS2, SS4, SS5
	Product status	SS4	Circularity Recyclability	Impact on the shape and material design	The status of the product when collected at EoL affects disassembly performances	Medium	Not Available	C1, C2, C4, P3
	Failure causes	SS5	Circularity Reparability Recyclability	Adjusts shape, material, and disassembly plans to increase lifespan	The way in which product is used by users affect the reuse and harvest of target components	Medium	Not Available	C1, C2, C4, P2, SB3, SB4, S1, SS1, SS7
	Environmental policies	SS6	Circularity Reparability Recyclability	Influences on material and recovery process	Regulations and policies affect the product design, increasing/decreasing circularity and recyclability performances	High	Not Available	C1, P3, SS6, S2, SS2, SS3
	User preferences	SS7	Circularity Recyclability	Influences on material and shape	User feedback impacts the product design, increasing/decreasing circularity, and recyclability performances	High	Not Available	C1, C2, P3, SB7, SS1, SS5, SS6

mapping) and SB4 (Connection reversibility), indicating the increased importance of design choices that facilitate easy access and reversible connections for repair scenarios. Finally, for Recyclability, while C4 (Joining type) remains fundamentally important to overall DSE, the influence of SS5 (Failure causes) appears to diminish, suggesting a shift in focus away from product lifespan and failure modes towards material-centric considerations in recycling-oriented disassembly design.

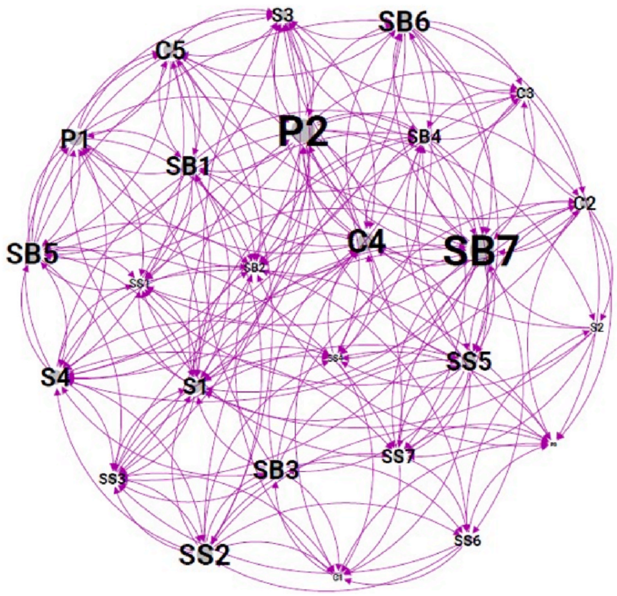
The DSE model sheds light on the importance of considering disassembly as a system engineering issue when products are designed to be easy to disassemble. Depending on the disassembly goal—whether to make the recycling process easier, to extract target components faster to improve reparability, or to harvest components at the EoL to achieve circular solutions—different disassembly parameters at different system levels (and thus, different granularities) must be considered. The system overview provides a better understanding of the overall complexity and the effect that disassembly parameters have on product design and the entire disassembly system. However, when parameters from different levels are affected, it leads to an increase in data and information sharing, shifting the design effort from a purely engineering design problem to a communication and data availability problem.

5. Impact

In this section, the impact of the literature review on DfD is analysed through the DSE framework, together with possible future research directions.

5.1. DSE framework as a tool to analyze DfD literature review

The presented literature review provides an overview of DfD methodologies used to study CE. In particular, the DSE framework offers insights into the disassembly systems that need to be considered within CE thinking. The DSE framework helps to understand how disassembly systems are, in themselves, system-of-systems, and how, in order to successfully implement CE practices, these systems must be integrated into CE approaches. The DSE framework also helps identify which parameters are most critical to the disassembly system, particularly during the design phase through DfD methodologies. It enables practitioners and designers to shed light on which parameters should be prioritized during the design process of products developed with circularity in mind.



Symbol	Parameter
C1	Material
C2	Geometry shape
C3	Parametric dimensions
C4	Joining type
C5	Component number
P1	Assembly liaisons
P2	Operation type
P3	Component properties
SB1	Module assessment
SB2	Architecture mapping
SB3	Material compatibility
SB4	Connection reversibility
SB5	Disassembly depth
SB6	Motion-based disassembly time
SB7	Tool requirement
S1	Operation mode
S2	Energy
S3	Time
S4	Task planning
SS1	Maintenance guidelines
SS2	Distribution model
SS3	EoL activities
SS4	Product status
SS5	Failure causes
SS6	Environmental policies
SS7	User preferences

Fig. 4. – DfD parameters relation among different DSE levels.

It is noteworthy that, even though all parameter groups influence each other at every level of the DSE, five parameters appear to have a relatively higher influence. Specifically*,* **SB7 – Tool requirement** plays a crucial role in the majority of disassembly parameters as disassembly tasks heavily rely on the tools required, though some researchers have focused on developing disassembly techniques that require no tools (Liu et al., 2012, 2013). **C4 – Joining type** plays a crucial role in disassembly processes. The type of joint can significantly affect the overall disassembly performance throughout the life cycle. For instance, choosing welding over screws can jeopardize the disassembly process, making it infeasible. The role of joining is widely recognized in academia and industries as a central aspect of disassembly (Shetty et al., 2000; Favi et al., 2012). **P2 – Operation type** highly affects several aspects of the DSE model. Performing manual or automatic disassembly can change the entire disassembly process and setup, as well as collection practices. Automatic disassembly could improve the process, but it requires a high level of standardization to be maintained throughout the product life cycle. **SS2 – Distribution model** is recognized as a central parameter in enabling CE practices. Distribution and collection of products once dismantled poses challenges, especially in large enterprises. **SB5 – Disassembly depth** is central to disassembly practices, from reparability to circularity. Reducing the disassembly depth impacts parameters such as disassembly time, process, and joining type. Disassembly depth needs to be carefully evaluated when designing products for disassembly, as it can also affect user experience (e.g., maintenance).

Another interesting result from the literature review, when analysed using the DSE framework, is that the impact of parameters on disassembly performance varies depending on the design focus. For instance, considering the parameter SB7 – Tool requirements, if the goal is to improve product recyclability, this parameter is directly linked to 12 other parameters. However, if the aim is to enhance disassembly performance for reparability, 16 parameters are affected. Finally, when circularity is of interest, the affected parameters remain 16, but parameters at the "system" and "system of systems" levels become more important. This aligns with studies showing that systems thinking plays a key role when CE is the focus (Jerome et al., 2022).

The DSE framework helps in understanding how disassembly systems affect product design and highlights that, depending on the design goal (recycling, reparability, or circular economy), different parameters within the disassembly system have varying levels of importance. In other words, depending on the disassembly goal, whether to simplify the recycling process, extract target components more efficiently for reparability, or harvest components at the end-of-life to enable circular solutions, different disassembly parameters at various system levels (and thus, different granularities) must be considered. Specifically, when CE is of interest, the DSE framework helps understand how disassembly plays a central role, shifting the view of disassembly from a single-product activity to a system-level perspective. It uncovers the disassembly value chain, offering insights into how product design parameters affect the overall disassembly system. The DSE framework has been used to shed light on the extensive literature on DfD methodologies, providing a better understanding of how the discussed parameters fit into the broader picture.

