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A critical analysis of circular product attributes and limitations of product circularity assessment methods

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ABSTRACT

The Circular Economy (CE) has been proposed as a strategy to promote the efficient use of resources, maximizing the benefits derived from materials and products through value recovery strategies, and minimizing waste generation. However, ambiguity remains in defining what makes a product circular and its characteristics when adapting the CE concept for application at the product level. More clarity about the constitutive characteristics of Circular Products (CPs) is also vital to facilitate their design. To address this challenge, and with the intention to increase the adoption of CE concept within the industry, the descriptions and attributes of a Circular Product (CP) were examined through a scoped literature review and analysis. Findings were then synthesized to establish a preliminary framework of CP attributes. These attributes were used to review the existing product circularity assessment methods. The results highlight limitations in the coverage of CP attributes in the existing methods and research opportunities for their improvement. The findings from this study will contribute to the development of a comprehensive and accurate product circularity assessment method.

1. Introduction

The linear economy has been the predominant production and consumption model since the Industrial Revolution and operates on a "take-make-use-dispose" approach (Aggeri, 2021). Under this paradigm, materials are extracted to manufacture products that are primarily discarded as waste at end-of-life (EoL). The linear approach is no longer suitable to meet the needs of a growing global population striving for higher living standards given the finite resources available on Earth. Moreover, the significant increase in production and consumption associated with the linear model has led to issues including the escalation of waste generation and the resulting environmental and health concerns.

CE has emerged as a business model to shift industrial systems away from linear practices and towards more circular approaches that incorporate restorative and regenerative strategies (EMF, 2013). The International Organization for Standardization (ISO), in the final draft international standard (FDIS) titled “Circular Economy – Terminology, Principles, and Guidance for Implementation”, describes the CE as “an economic system that utilizes a systematic approach to maintain a circular flow of resources, by recovering, retaining, or adding value to them, while contributing to sustainable development” (ISO FDIS 59004, 2023). While CE can be implemented across various scales, including micro, *meso*, and macro levels (Zhu et al., 2011; Linder et al., 2017; Saidani et al., 2019), the macro-level economic transformation heavily relies on and is driven by the application of CE at the micro level (Kirchherr et al., 2017). Therefore, it becomes essential that products are designed, manufactured, used, and managed at EoL based on the CE principles to fully realize the benefits of circularity at all levels (Circular Tayside, 2017; Mestre and Cooper, 2017; EMF, 2022).

While interest in a circular approach to material use is rapidly growing, the change requires a deep transition of our global economy with many hurdles to overcome, both technical and social. The recovery of material at EoL is non-trivial with challenges in collection, sorting, and reprocessing. At the product level, questions arise regarding the best means for re-entering the product into the economy after its initial use is completed. Should it be reused, remanufactured, recycled, or something else? The answers to these questions and others depend on very

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fundamental assessments of both the product and its potential value in the economy, and such assessments need to be supported by data. Research into what data should be used in such assessments and how to evaluate its meaning is ongoing and is the focus of a new area of research at the National Institute of Standards and Technology (NIST) examining needs for circular product design (CPD) (Ferrero et al., 2022), for process models (Mathur et al., 2023; Raman et al., 2023), and at the broader CE level (Hapuwatte et al., 2022; Beers et al., 2022; Reslan et al., 2022; Schumacher et al., 2022). In addition, addressing these technical questions needs to be accompanied by new standards, governance, policy, and regulations, integrated into the social aspects of the economy through new systems for product design, production, use, and recovery (Kumar et al., 2021). Similarly, these new systems need models for predicting and evaluating outcomes before wide-scale deployment.

To transform existing systems for product design, comprehensive capabilities to measure and evaluate product circularity will be crucial. Ongoing research contributes towards establishing a definition of CP and reiterates requirements such as designing for servitization and lifecycle extension, incorporating materials that can circulate within closed-loop systems, and avoiding any mixture of biological and technological components to make the disassembly easier for composting and recycling (Romero and Rossi, 2017). On the other hand, the Ellen MacArthur Foundation (EMF) states that CPs are physical products developed in accordance with one or multiple CE principles while remaining neutral towards principles that are not aligned (EMF, 2020). More recently, Gossen et al. (2022) describe CPs as “recyclable or biodegradable products or products made from recycled or upcycled materials.” ISO/FDIS 59004 on CE does not offer a CP definition (ISO FDIS 59004, 2023). A consensus definition for CP must provide a uniform foundation on which to measure product circularity. This absence of a concrete CP definition has led to gaps in methods proposed for product circularity assessment. The criteria and attributes – the constitutive characteristics that describe desired features or properties of a CP – considered in each method vary greatly, making consensus hard to achieve. The ambiguity (in addition to other factors discussed later) also makes these methods less appealing to industry, hindering their practical adoption. Thus, it is imperative that the constitutive characteristics or attributes of CPs are clearly identified to overcome these challenges. This paper aims to address this research gap to identify essential CP attributes through a synthesis of information in academic and industry literature in comparison with CE principles. Identification of CP attributes will then enable evaluating existing product circularity assessment methods to analyze the extent to which they incorporate measurement of these attributes and improvement needs.

This paper first discusses the CE concept and its evolution to extract key principles pertinent when applied at the product level. This is followed by a review of literature related to CPD and those focusing on product circularity to identify commonly referenced CP attributes. All this information is synthesized to identify a set of core CP attributes. Based on these attributes, the existing product circularity assessment methods are evaluated, and their limitations are presented to enable establishing a consensus understanding of CPs and the development of a comprehensive and accurate product circularity assessment method in the future. The paper is organized as follows: Section 2 discusses the literature review process; Section 3 provides the review of existing methods for assessing product circularity based on the Section 2 results; and Section 4 concludes the paper with a discussion on future work.