To further illustrate the operationalization of the DSE framework and the interdependencies between its levels, Fig. 5 presents a UML-style diagram that visually maps key functions within each DSE level along with a non-exhaustive list of associated disassembly functions. The diagram depicts how functions at each level are interconnected, with arrows indicating the direction of parameter influence across levels. Distinctly, the width of these arrows is visually weighted to represent the relative level of interaction between DSE levels, with thicker arrows emphasizing the central and integrative role of the Product level in mediating information and influence flow across the entire framework.

Furthermore, the diagram highlights the presence of existing standards associated with certain DfD parameters, particularly at the 'Standards' box linked to various levels. However, it also implicitly reveals gaps in standardization, with several parameters and functions across different DSE levels lacking direct standard coverage. This lack of comprehensive standardization can create a cascade effect, potentially hindering effective implementation of DfD methodologies even at levels where standards exist. For instance, if foundational parameters at the Component level lack standardized metrics, this deficiency can propagate upwards, limiting the effective application of standards intended for higher system levels. This visual representation reinforces the need for more holistic and comprehensive standardization efforts across all DSE levels to fully realize the framework's potential impact on circular product design.

5.2. Future research directions

Moving forward, the Disassembly Systems Engineering (DSE) framework opens numerous avenues for future research, each crucial for

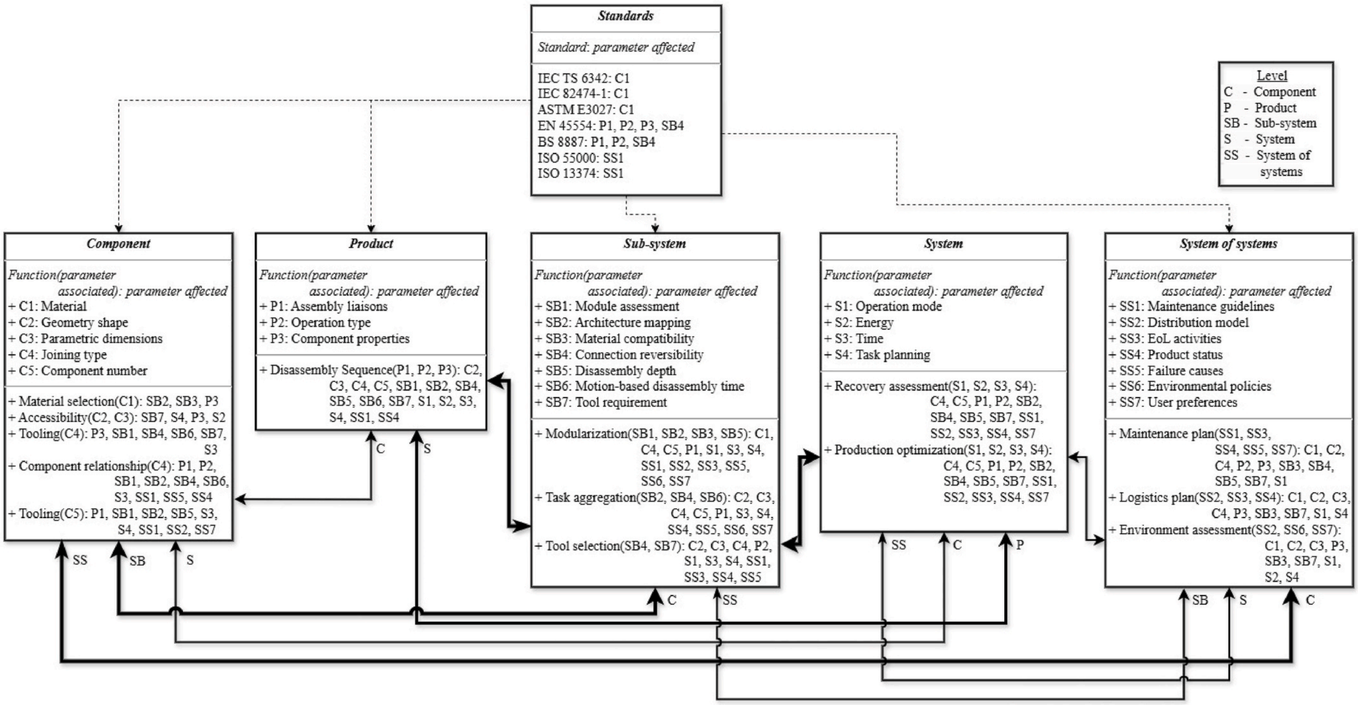


Fig. 5. – UML-style diagram of DfD parameters with DSE levels.

realizing the full potential of disassembly in circular economies. At the component level, a key direction lies in innovating component designs themselves, prioritizing circularity through advanced material selection and reversible joining techniques. This necessitates research into materials optimized for recyclability and novel joining methods like smart materials or reversible adhesives. Future work should focus on developing component-level eco-design guidelines and standardized material passports to facilitate efficient material loops and component sorting, directly addressing gaps in both CE and Ecodesign domains, while leveraging DfD principles and driving standardization. Expanding to the product level, a promising research direction is the integration of Artificial Intelligence and robotics for automated disassembly planning and optimization. This includes developing AI-driven methods for disassembly sequencing and creating CAD-integrated DfD tools specifically for product-level analysis.

At the sub-system level, future research should explore modular product family design principles that champion component and module reuse across product variants. This necessitates investigating circular business models that leverage modularity for module reuse and repurposing, effectively bridging the gap between CE principles and practical business implementation. Coupled with this, comprehensive environmental assessments of modular designs are needed. Specific modular architectures and standards for module interfaces are also crucial for realizing scalable module reuse and remanufacturing, driving progress in standardization. Stepping up to the system level, decision support systems for disassembly process selection and optimization are paramount. Research should focus on developing tools that guide the choice and refinement of disassembly processes (e.g., manual, automated, etc.) considering operational constraints and circularity goals. This direction directly addresses the need to optimize industrial symbiosis and closed-loop manufacturing, minimize the environmental footprint of disassembly processes, and develop system-level for efficient facility planning. Data exchange standards within disassembly systems are also vital for seamless integration and optimized operation.

Finally, at the system-of-systems level, research must investigate policy and infrastructure frameworks to support regional and national disassembly ecosystems. This includes analyzing the broader socio-economic impacts of large-scale disassembly and developing effective policy instruments such as extended producer responsibility schemes. Future research can significantly build upon DSE by specializing it to specific regional contexts. These regions can be considered as distinct "disassembly perimeters," each with unique infrastructure, regulations, and market conditions influencing optimal EoL strategies and thus, disassembly approaches. Future work could investigate how DSE can be adapted to guide decisions on disassembly possibilities (complete, partial, selective) within these specific regional perimeters, considering factors like local recycling capabilities and collection infrastructure. This regional specialization would enhance DSE's practical applicability and relevance in diverse circular economy implementations. Analyzing regional variations in reverse logistics infrastructure, regulatory landscapes for waste management, and the economic viability of different EoL strategies within specific regions would allow for the development of more tailored and effective DSE implementations, further strengthening the link between policy, infrastructure, and circular economy objectives.

To enhance DSE's analytical capabilities and adoption, future research should focus on developing a formal ontology that standardizes terminology and relationships across DfD parameters, ensuring better data integration and interoperability with product lifecycle management systems. Additionally, incorporating quantitative elements—such as equations and databases linking DfD parameters to disassembly performance metrics—would enable more rigorous analysis, simulation, and optimization, shifting DSE beyond qualitative assessments toward data-driven decision-making. While this paper establishes a literature-based foundation for DSE, empirical validation remains essential. Future studies should apply DSE to diverse product categories and industries, using real-world case studies to assess its predictive accuracy and effectiveness in improving disassembly performance. This empirical approach will not only solidify DSE's credibility but also uncover practical challenges and opportunities for its broader implementation in circular economy applications.

6. Conclusions

The rising interest in sustainability and circularity across industries is driven by new regulations like the EU Circular Economy action plan (European Commission, 2020), which promotes shifting from a linear to a circular economy to enhance economic resilience. The Circular Economy (CE) focuses on keeping products, components, materials, and energy in circulation to sustain value. Key to CE is product design, incorporating guidelines and methods for sustainable and circular products. Design for Environment (DfE) or ecodesign approaches can minimize environmental impacts by considering the entire product life cycle, including standards like the Ecodesign Directive (Directive, 2009) and ISO 14006 (ISO 14006, 2020), which focus on value recovery, resource consumption reduction, and renewable resources. Several approaches, methods, and indicators have been proposed in the literature to quantify the circularity performances of products. For example, Product circularity assessment methods evaluate how well products meet circularity requirements but often lack consistency, comprehensive coverage, and practitioner engagement. Moreover, sustainability standards serve as benchmarks for circular product design, but comprehensive application at the design stage remains challenging without dedicated CE-oriented standards for disassembly and value recovery.

The ability to effectively disassemble products is considered crucial for transitioning to CE. However, product disassembly performance is often viewed through the lens of product design without considering the broader system in which the product disassembly takes place. Even though DfD methodologies are essential for improving reparability, remanufacturing, and recycling, it is mandatory to consider the overall product life cycle system to achieve higher circularity product performances.

The proposed framework, called Disassembly Systems Engineering (DSE), provides an understanding of the complexity inherent in product disassembly at different levels. Moreover, a literature review of Design for Disassembly (DfD) methods has been performed, and relevant literature has been clustered according to the DSE framework to understand what types of parameters and information are required at different stages of product disassembly and how this information can be retrieved. Furthermore, standards currently available in the literature for disassembly practices have been identified and analysed using the same framework. More comprehensive standards are necessary, particularly to improve the technical and communication gaps in information sharing within and between different DSE levels. The literature review described through the proposed framework identified five key parameters that drive product circularity performances in terms of disassembly properties. The identified parameters are Tool Type, Joining Type, Operation Type, Distribution Model, and Disassembly Depth. These parameters heavily affect the disassembly performance of a product when enhancing circularity is desired. Finally, we showed how different aims at the design phase (i.e., DfD to improve circularity, reparability or recyclability) can affect parameters differently, increasing the overall system complexity.

The proposed novel DSE framework, along with the associated literature review, aims to provide new insights on the complexity of disassembly practices in enabling a Circular Economy, offering a new holistic perspective on disassembly practices.

CRediT authorship contribution statement

Giovanni Formentini: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joao PJ. Prioli:** Writing – review & editing, Writing – original draft, Validation, Investigation, Data curation. **Junwon Ko:** Writing – original draft. **Buddhika Hapuwatte:** Writing – original draft, Investigation. **Vincenzo Ferrero:** Writing – review & editing, Investigation. **Fazleena Badurdeen:** Writing – review & editing. **Jeremy L. Rickli:** Writing – review & editing, Investigation. **Devarajan Ramanujan:** Writing – review & editing.

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.

Acknowledgements

This research conducted in this article is partly supported by European Union's Horizon 2020 research and innovation program under grant agreement No. 958448, project CircThread (Building the Digital Thread for Circular Economy Product, Resource & Service Management). The findings and opinions stated in this paper reflect the opinion of the authors and not the opinion of the European Commission.

This work represents an official contribution of the National Institute of Standards and Technology (NIST) and hence is not subject to copyright in the United States. Identification of commercial systems are for demonstration purposes only and does not imply recommendation or endorsement by NIST.

APPENDIX A

Literature Review Approach

The review was carried out using a structured approach, specifically investigating the SCOPUS database, which the authors consider the most suitable for engineering and design practices. The database was searched using keywords such as "method*", "indicator*", "parameter*", "model*", and "design for disassembly" within the title, as well as "design for disassembly" within the title, abstract, and article keywords. Due to the large quantity of results, a filtering process was applied, excluding journal articles published in lower ranked journals (Q3 and Q4), articles focusing only on specific case studies (e.g., methodology to design a hydro turbine), articles unrelated to engineering design science, and articles not related to disassembly. This led to the inclusion of 38 articles. Additionally, based on the references of the articles found, a snowballing approach was applied, adding 11 more articles. In total, 49 articles were considered. This review aims to address and understand the complexity associated with disassembly methodologies when a holistic and systems view is used. The overall approach is outlined in Fig. 6.