2. Literature review process

This section presents the literature review conducted to identify CP attributes. The review was designed as a focused literature review, concentrating specifically on publications that directly relate to circular economy principles, circular product design, and product circularity. To gather the necessary literature, carefully chosen keywords such as product-level CE, product circularity assessment, closed-loop product design, and others were employed. These terms were selected to ensure that all sourced contents are highly related to the study scope. Additionally, the relevant references cited within the initially identified papers were thoroughly reviewed to trace the origins of the information, confirm its credibility, and further the understanding of a CP by exploring these foundational sources.

Due to the absence of a concrete definition of CE (Kirchherr et al., 2017), understanding the fundamental principles underlying CE is essential. Therefore, literature related to the CE concept was initially reviewed to identify key elements that must be incorporated into CPs. Implementation of CE at the product level requires translating the information gathered by using product circularity assessment methods (i.e., improvement needs) into actionable decisions for CPD. However, product circularity as well as its assessment and CPD are often discussed in literature separately. To gain a better understanding of CP attributes identified in each of these areas, to develop more comprehensive assessment methods, and to facilitate future research towards operationalizing CPD, the review is organized into two categories: CP attributes identified in CPD literature and CP attributes identified in product circularity-related literature. Fig. 1 illustrates the methodology employed in this paper.

To clearly communicate the process followed in achieving the outcomes outlined, this section is divided into four subsections: SubSection 2.1 explores the CE concept as observed in the relevant literature and presents what a product must achieve to be considered circular, SubSection 2.2 discusses the attributes of CP identified in the literature on CPD; SubSection 2.3 describes the characteristics of CP that were found in the literature on product circularity; and SubSection 2.4 presents CP attributes identified in this study, based on the synthesized results of 2.1, 2.2 and 2.3.

2.1. *Principles of CE & preliminary CP attributes*

Some of the early discussions of the CE concept in the context of the ecological impacts of industrial activities can be traced back to 1990 when Pearce and Turner (1990) first mentioned the term “circular economy”. Later, various schools of thought, including industrial ecology, regenerative design, biomimicry, and others, have played significant roles in shaping the evolution of the CE concept (Pearce and Turner, 1990; Stahel and Ready, 1981; EMF, 2013; PLI, 2023), emphasizing the promotion of the circular flow of resources to achieve both environmental and economic benefits. However, the EMF is recognized for its contribution to the widespread increase in CE awareness. The EMF stated CE is “an industrial system that is restorative or regenerative by intention and design. It replaces the “end-of-life” concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through superior design of materials, products, systems, and within this, business models” (EMF, 2013). The EMF further described that the fundamental principles of CE are aligned with waste and pollution minimization, the regeneration of nature, as well as the circulation of materials and products to preserve their highest value, all of which must be guided by design to operationalize a CE (EMF, 2023). Regeneration within the framework of the CE refers to emulating the inherent waste-free and self-sustaining processes found in natural systems, like forests and wetlands, where every output is repurposed as an input for another cycle (EMF, 2023). Restoration, on the other hand, is described as “the return to a previous or original state” (Morseletto, 2020). It encompasses bringing EoL products, components, or materials back to a working condition through strategies such as reuse, remanufacturing, and recycling.

Later in 2017, Kirchherr et al. performed a review of 114 existing definitions of the CE and provided a more synthesized CE definition that underscores the importance of value recovery strategies of materials such as redesign, recover, reuse, remanufacture, and recycle. Various operational levels of a CE (micro, *meso*, macro) and the benefits of the CE

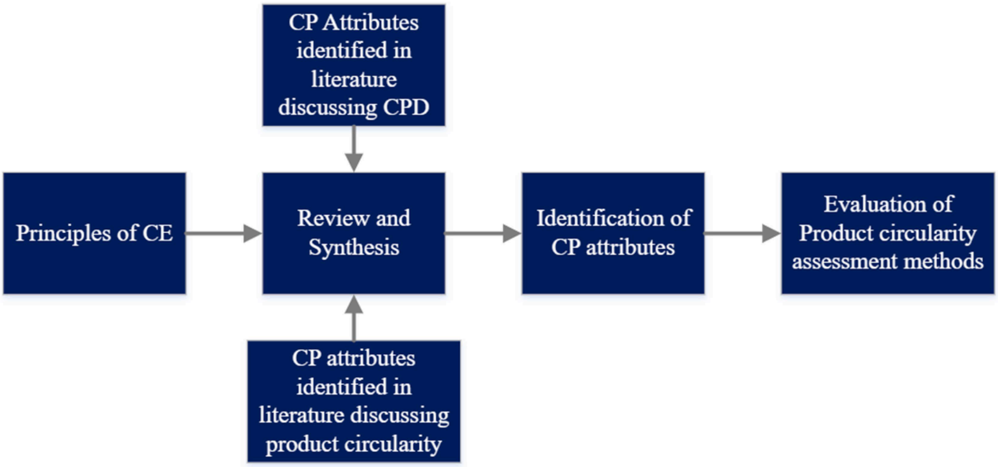

Fig. 1. Research methodology.

model toward the environment, economy, and society were also emphasized in the definition. In the current FDIS for ISO 59004, the definition of CE highlights the circulation of resources and the value recovery strategies (ISO FDIS 59004, 2023). The common principles of CE observed in relevant literature emphasize closed-loop resource flows, value recovery strategies enabling restoration, regeneration, application at various operational levels, and economic and environmental benefits. It is important to note that more recent definitions of CE emphasize CE's capability to benefit the environment, while this aspect was simply assumed as a given in the early phases of the evolution of the CE concept. Based on the analysis of key elements of the CE concept, for a product to be considered circular, it must:

- Incorporate closed-loop material flows
- Facilitate restoration through the value recovery strategies
- Facilitate regeneration through materials selection
- Lead to long-term economic and environmental benefits

These results were taken into consideration during the review of literature on CPD and those addressing product circularity in the subsequent section to more comprehensively identify the attributes that characterize CP.