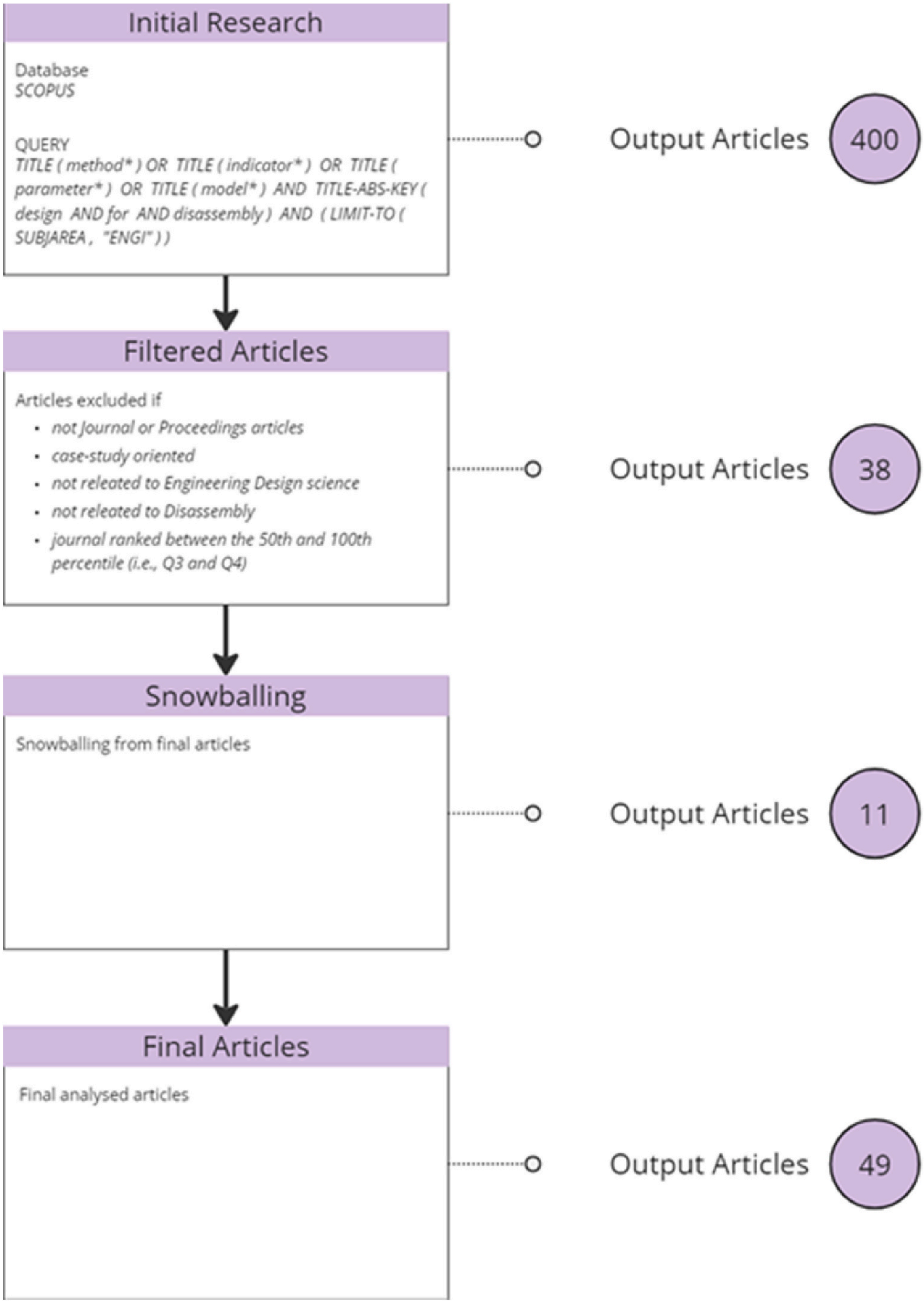


Fig. 6. Review methodology

Centrality Metrics

Table 7
DfD parameters centrality metrics

Methodology main scope	Centrality Metric	C1	C2	C3	C4	C5	P1	P2	P3	SB1	SB2	SB3	SB4	SB5
Overall DfD	*Degree*	0.44	0.56	0.48	0.8	0.64	0.64	0.88	0.44	0.56	0.68	0.48	0.72	0.68
	Betweenness	0.02	0.04	0.02	0.07	0.02	0.02	0.06	0.02	0.02	0.04	0.02	0.05	0.02
	Closeness	0.52	0.56	0.56	0.61	0.53	0.56	0.58	0.58	0.5	0.66	0.43	0.64	0.52
Circularity	*Degree*	0.46	0.58	0.5	0.79	0.63	0.63	0.92	0.42	0.54	0.71	0.5	0.71	0.63
	Betweenness	0.02	0.05	0.02	0.07	0.02	0.02	0.07	0.02	0.02	0.04	0.02	0.05	0.01
	Closeness	0.53	0.56	0.56	0.62	0.53	0.56	0.59	0.56	0.51	0.67	0.44	0.63	0.5
Reparability	*Degree*	0.35	0.55	0.55	0.9	0.7	0.8	0.95	0.4	0.6	0.85	0.5	0.85	0.75
	Betweenness	0.03	0.03	0.02	0.09	0.02	0.03	0.06	0.03	0.01	0.08	0.02	0.08	0.03
	Closeness	0.41	0.53	0.53	0.63	0.59	0.59	0.57	0.56	0.53	0.71	0.37	0.69	0.54
Recyclability	*Degree*	0.67	0.53	0	0.8	0	0.27	0.67	0.53	0	0	0.6	0.6	0
	Betweenness	0.06	0.03	0	0.17	0	0.01	0.06	0.04	0	0	0.07	0.11	0
	Closeness	0.58	0.63	0	0.63	0	0.45	0.54	0.6	0	0	0.45	0.63	0

Methodology main scope	Centrality Metric	**SB6**	**SB7**	**S1**	**S2**	**S3**	**S4**	**SS1**	**SS2**	**SS3**	**SS4**	**SS5**	**SS6**	**SS7**
Overall DfD	*Degree*	0.64	1	0.8	0.32	0.68	0.76	0.6	0.6	0.6	0.52	0.64	0.48	0.6
	Betweenness	0.02	0.09	0.04	0.01	0.03	0.05	0.02	0.04	0.03	0.02	0.04	0.02	0.03
	Closeness	0.56	0.64	0.63	0.45	0.61	0.63	0.6	0.49	0.58	0.6	0.57	0.54	0.57
Circularity	*Degree*	0.67	0.96	0.75	0.33	0.71	0.75	0	0.63	0.63	0.54	0.63	0.5	0.58
	Betweenness	0.02	0.08	0.03	0.01	0.03	0.05	0	0.04	0.03	0.03	0.04	0.03	0.04
	Closeness	0.56	0.63	0.62	0.46	0.62	0.63	0	0.5	0.59	0.6	0.57	0.55	0.57
Reparability	*Degree*	0.75	0.95	0.75	0	0.8	0.7	0.7	0	0	0	0.65	0.35	0
	Betweenness	0.03	0.08	0.02	0	0.03	0.03	0.04	0	0	0	0.08	0.03	0
	Closeness	0.57	0.61	0.61	0	0.65	0.63	0.61	0	0	0	0.51	0.54	0
Recyclability	*Degree*	0.47	0	0.73	0	0	0	0	0.67	0.6	0.67	0.93	0.6	0.53
	Betweenness	0.01	0	0.11	0	0	0	0	0.03	0.06	0.06	0.19	0.04	0.07
	Closeness	0.48	0	0.56	0	0	0	0	0.34	0.44	0.58	0.6	0.41	0.48

Data availability

Data will be made available on request.

References

2000/53, 20002000/53, D., 2000. On end-of life vehicles. In: Parliament, E. (Ed.), L 269. Official Journal of the European Union.

2009/125/EC, D, 2009. Establishing a framework for the setting of ecodesign requirements for energy-related products. In: Parliament, E. (Ed.), L 285/10. Official Journal of the European Union.

2012/19, 20122012/19, D, 2012. On waste electrical and electronic equipment (WEEE). In: Parliament, E. (Ed.), L 197/38. Official Journal of the European Union.

Abuzied, H., Senbel, H., Awad, M., Abbas, A., 2020. A review of advances in design for disassembly with active disassembly applications. Engineering Science and Technology, an International Journal 23, 618–624.

Acerbi, F., Sassanelli, C., Terzi, S., Taisch, M., 2021. A systematic literature review on data and information required for circular manufacturing strategies adoption. Sustainability.

Adisorn, T., Tholen, L., Götz, T., 2021. Towards a digital product passport fit for contributing to a circular economy. Energies 14.

Aher, G., Boudjadar, J., Ramanujan, D., 2023. Towards simulation-based circular product design. Procedia CIRP 116, 690–695.

Anil Kumar, G., Bahubalendruni, M.V.A.R., Prasad, V.S.S., Sankaranarayanasamy, K., 2021. A multi-layered disassembly sequence planning method to support decision making in de-manufacturing. Sādhanā 46, 102.

Arduin, R.H., Grimaud, G., Leal, J.M., Pompidou, S., Charbuillet, C., Laratte, B., et al., 2019. Influence of scope definition in recycling rate calculation for european e-waste extended producer responsibility. Waste Manag. 84, 256–268.

Bauer, D.J., Khazdozian, H., Mehta, J., Nguyen, R.T., Severson, M.H., Vaagensmith, B.C., Quaresima, J., 2023. 2023 Critical Materials Strategy (No. INL/RPT-23-72323-Rev. 001). Idaho National Laboratory (INL), Idaho Falls, ID (United States).

Benabdellah, A.C., Bouhaddou, I., Benghabrit, A., Benghabrit, O., 2019. A systematic review of design for X techniques from 1980 to 2018: concepts, applications, and perspectives. Int. J. Adv. Des. Manuf. Technol. 102, 3473–3502.

Bernstein, W., Ramanujan, D., Devanathan, S., Zhao, F., Ramani, K., Sutherland, J.W., 2010. Development of a framework for sustainable conceptual design. In: Proceedings of the 17th CIRP International Conference on Life Cycle Engineering.

Blomsma, F., Pieroni, M., Kravchenko, M., Pigosso, D.C., Hildenbrand, J., Kristinsdottir, A.R., Kristoffersen, E., Shahbazi, S., Nielsen, K.D., Jönbrink, A.-K., 2019. Developing A circular strategies framework for manufacturing companies to support circular economy-oriented innovation. J. Clean. Prod. 241, 118271.

Boix Rodríguez, N., Favi, C., 2023. Disassembly and repairability of mechatronic products: insight for engineering design. J. Mech. Des. 146, 1–69.

Boothroyd, G., 1994. Product design for manufacture and assembly. Comput. Aided Des. 26 (7), 505–520.

Boothroyd, G., Alting, L., 1992. Design for assembly and disassembly. Annals of CIRP 41 (2), 625–636.

Borgatti, S.P., 2005. Centrality and network flow. Soc. Netw. 27 (1), 55–71.

Brezet, H., 1997. Ecodesign-A Promising Approach to Sustainable Production and Consumption. United Nations Environmental Programme (UNEP).

BSI 8887, 2010. Design for Manufacture, Assembly, Disassembly and end-of-life Processing (MADE): the Process of Remanufacture–Specification. British Standards Institution (BSI).

BSI 8887, 2018. Design for Manufacture, Assembly, Disassembly and end-of-life Processing (MADE). British Standard Institution (BSI).

Ceschin, F., Gaziulusoy, I., 2016. Evolution of design for sustainability: from product design to design for system innovations and transitions. Des. Stud. 47, 118–163.

Chapman, J., 2009. Design for (emotional) durability. Des. Issues 25 (4), 29–35.

Chen, R.W., Navin-Chandra, D., Print, F., 1994. A cost-benefit analysis model of product design for recyclability and its application. IEEE Trans. Compon. Packag. Manuf. Technol. 17, 502–507.

Chiodo, J.D., Boks, C., 2002. Assessment of end-of-life strategies with active disassembly using smart materials. J. Sustain. Prod. Des. 2, 69–82.

Chiodo, J., Jones, N., 2012. Smart materials use in active disassembly. Assem. Autom. 32, 8–24.

Chiodo, J.D., Billett, E.H., Harrison, D.J., 1998. Active disassembly. J. Sustain. Prod. Des. 30–36.

Chiodo, J.D., Billett, E.H., Harrison, D.J., Harry, P., 1998b. Investigations of generic self disassembly using shape memory alloys. In: Proceedings of the 1998 IEEE International Symposium on Electronics and the Environment. ISEE - 1998 (Cat. No.98CH36145), pp. 82–87, 6-6 May 1998.

Chiu, M., Kremer, G.E., 2011. Investigation of the applicability of design for X tools during design concept evolution: a literature review. Int J Product Development 13, 132–167.

Cong, L., Jin, H., Fitsos, P., Mcintyre, T., Yih, Y., Zhao, F., Sutherland, J.W., 2015. Modeling the value recovery of rare earth permanent magnets at end-of-life. Procedia CIRP 29, 680–685.

Cooper, D.R., Gutowski, T.G., 2017. The environmental impacts of reuse: a review. J. Ind. Ecol. 21, 38–56.

Corsini, L., Moultrie, J., 2021. What is design for social sustainability? A systematic literature review for designers of product-service systems. Sustainability 13, 5963.

Costa, C.M., Veiga, G., Sousa, A., Rocha, L., Oliveira, E., Cardoso, H.L., Thomas, U., 2018. Automatic generation of disassembly sequences and exploded views from solidworks symbolic geometric relationships. In: 2018 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC). IEEE, pp. 211–218.

Crowther, P., 2005. Design for disassembly–themes and principles. Environment design guide 1–7.

Cruz, P.J.S., Hvejsel, M.F., 2022. Structures and Architecture A Viable Urban Perspective?.

CSN EN 45554, 2020. General Methods for the Assessment of the Ability to Repair, Reuse and Upgrade energy-related Products. Commonwealth Standards Network.

Damiani, M., Ferrara, N., Ardente, F., 2022. Understanding Product Environmental Footprint and Organisation Environmental Footprint Methods, EUR 31236 EN. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/11564. ISBN 978-92-76-57214-5.

Daneshmand, M., Noroozi, F., Corneanu, C., Mafakheri, F., Fiorini, P., 2023. Industry 4.0 and prospects of circular economy: a survey of robotic assembly and disassembly. Int. J. Adv. Des. Manuf. Technol. 124, 2973–3000.

Dangal, S., Faludi, J., Balkenende, R., 2022. Design aspects in repairability scoring systems: comparing their objectivity and completeness. Sustainability 14, 8634.

De Fazio, F., Bakker, C., Flipsen, B., Balkenende, R., 2021. The disassembly map: a new method to enhance design for product repairability. J. Clean. Prod.

Den Hollander, M.C., Bakker, C.A., Hultink, E.J., 2017. Product design in a circular economy: development of a typology of key concepts and terms. J. Ind. Ecol. 21, 517–525.