2.2. Attributes identified in CPD literature

Numerous early studies on CE have explored CPD. The most relevant ones among them were chosen for further analysis in this study based on whether they explicitly discussed what attributes characterize CP. This subsection presents the attributes discussed in those papers, as summarized in Table 1.

In 2013, EMF put forth economic and business strategies to facilitate the transition towards CE. Their report emphasized key characteristics of CPD, such as the use of non-toxic materials, easy disassembly, and component modularization. Furthermore, the report underscored the importance of long-lasting usage of components and products designed for multiple reuse cycles as integral elements of CP (EMF, 2013). In a study presenting a product design framework for CE by Van der Berg and Bakker (2015), CP development was described as the creation of products capable of re-entering their lifecycles multiple times while minimizing environmental harm. The authors also highlighted the value of multiple product lifecycles and the environmental benefits associated with CP. Circular Tayside, a collaborative group advocating for CE adoption in local businesses and organizations, placed significant emphasis on CP. They stated that CP uses reduced or no virgin resources and emphasized the need for the incorporation of the EoL consideration into CPD (Circular Tayside, 2017). In the same year, Romero and Rossi (2017) demonstrated the compatibility between CE and lean principles within product-service systems. According to the authors, CP is designed to enable "servitization and lifecycle extension" while incorporating easy disassembly through the exclusion of biological and technological material mixtures. Furthermore, they suggested that CP should feature closed-loop material flows and rely on recycled resources.

More recently, Bressanelli et al. (2020) in their review focusing on CE in the Electric and Electronic Equipment industry waste suggested the following as CP attributes: consideration of all stakeholders during the CPD process, as well as economic and environmental benefits derived from establishing closed-loop systems for products, components, and materials. In 2021, Pretner et al. presented an investigation of consumer awareness and interest in CP. The authors defined CP as optimizing resource efficiency and highlighted the operation of CP within closed-loop systems, the extension of product lifecycles, as well as the integration of design features that facilitate product reuse, remanufacturing, and refurbishment. Institutional Shareholder Services (ISS) also underscored the need for closing the loop of products and considering the next lifecycle of products during the initial design phase of CP (ISS, 2022). The EMF, renowned for its efforts in raising CE awareness, stated that CP is designed based on CE principles (EMF, 2020). They emphasized the significance of design considerations such as disassembly, remanufacturing/refurbishment, recycling, and nutrient recirculation (EMF, 2022). Furthermore, the EMF underscored the importance of maintenance, repair, longevity, durability, multiple product lifecycles, waste, pollution prevention, safe return, and the use of renewable energy in CP. A review conducted by Nag et al. (2022) examined the outcomes, challenges, and benefits of multiple lifecycle products for a CE. The authors identified attributes of CP, including modularization, easy disassembly, the use of recyclable materials, extended product lifespan, and the importance of involving stakeholders, such as customers, in the development of CP. Gossen and Kropfeld (2022) defined CP as products that are "recyclable or biodegradable", composed of "recycled or upcycled" materials. Lastly, Suppipat and Hu (2022), in their review of the circularity design tools in the electrical and electronics industry, demonstrated sixteen product design concepts derived from seven circularity design characteristics of business models that they identified. These concepts were then categorized into three groups: societal (e.g., collaborative community design, scalable design, customization), emotional (e.g., classic design, design for attachment and trust, design for reliability), and physical (e.g., modular design, design for durability, etc.).

2.3. Attributes identified in product circularity literature

While many papers delve into product circularity, the ones

Table 1
Attributes identified in CPD literature.

Identified attributes	Source
• Long-lasting usage of components • Easy disassembly • No toxic materials use • Developed reverse cycle processes (e.g., efficient collection, transportation, and treatment • Modularization • Designed for disassembly and reuse	EMF, 2013
• Long-lasting use of products • Designed for disassembly, remake, and recycling at EoL • Operate within the CE • Reduced or no virgin resource use • Designed with consideration of EoL • Keep products and materials in use for as long as possible	Van der Berg and Baker, 2015 Circular Tayside, 2017
• Lifecycle extension • Designed for servitization (Products in sharing platforms) • No mixture of biological and technological materials • Closed-loop material flow • Use of recycled resources	Romero and Rossi, 2017
• Stakeholder consideration • Economic and environmental benefits • Closed-loop products, components, and materials (driven by improved designs) • Reuse, remanufacture, recycle • Extended product lifetime	Bressanelli et al., 2020
• Optimized resource efficiency • Closed-loop products and materials • Extended lifecycle of products • Designed for reuse, remanufacture, and refurbish	Pretner et al., 2021
• Designed for disassembly, remanufacturing/refurbishing, recycling, and materials recirculation • Designed for maintenance, longevity, durability, and multiple lifecycles of products • Reduced waste and pollution • Use of renewable energy	EMF, 2022
• Modularization • Easy disassembly • Use of recyclable materials • Product life extension with upgrade • Customer involvement in the development phase	Nag et al., 2022
• Use of recycled or upcycled materials • Recyclable or biodegradable products • Closed loop products • Consideration of the product's next life • Prolonging the use phase	Gossen and Kropfeld, 2022 ISS, 2022
• Collaborative community design • Scalable design • Customization • Classic design • Designed for attachment and trust, reliability, durability, standardization and compatibility, ease of maintenance and repair, upgradability and adaptability, and recycling • Product multifunctionality • Modular design • Simplify product's structure and manufacturing • Dematerialization	Suppipat and Hu, 2022

highlighted in this research were specifically selected based on their discussion of CP attributes. These attributes are shown in Table 2, and a thorough discussion of each source is presented.