Dias, V.M.R., Jugend, D., Fiorini, P.D., Razzino, C.D., Pinheiro, M.A.P., 2022. Possibilities for applying the circular economy in the aerospace industry: practices, opportunities and challenges. J. Air Transport. Manag. 102.

Directive, 2009/125/EC, 2009. Directive 2009/125/EC of the European Parliament and of the Council establishing a framework for the setting of ecodesign requirements for energy-related products. In: Council, T.E.P.A.O.T. (Ed.), Official Journal of the European Union.

Dos Santos, L.C.T., Giannetti, B.F., Agostinho, F., Almeida, C.M., 2022. Using the five sectors sustainability model to verify the relationship between circularity and sustainability. J. Clean. Prod. 366, 132890.

Duflou, J., Seliger, G., Kara, S., Umeda, Y., Ometto, A., Willems, B., 2008. Efficiency and feasibility of product disassembly: a case-based study. CIRP Ann. - Manuf. Technol. 57, 583–600.

Eheliyagoda, D., Veluri, B., Liu, G., Ramanujan, D., 2025. Unveiling the multiregional circular economy pathways for global dysprosium constraints. Resour. Conserv. Recycl. 215, 108121.

Escoto, P.A.O., Muñoz, M.Á.Z., 2020. Design for disassembly (DFD) as strategy for redesign and optimization of products. In: Proceedings IRF2020: 7Th International Conference integrity-reliability-failure. INEGI-FEUP, pp. 445–458.

EU Regulation, 2024. Regulation 2024/1252 of the European Parliament and of the Council of 11 April 2024 Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials and Amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020 (Text with EEA relevance).

European Commission, 2020. Circular Economy Action Plan : for a Cleaner and More Competitive Europe. Publications Office of the European Union.

European Commission, 2024. In: Parliament, E. (Ed.), Directive 2024/1799: on Common Rules Promoting the Repair of Goods and Amending, L 1799. Official Journal of the European Union.

European Commission, 2020. Directive 2020/1828: on common rules promoting the repair of goods. In: Parliament, E. (Ed.), L 409/1. Official Journal of the European Union.

European Environment Agency, 2024. Circular material use rate in Europe [Online]. Available: https://www.eea.europa.eu/en/analysis/indicators/circular-material-use-rate-in-europe. (Accessed 10 June 2024).

Fabricius, F., 1994. Seven step procedure for design for manufacture. World Class Des. Manufact. 1 (2), 23–30.

Fang, L., Romano, T.T., Alix, T., Crébier, J.C., Lefranc, P., Rio, M., Zwolinski, P., 2023. Eco-design implementation in power electronics: a literature review. In: International Symposium on Advances Technologies in Electrical Systems (SATES 23). March.

Favi, C., Germani, M., Mandolini, M., Marconi, M., 2012. Promoting and managing end-of-life closed-loop scenarios of products using a design for disassembly evaluation tool. In: International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, pp. 1339–1348.

Favi, C., Marconi, M., Germani, M., Mandolini, M., 2019. A design for disassembly tool oriented to mechatronic product de-manufacturing and recycling. Adv. Eng. Inform. 39, 62–79.

Formentini, G., 2022. Towards the definition of an engineering method to support the design for assembly and installation of aircraft systems at the conceptual design stage. [Doctoral thesis, Università degli studi di Parma. Dipartimento di Ingegneria e architettura].

Formentini, G., Ramanujan, D., 2023a. Accounting for product end-of-life status in disassembly time estimation using modified maynard operation sequences. Procedia CIRP 116, 305–311.

Formentini, G., Ramanujan, D., 2023b. Design for circular disassembly: evaluating the impacts of product end-of-life status on circularity through the parent-action-child model. J. Clean. Prod. 405, 137009.

Formentini, G., Koppelaar, R., Leone, D., Dell'ambrogio, S., Fontana, A., Guggiari, F., Frangez, T., Ramanujan, D., 2023. Information needs for establishing circularity-focused collaborations among product manufacturers and recyclers. In: Proceedings of Ecodesign Conference. *Nara, JP*.

Formentini, G., Martiny, T.A., Møller, C., Vernica, T., Ramanujan, D., 2024. Assessing the disassembly performance of washing machines through the design for circular disassembly methodology. Proceedings of the Design Society 1249–1258.

Fraser, M., Haigh, L., Soria, A.C., 2023. The Circularity Gap Report 2023.

Frosch, R.A., Gallopoulos, N.E., 1989. Strategies for Manufacturing, vol. 261, p. 3.

Gauss, L., Lacerda, D., Miguel, P., 2021. Module-based product family design: systematic literature review and meta-synthesis. J. Intell. Manuf. 32.

Güngör, A., 2006. Evaluation of connection types in design for disassembly (DFD) using analytic network process. Comput. Ind. Eng. 50, 35–54.

Hapuwatte, B.M., Mathur, N., Last, N., Ferrero, V., Reslan, M., Morris, K., 2022a. Optimizing product life cycle systems for manufacturing in a circular economy. In: Global Conference on Sustainable Manufacturing. Springer International Publishing, Cham, pp. 419–427.

Hapuwatte, B.M., Seevers, K.D., Jawahir, I., 2022b. Metrics-based dynamic product sustainability performance evaluation for advancing the circular economy. J. Manuf. Syst. 64, 275–287.

Hellmuth, J., Difilippo, N., Jouaneh, M., 2021. Assessment of the automation potential of electric vehicle battery disassembly. J. Manuf. Syst. 59, 398–412.

Hilton, B., Thurston, M., 2019. Design for remanufacturing. In: Naser, N. (Ed.), Remanufacturing in the Circular Economy. Scrivener Publishing LLC, pp. 137–168.

Hu, B., Feng, Y., Zheng, H., Tan, J., 2018. Sequence planning for selective disassembly aiming at reducing energy consumption using a constraints relation graph and improved ant colony optimization algorithm. Energies 11, 2106.

Iacovidou, E., Hahladakis, J., Purnell, P., 2021. A systems thinking approach to understanding the challenges of achieving the circular economy. Environ. Sci. Pollut. Control Ser. 28, 1–22.

Imen, B., Moncef, H., Moez, T., Nizar, A., 2020. Generation of disassembly plans and quality assessment based on CAD data. Int. J. Comput. Integrated Manuf. 33, 1300–1320.

ISO 14006, 2020. Environmental Management Systems – Guidelines for Incorporating Ecodesign. the International Organization for Standardization.

ISO 14040, 2006. Environmental Management — Life Cycle Assessment — Principles and Framework. the International Organization for Standardization.

ISO 14044, 2006. Environmental Management — Life Cycle Assessment — Requirements and Guidelines. the International Organization for Standardization.

ISO 59004, 2024. Circular Economy — Vocabulary, Principles and Guidance for Implementation the International Organization for Standardization.

ISO 59010, 2024. Circular Economy — Guidance on the Transition of Business Models and Value Networks *the.* International Organization for Standardization.

ISO 59020, 2024. Circular Economy — Measuring and Assessing Circularity Performance. the International Organization for Standardization.

ISO 8887, 2017. Technical Product Documentation — Design for Manufacturing, Assembling, Disassembling and end-of-life Processing. the International Organization for Standardization.

Issaoui, L., Aifaoui, N., Benamara, A., 2017. Modelling and implementation of geometric and technological information for disassembly simulation in CAD environment. Int. J. Adv. Des. Manuf. Technol. 89, 1731–1741.

Jabbour, C.J.C., Jabbour, A.B.L.D., Sarkis, J., Godinho, M., 2019. Unlocking the circular economy through new business models based on large-scale data: an integrative framework and research agenda. Technol. Forecast. Soc. Change 144, 546–552.

Jacomini Prioli, J.P., Rickli, J.L., 2023. Human-robot interaction for extraction of robotic disassembly information. Int. J. Comput. Integrated Manuf. 1–16.

Jerome, A., Helander, H., Ljunggren, M., Janssen, M., 2022. Mapping and testing circular economy product-level indicators: a critical review. Resour. Conserv. Recycl. 178, 106080.

Joustra, J., Flipsen, B., Balkenende, R., 2021a. Structural reuse of high end composite products: a design case study on wind turbine blades. Resour. Conserv. Recycl. 167, 105393.

Joustra, J., Flipsen, B., Balkenende, R., 2021b. Structural reuse of wind turbine blades through segmentation. Compos Part C: Open Access 5, 100137.

Kallipoliti, L., 2018. History of Ecological Design. Oxford University Press.

Karaeva, A., Tolkou, A., Cioca, L.-I., Lakatos, E., 2023. Family ISO 14000 standards as a tool of achieving environmental sustainability of enterprises. IOP Conf. Ser. Earth Environ. Sci. 1126, 012036.

Kim, J., Saidani, M., Kim, H.M., 2021. Designing an optimal modular-based product family under intellectual property and sustainability considerations. J. Mech. Des. 143.

King, A.M., Burgess, S.C., Ijomah, W., Mcmahon, C.A., 2006. Reducing waste: repair, recondition, remanufacture or recycle? Sustain. Dev. 14, 257–267.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232.

Ko, J., Guedes, G.B., Badurdeen, F., Jawahir, I.S., Morris, K.C., Ferrero, V., Hapuwatte, B., Bradley, R., Raihanian, A., 2024. A critical analysis of circular product attributes and limitations of product circularity assessment methods. Resources, Conservation & Recycling Advances 23, 200219.

Kręt-Grześkowiak, A., Baborska-Narożny, M., 2023. Guidelines for disassembly and adaptation in architectural design compared to circular economy goals - a literature review. Sustain. Prod. Consum. 39, 1–12.

Laili, Y., Tao, F., Pham, D.T., Wang, Y., Zhang, L., 2019. Robotic disassembly re-planning using a two-pointer detection strategy and a super-fast bees algorithm. Robot. Comput. Integrated Manuf. 59, 130–142.

Lander, L., Tagnon, C., Nguyen-Tien, V., Kendrick, E., Elliott, R., Abbott, A., Edge, J., Offer, G., 2023. Breaking it Down: a techno-economic assessment of the impact of battery pack design on disassembly costs. Appl. Energy 331, 120437.

Li, J., Barwood, M., Rahimifard, S., 2018. A multi-criteria assessment of robotic disassembly to support recycling and recovery. Resour. Conserv. Recycl. 140, 158–165.

Lima, M., Kubota, F., 2021. A Modular Product Design Framework for the Home Appliance Industry.

Liu, Z., Cheng, H., Li, X., Zhan, Y., Zhang, J., 2012. Design methodology for active disassembly based on the decapitated head method. Int. J. Sustain. Eng. 5, 220–227.

Liu, Z., Zhan, Y., Cheng, H., Li, X., Pan, S., 2013. Design method of active disassembly structure triggered by temperature-pressure coupling. Int. J. Precis. Eng. Manuf. 14, 1223–1228.

Liu, J., Zhou, Z., Pham, D.T., Xu, W., Ji, C., Liu, Q., 2018. Robotic disassembly sequence planning using enhanced discrete bees algorithm in remanufacturing. Int. J. Prod. Res. 56, 3134–3151.

Macarthur, F.E., 2013. Towards the Circular Economy Vol. 1: an Economic and Business Rationale for an Accelerated Transition. Ellen McArthur.

Marconi, M., Germani, M., 2017. An End of Life Oriented Framework to Support the Transition Toward Circular Economy.

Martínez Leal, J., Pompidou, S., Charbuillet, C., Perry, N., 2020. Design for and from recycling: a circular ecodesign approach to improve the circular economy. Sustainability 12 (23), 9861.

Mcdonough, W., Braungart, M., 2010. Cradle to Cradle: Remaking the Way We Make Things. North point press.

Mircheski, I., Pop-Iliev, R., Kandikjan, T., 2016. A method for improving the process and cost of nondestructive disassembly. J. Mech. Des. 138.

Nag, U., Sharma, S.K., Kumar, V., 2022. Multiple life-cycle products: a review of antecedents, outcomes, challenges, and benefits in a circular economy. J. Eng. Des. 33, 173–206.

Opferkuch, K., Caeiro, S., Salomone, R., Ramos, T.B., 2022. Circular economy disclosure in corporate sustainability reports: the case of European companies in sustainability rankings. Sustain. Prod. Consum.

Oturu, K., Oluah, C.K., 2024. The importance of design for remanufacture in achieving net zero. Lecture Notes in Mechanical Engineering 449–457.

Papanek, V., Lazarus, E.L., 2005. Design for the Real World: Human Ecology and Social Change, second ed. Academy Chicago Publishers.

Parsa, S., Saadat, M., 2021. Human-robot collaboration disassembly planning for end-of-life product disassembly process. Robot. Comput. Integrated Manuf. 71, 102170.

Pedersen, E., Remmen, A., 2022. Challenges with product environmental footprint: a systematic review. Int. J. Life Cycle Assess. 27 (2), 342–352.

Peeters, J.R., Dewulf, K., 2012. Design for End of Life: a Design Methodology for the Early Stages of an Innovation Process.

Peeters, J.R., Vanegas, P., Dewulf, W., Duflou, J.R., 2012. Active disassembly for the end-of-life treatment of flat screen televisions: challenges and opportunities. In: Matsumoto, M., Umeda, Y., Masui, K., Fukushige, S. (Eds.), Design for Innovative Value Towards a Sustainable Society. 2012 Dordrecht. Springer, Netherlands, pp. 535–540.

Peeters, J.R., Vanegas, P., Dewulf, W., Duflou, J.R., 2015. Economic and environmental evaluation of fasteners for active disassembly: a case study for payment terminals. Procedia CIRP 29, 704–709.

Peeters, J., Vanegas, P., Dewulf, W., Duflou, J., 2016a. Economic and environmental evaluation of design for active disassembly. J. Clean. Prod. 140.

Peeters, J.R., Van Den Bossche, W., Devoldere, T., Vanegas, P., Dewulf, W., Duflou, J.R., 2016b. Pressure-sensitive fasteners for active disassembly. Int. J. Adv. Des. Manuf. Technol. 87, 1519–1529.