The concept of product circularity has gained significant attention due to the increasing awareness of CE and CP, leading to numerous recent studies focusing on this discussion. In a study conducted by Linder et al. (2017), a metric for measuring product circularity was proposed. The authors emphasized the need for reusing, remanufacturing, and recycling materials, components, and products to establish closed-loop cycles at the product level in the context of CE. Similarly, in 2017, Cayzer et al. presented the design of indicators to assess the performance of a product in CE. They placed emphasis on the consideration of lifecycle stages, such as manufacturing, usage, and EoL, when evaluating product circularity. Expanding on this topic, Conte and Brogna (2019) developed a methodology to evaluate the degree of product circularity. They identified several catalysts of product circularity, including "product design, technological revolution, business model, materials management, promotion, and customer involvement" (Conte and Brogna, 2019).

Table 2
Attributes identified in product circularity literature.

Identified attributes	Source
• Closed-loop cycles • Reuse, remanufacture, recycle (materials, components, products)	Linder et al., 2017
• Consideration of lifecycle stages (manufacture, use, end of life)	Cayzer et al., 2017
• Enabled by product design, technological revolution, business model, materials management, and stakeholder involvement	Conte and Brogna, 2019
• Product life extension through repair, reuse, remanufacture • Material recovery (recycling) • Minimize disperse product and materials flows by the coordination of multiple stakeholders	Hansen and Revellio, 2020
• Multiple lifecycles of products • Minimal harm to the environment • Efficient usage of materials • Consideration of all life cycle stages of products • Reuse, remanufacture, recycle, recover, recondition, repair, reduce, responsibility	Vimal et al., 2021
• Environmental savings • Economic profits • Reuse, remanufacture, recycle	Saidani and Kim, 2021
• Material recirculation • High utilization of products • High endurance in products • Material recovery	Boyer et al., 2021
• Potential to create societal benefits • Recirculation of economic value • Component standardization • Product longevity • Closed-loop cycles • Stakeholder consideration	Hapuwatte and Jawahir, 2021

In recent years, there have been notable contributions to the understanding of product circularity. Hansen and Revellio (2020) focused on creating a typology of circular value creation architectures (CVCAs). Their study underscored the importance of extending product life through repair, reuse, and remanufacture, as well as material recovery. They also highlighted the need to minimize dispersed product and material flows through the coordination of multiple stakeholders to promote product circularity. Another recent study by Vimal et al. (2021) introduced a framework for measuring circularity and emphasized the importance of considering all lifecycle stages of products in the circularity assessment. They also highlighted how CP fosters minimal environmental harm by enabling multiple lifecycles of products. In a similar vein, Saidani and Kim (2021) proposed indicators for product circularity and stressed that monitoring the circularity potential of products and materials is crucial for achieving environmental savings and economic profitability in a CE, implying that a fully developed CP brings both environmental and economic benefits. Another study by Boyer et al. (2021) argued that product circularity measurement should consider strategies to enable high material recirculation, utilization, and endurance in products and service offerings. Expanding on this, Hapuwatte and Jawahir (2021) developed a metrics-based product evaluation framework to foster the integration of sustainability and circularity elements in product design. They highlighted the potential of CP to create societal benefits and recirculate the economic value of products, while also putting emphasis on the importance of standardized components and product longevity in CP.

Collectively, the above studies provided valuable insights into product circularity and indicated the characteristics of CP. The results of subSections 2.2 and 2.3 were then synthesized to establish CP attributes presented next.

2.4. CP attributes

This subsection proposes a core set of CP attributes derived from the synthesis of outcomes discussed in subSections 2.1, 2.2, and 2.3. To effectively identify the essential elements of CP, the attributes identified in the previous subsections were carefully analyzed and consolidated based on their inherent characteristics and indications of similar outcomes or goals. For instance, the attribute of long-lasting usage of components, as suggested by EMF (2013), the long-lasting use of products mentioned by Van der Berg and Baker (2015), and product longevity proposed by Hapuwatte and Jawahir (2021) all aim to extend the lifecycle of either a product or components. Consequently, these were clustered into the “Lifecycle Extension” attribute. Similarly, the importance of using recycled or upcycled materials proposed by Gossen & Kropfeld (2022), as well as avoiding toxic materials use mentioned by EMF (2013), were considered within the “Effective Selection of Resources” attribute because all these aspects relate to selecting resources effectively. Following the same approach, the attributes identified in the literature were consolidated based on their explicit and underlying meanings. Some of these were relevant to multiple consolidated attributes, and therefore, were considered in all those instances. For example, the use of recyclable materials noted by Mestre and Copper 2017, Nag et al., 2022, and Gossen and Kropfeld, 2022, is relevant to multiple consolidated attributes including value recovery strategies, effective resource selection, and closed-loop resource flow. The Appendix presents the outcomes of the consolidation process. These attributes were subsequently assessed through Pareto analysis to determine and prioritize the 20 % of the attributes that represent the majority, or 80 %, of CP characteristics. This evaluation, depicted in Fig. 2, emphasizes the attributes most commonly mentioned in the reviewed literature.

Based on the findings from the Pareto analysis, the eight attributes were identified as essential attributes of CPs and are presented in Fig. 3. A brief description of each attribute is provided below.

- Incorporate value recovery strategies: This attribute indicates the importance of maximizing the application of strategies such as recover, reuse, remanufacture, recycle, and redesign.
- Lifecycle extension: A CP is designed to have an extended operational lifespan, achieved by carefully selecting resources and designing for increased durability, ease of maintenance and repair through modularity, and upgradability to combat obsolescence.
- Effective resource selection: This attribute signifies the strategic selection of resources used throughout the entire lifecycle of a product, including its design, production, delivery (covering packaging and transportation), use, and EoL stages. Preferred materials are those that are recycled, recyclable, biodegradable, long-lasting, and safe (free from hazards and toxins), along with resources that are renewable.
- Closed-loop resource flow: This attribute means that a CP utilizes resources that are not solely derived from virgin resources. This approach aims to reinforce the application of value recovery strategies and also replicate the natural cycle where nothing is wasted.
- Stakeholder collaboration and engagement: The development of a CP relies on the active collaboration and engagement of key stakeholders. Their united participation is vital for ensuring transparency and the exchange of information for effective resource selection as well as EoL value recovery. Engaging a diverse range of stakeholders, particularly during the design stage, is crucial as their input greatly aids in enabling the value recovery strategies.
- Provide environmental benefits: Through the effective use of resources, prolonging the lifespan, and the value recovery, a CP contributes to minimizing pollution, cutting down on greenhouse gas emissions, and mitigating the harmful impacts associated with the extraction of raw materials, production processes, and the disposal of waste.
- Consideration of total lifecycle stages: This attribute refers to the importance of considering the entire lifecycle of a product from its initial design phase through pre-manufacturing, use, and post-use, to facilitate lifecycle extension, closed-loop resource flow, and value recovery strategies.
- Provide economic benefits: By using resources to their fullest potential, significant savings can be achieved in material procurement and waste management costs. Implementing value recovery strategies can also lead to the development of new business models and new sources of revenue, thus promoting the creation of economic value.

While all categories shown in Fig. 3 are based on the findings of literature and depict how the different aspects related to CP are conveyed in the literature, it must be noted that not all of them can be considered “features” of the product itself. Collaboration and

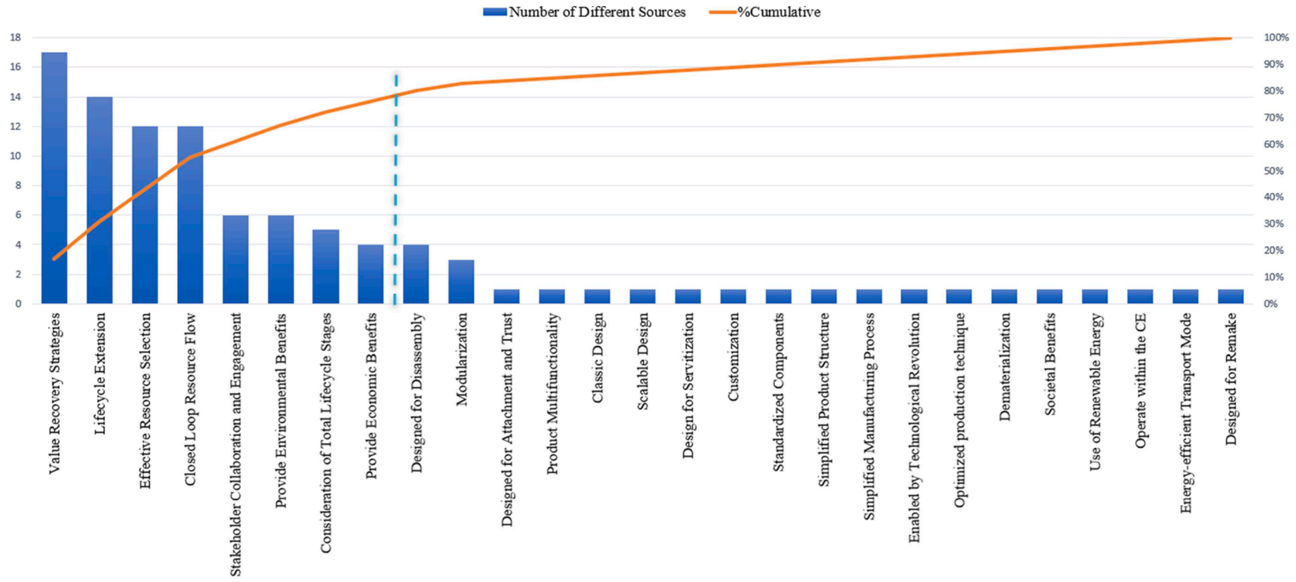

Fig. 2. Pareto analysis for the identified attributes.