Peeters, J., Tecchio, P.A., Fulvio, Vanegas, Pena, P., Coughlan, D., Duflou, J., 2018. Edim: Further Development of the Method to Assess the Ease of Disassembly and Reassembly of Products: Application to Notebook Computers.

Popescu, D., Iacob, R., 2013. Disassembly method based on connection interface and mobility operator concepts. Int. J. Adv. Des. Manuf. Technol. 69, 1511–1525.

Pozo Arcos, B., Balkenende, A.R., Bakker, C.A., Sundin, E., 2018. Product design for a circular economy: functional recovery on focus. In: Proceedings of the Design 2018 – 15th International Design Conference, pp. 2727–2738.

Prioli, J.P.J., Alrufaifi, H.M., Rickli, J.L., 2022. Disassembly assessment from CAD-Based collision evaluation for sequence planning. Robot. Comput. Integrated Manuf. 78, 102416.

Ramanujan, D., Bernstein, W.Z., Totorikaguena, M.A., Ilvig, C.F., Ørskov, K.B., 2018. Generating contextual design for environment principles in sustainable manufacturing using visual analytics. J. Manuf. Sci. Eng. 141.

Reslan, M., 2022. Relevant standards that are published or under development as of August, 2022. [Online]. Available: https://www.nist.gov/el/systems-integration-division-73400/manufacturing-circular-economy. (Accessed 19 April 2024).

Reuter, M., Schaik, A., Gutzmer, J., Bartie, N., Abadias Llamas, A., 2019. Challenges of the circular economy: a material, metallurgical, and product design perspective. Annu. Rev. Mater. Res. 49.

Rockström, J., Gupta, J., Qin, D., Lade, S.J., Abrams, J.F., Andersen, L.S., Armstrong Mckay, D.I., Bai, X., Bala, G., Bunn, S.E., Ciobanu, D., Declerck, F., Ebi, K., Gifford, L., Gordon, C., Hasan, S., Kanie, N., Lenton, T.M., Loriani, S., Liverman, D. M., Mohamed, A., Nakicenovic, N., Obura, D., Ospina, D., Prodani, K., Rammelt, C., Sakschewski, B., Scholtens, J., Stewart-Koster, B., Tharammal, T., Van Vuuren, D., Verburg, P.H., Winkelmann, R., Zimm, C., Bennett, E.M., Bringezu, S., Broadgate, W., Green, P.A., Huang, L., Jacobson, L., Ndehedehe, C., Pedde, S., Rocha, J., Scheffer, M., Schulte-Uebbing, L., De Vries, W., Xiao, C., Xu, C., Xu, X., Zafra-Calvo, N., Zhang, X., 2023. Safe and just Earth system boundaries. Nature 619, 102–111.

Rodríguez, N.B., Favi, C., 2022. Eco-design guidelines takeaways from the analysis of product repairability and ease of disassembly: a case study for electric ovens. Procedia CIRP 595–600.

Rossi, M., Germani, M., Zamagni, A., 2016. Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies. J. Clean. Prod. 129, 361–373.

Saidani, M., 2023. The circularity potential indicator (CPI) tool (beta version) [Online]. Available: https://circulareconomyindicators.com/publications.php. (Accessed 24 June 2023).

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., 2017. How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework. Recycling 2, 6.

Schäfer, M., Löwer, M., 2021. Ecodesign—A review of reviews. Sustainability 13, 315.

Scott, S., Islam, Z., Allen, J., Yingnakorn, T., Alflakian, A., Hathaway, J., Rastegarpanah, A., Harper, G.D.J., Kendrick, E., Anderson, P.A., Edge, J., Lander, L., Abbott, A.P., 2023. Designing lithium-ion batteries for recycle: the role of adhesives. Next Energy 1, 100023.

Shahbazi, S., Jönbrink, A.K., 2020. Design guidelines to develop circular products: action research on nordic industry. Sustainability 12, 3679.

Shetty, D., Rawolle, K., Campana, C., 2000. A New Methodology for ease-of-disassembly in Product Design.

Sillitto, H., Martin, J., Mckinney, D., Griego, R., Dori, D., Krob, D., Godfrey, P., Arnold, E., Jackson, S., 2019. Systems Engineering and System Definitions: INCOSE. USCA, San Diego.

Simpson, T., Siddique, Z., Jiao, R., 2005. Product Platform and Product Family Design: Methods and Applications.

Stahel, W., 2010. The Performance Economy. Springer.

Sun, L., Huang, W.M., Lu, H.B., Wang, C.C., Zhang, J.L., 2014. Shape memory technology for active assembly/disassembly: fundamentals, techniques and example applications. Assem. Autom. 34, 78–93.

Suppipat, S., Hu, A.H., 2022. A scoping review of design for circularity in the electrical and electronics industry. Resources, Conservation & Recycling Advances 13, 200064.

Telenko, C., Seepersad, C.C., Webber, M.E., 2009. A method for developing design for environment guidelines for future product design. In: ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, pp. 291–302.

Turkbay Romano, T., Fang, L., Alix, T., Rio, M., Mélot, J., Serrano, F., et al., 2024. Disassemblability assessment of power electronic converters for improved circularity. Sustainability 16 (11), 4712.

Upadhyay, A., Ladrecha, B., Dubey, A., Kuriakose, S., Goenka, P., 2023. 3D-PDNet: Automated Product Disassembly Sequence Planning.

Van Den Berg, M., Bakker, C., 2015. A product design framework for a circular economy. Product Lifetimes And The Environment 365–379.

Van Der Ryn, S., Cowan, S., 2013. Ecological Design. Island press.

Vanegas, P., Peeters, J.R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., Duflou, J.R., 2018. Ease of disassembly of products to support circular economy strategies. Resour. Conserv. Recycl. 135, 323–334.

Walden, D.D., 2015. In: Systems Engineering Handbook: a Guide for System Life Cycle Processes and Activities.

Wang, P., Yang, Y.Y., Heidrich, O., Chen, L.Y., Chen, L.H., Fishman, T., Chen, W.Q., 2024. Regional rare-earth element supply and demand balanced with circular economy strategies. Nat. Geosci. 17 (1), 94–102.

Willems, B., Dewulf, W., Duflou, J., 2005. Design for active disassembly (DfAD): an outline for future research. In: Proceedings of the 2005 IEEE International Symposium on Electronics and the Environment, pp. 129–134, 16-19 May 2005 2005.

Xing, Y., Wu, D., Qu, L., 2021. Parallel disassembly sequence planning using improved ant colony algorithm. Int. J. Adv. Des. Manuf. Technol. 113.

Zhang, S., Liu, P., Guo, X., Wang, J., Qin, S., Tang, Y., 2022. An improved tabu search algorithm for multi-Robot hybrid disassembly line balancing problems. In: 2022 International Conference on Cyber-Physical Social Intelligence (ICCSI), pp. 315–320.