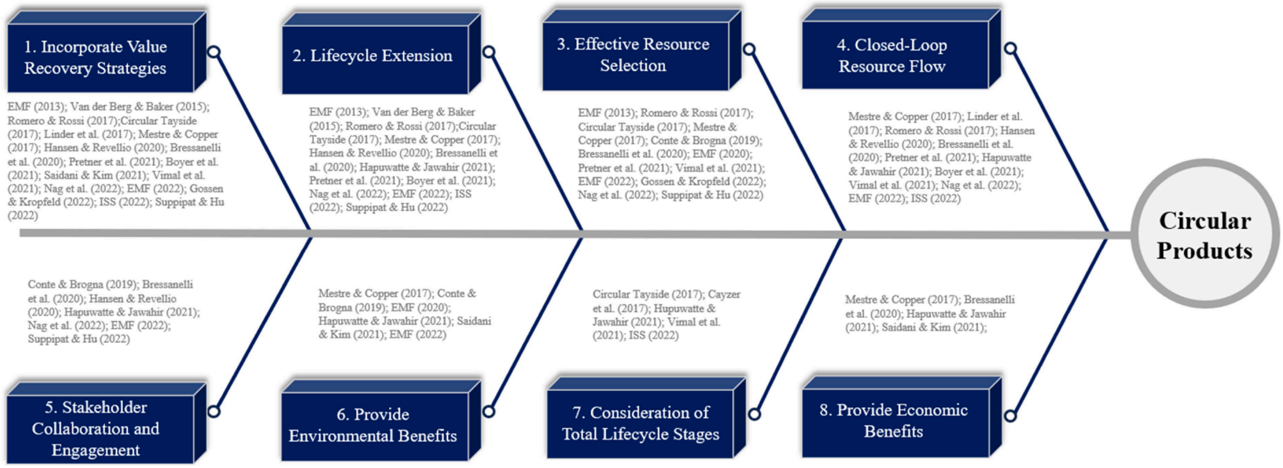

Fig. 3. CP attributes.

engagement with stakeholders across the total lifecycle, identified in numerous sources such as Bressanelli et al. (2020), Hapuwatte and Jawahir (2021), and others, is one of them. Similarly, effective selection of resources is not a feature of the product itself but enables cognizant resource selection to facilitate circular flow as well as to derive various benefits. This means that some of the items classified in the literature as attributes are in fact characteristics that can be considered enablers or drivers for CPs while others are benefits and implications (e.g., economic benefits) derived as a result of the circular flow of resources in the CPs. However, as the focus of this section is the presentation of a synthesis of criteria identified as attributes in the literature, they are categorized and discussed as shown in Fig. 3.

The effectiveness of any product circularity assessment method depends on whether it enables evaluating how well a product's characteristics or features embody or satisfy the requirements to qualify it as a CP. Such requirements to qualify a product as circular are the CP attributes compiled in the above section. Thus, whether a given product circularity assessment method is effective in assessing a product's circularity can be discerned based on whether or not it incorporates means to comprehensively evaluate all the required CP attributes. This aspect is further examined in Section 3.

3. Review of existing product circularity assessment methods

To enhance performance in any domain, including CPD and product circularity, measurement serves as the fundamental starting point. Numerous studies have emphasized the need for developing frameworks and metrics to evaluate product circularity. For instance, Saidani et al. (2019) examined 55 CE indicators, identifying 20 sets at the product level. Lindgreen et al. (2020) documented 74 methodologies for assessing circularity at the micro (product and company) level, with 22 specifically focusing on product circularity. More recently, De Oliveira et al. (2021) compiled 58 circularity measures, out of which 38 are at the product level. While these studies offer a broad spectrum of circularity indicators and methodologies, not all the product-level methods outlined by these scholars are aimed explicitly at assessing a product's circularity. For instance, the Global Resource Indicator (GRI) proposed by Adibi et al. (2017) and categorized under nano-level indicators by De Oliveira et al. (2021), targets resource assessment. Although resource efficiency is a facet of circularity, GRI does not provide a holistic assessment of a product's circularity. Similarly, REApro, developed by Ardente and Mathieux (2014) and classified as a product-level circularity assessment technique by Lindgreen et al. (2020), primarily evaluates resource efficiency rather than the circularity of a product. Our selection criteria were, therefore, rooted in the pursuit of methodologies that offer a holistic assessment of product circularity. This means prioritizing methods that not only address a singular aspect of circularity but also encompass a broader evaluation of a product's lifecycle and its alignment with CE principles. Also, methods with insufficient information were excluded. Table 3 presents a review of the selected methods, indicating their general scope and the extent to which CP attributes discussed above are covered.

Various methods have been proposed to assess product circularity, with early methods like the CE Toolkit (CET) by Evans and Bocken in 2013 and the Material Circularity Indicator (MCI) by EMF and Granta Design in 2015. However, as evident from Table 3, neither method comprehensively addresses the eight attributes of a CP. For instance, the CET is marked as "Partially" for "Effective Resource Selection," suggesting that while it considers the use of certain materials like biodegradable or recycled ones, it does not assess all material aspects such as packaging materials. On the other hand, a response of "No" implies that the method does not address the attribute aspect at all. Continuing with the CET example, it has a "No" for "Stakeholder Collaboration and Engagement" which means that it does not incorporate any criteria related to the involvement or consideration of stakeholders in the circularity assessment. This evaluative approach using qualifiers Yes, Partially, and No was applied consistently across all reviewed methods for each attribute, except for two specific attributes. For Attribute 1: Incorporate Value Recovery Strategies and Attribute 7: Consideration of Total Lifecycle Stages, more specific qualifiers were necessary due to the distinct strategies and stages covered by each method. For instance, the CET method was noted for its inclusion of reuse, remanufacturing, and recycling aspects, though it does not encompass recover and redesign. Similarly, this method addresses the manufacturing, use-stage, and post-use stages, but not the pre-manufacturing stage. The results outlined in Table 3 are based on a thorough review of how each method's criteria align with the attributes identified in this study. A brief description of these methods and their scope of coverage are presented below.

The MCI overlooks the source and destination of reused components and recycled materials (Bracquene et al., 2020), as well as the closed-loop nature of material cycles (Linder et al., 2017). The CE Index (CEI) (Di Maio and Rem, 2015) focuses solely on recycling, while the C metric (Linder et al., 2017) emphasizes closed-loop flow and incorporates the economic value of recirculated parts. The CE Prototype Indicator (CEPI) (Cayzer et al., 2017) is a qualitative method for evaluating product circularity, and the Circularity Potential Indicator (CPI) (Saidani, 2023) considers 20 attributes on a 0–10 scale but doesn't explicitly address the environmental and economic impacts of the total lifecycle. The Product Circularity Indicator (PCI) (Bracquene et al., 2020) overcomes some limitations of the MCI but only assesses materials recirculation. The Sustainable Product Circularity Index (SPCI) (Vimal

Table 3
Scope of some existing product circularity assessment methods.

Method name	Details (Industry sector, application, etc.)	Intended end-use(r)	1. Incorporate value recovery strategies[**] (Total: 5)	2. Lifecycle extension	3. Effective resource selection	4. Closed-loop resource flow	5. Stakeholder collaboration and engagement	6. Provide environmental benefits	7. Consideration of total lifecycle stages[***]	8. Provide economic benefits
CET (Evans and Bocken, 2013)	Not sector-specific	Multiple	Reuse, remanufacture, recycle	Partially	Partially	Partially	No	No	M, U, PU	No
MCI (EMF & GD, 2015)	Not sector-specific	OEM	Reuse, recycle	Partially	Partially	Partially	No	No	PM, U, PU	No
CEI (Di Maio and Rem, 2015)	Recycling only	Policymakers	Recycle	No	Partially	Partially	No	No	PU	No
CEIP (Cayzer et al., 2017)	Qualitative ratings	Multiple	Reuse, recycle, recover	Partially	Partially	Partially	No	No	PM, M, U, PU	No
C metric (Linder et al., 2017)	Not sector-specific/ based on economic value	Not specified	0	No	No	Partially	No	No	U, PU	No
CPI (Circularity Potential Indicator) (Saidani, 2023)	Not sector-specific/for use in improving products & business practices	OEM	Reuse, remanufacture, recycle	Partially	Partially	Partially	Partially	No	PM, M, U, PU	No
PCI (Bracquene et al., 2020)	Not sector-specific	Multiple	Reuse, recycle	No	Partially	Partially	No	No	PM, U, PU	No
SPCI (Vimal et al., 2021)	Not sector-specific	Not specified	Reuse, recycle, recover, remnaufacture	No	Partially	Partially	No	Partially	PM, M, U, PU	Partially
Circularity Calculator (IDEAL and CO Explore, 2023)	Business practices	Product Designers	Reuse, remanufacture, recycle	Partially	Partially	Partially	No	No	PM, M, U, PU	No
CPI (Circularity Product Indicator) (Angioletti et al., 2017)	Not sector-specific/ based on ECI[*], MCI, RCI	OEM	Reuse, recycle	Partially	Partially	Partially	No	No	PM, U, PU	No
CEPI (Huysman et al. (2017)	Plastic waste only	Not specified	Recycle	No	Partially	Partially	No	Partially	PU	No
Longevity and Circularity (Figge et al., 2018)	Not-sector specific/ based on resource use	Not specified	Recycle	No	No	Partially	No	No	PU	No

[*] ECI: The circularity indicator for energy, RCI: the circularity indicator for auxiliary resources.

[**] Value Recovery Strategies: recover, reuse, remanufacture, recycle, redesign.

[***] Total Lifecycle Stages: PM (pre-manufacturing), M(manufacturing), U(use), PU (post-use).

et al., 2021) addresses some shortcomings of the CPI, but there are still ambiguities regarding circular enablers and criteria in the SPCI.

The Circularity Calculator (IDEAL and CO Explore, 2023) considers all lifecycle stages and some of the value recovery strategies, but its adoption in the industry is limited as it lacks specificity to any particular sector. The Circularity Product Indicator (CPI) (Angioletti et al., 2017) and Longevity and Circularity measures (Figge et al., 2018) also suffer from the lack of sector specificity. The CE Performance Indicator (CEPI) (Huysman et al., 2017) focuses on plastic waste treatment options but doesn't consider micro-level circularity analysis, the total lifecycle, or value recovery strategies other than recycling. Notably, none of these methods cover all the eight attributes of a CP presented in this paper, although their contribution is critical to operationalizing product circularity through effective decision-making during the product development process (PDP).

Thus, significant limitations still exist in methods for assessing product circularity. The criteria and attributes considered in existing methods vary and are inconsistent in the scale of analysis. The consideration of total lifecycle stages varies and value recovery strategies such as reuse, remanufacturing, and recycling are often not fully considered. Industry adoption of the proposed methods has also been low due to several reasons (Lindgreen et al., 2020; Saidani et al., 2019). Firstly, most have not actively engaged industry stakeholders early during the development process (Wisse, 2016; Lindgreen et al., 2020; Saidani et al., 2019). Without the input and perspectives of these stakeholders, the methods may not be able to address the industry's needs, leading to potential impracticality in the implementation of these methods. A lack of consideration of end-user(s), sector(s), or product(s) specific approaches in existing methods has also hindered widespread adoption (Lindgreen et al., 2020). The scope and specificity required for circularity assessment methods vary depending on the target end-users (e.g., a policymaker's needs differ from a design engineer's). The majority of the current methods have not considered the design engineer/product designer as end-users or deliberately engaged them during development.

In addition, the inherent complexity and diversity of products across various industries, coupled with the broad range of factors that must be considered to accurately measure circularity, present significant challenges to developing universally applicable circularity assessment methods. Factors such as the resources used in production, the durability of the product, the feasibility of establishing closed-loop material flows, and the potential for multiple lifecycle aspects play a critical role in determining a product's circularity; more importantly, their relevance across different product types vary significantly. For example, using biodegradable materials to promote circularity will be more relevant in the furniture industry compared to consumer electronic products. Therefore, considering the sector-specific requirements is important to ensure the relevance and widespread use of product circularity assessment methods. The limited availability of extensive data presents another barrier to industry-wide implementation of the methods. Some (e.g., MCI) require extensive data not readily available, limiting OEM's ability to easily adopt such methods for assessing product circularity (Cayzer, 2017; Nebel, 2020). Fig. 4 shows these and other main limitations of the current product circularity assessment methods identified in the review based on some general observations discussed above (left-hand side of the figure) and the coverage of the CP attributes (right-hand side of the figure).

Based on the review of the selected product circularity assessment methods with respect to the eight CP attributes identified in this paper, the authors found that the current methods face a limited assessment on the lifecycle extension aspect, meaning that none of the methods fully cover this aspect. There is also limited inclusion of the value recovery strategies, as none of the methods address all the strategies in their assessment. The evaluation of the selected resources is also limited, indicating a potential oversight in the consideration of preferred resource types (such as recycled, non-toxic, durable, etc.) and the origins of the selected resources. Additionally, there is a limited consideration of closed-loop resource flow, which reflects an incomplete examination of how resources are circulating without becoming waste. The review showed that not all the methods consider the total lifecycle stages of a product. The stakeholder collaboration and engagement are also inadequately considered. Finally, the environmental and economic impacts are not fully addressed in any of the reviewed methods, implying that the current methods do not capture the broader benefits of a CP. These limitations highlight areas for improvement in the development of comprehensive and effective product circularity assessment methods.

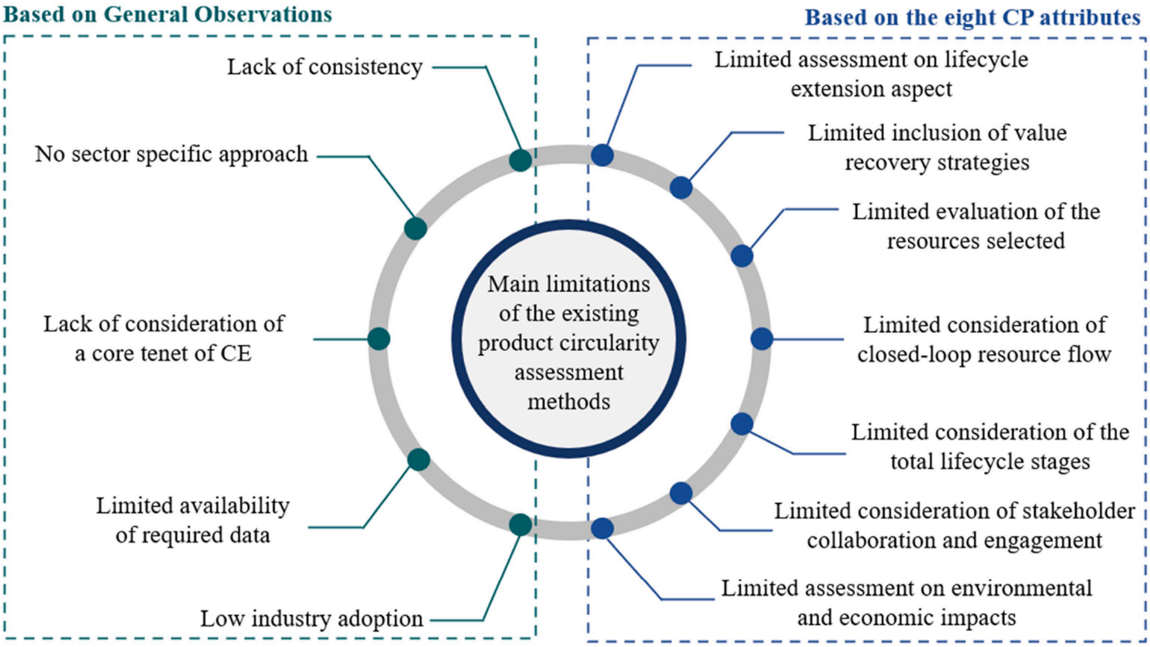

Fig. 4. Main limitations of the reviewed product circularity assessment methods.

4. Conclusions and future work

This paper established a basis for a comprehensive understanding of CP and identified CP attributes through a scoped review of literature related to CE, CPD, and product circularity. One of the major contributions of the work presented in this paper is identifying the core constitutive characteristics to describe the desired features and properties of a CP, based on foundational knowledge in related areas. This information is vital to evaluate the effectiveness of existing product circularity assessment methods as well as to ensure that new methods developed in the future will be comprehensive, incorporating relevant metrics to evaluate all the core characteristics. More consistency in the product circularity assessment methods developed, thereby avoiding ambiguity, can enhance the industry adoption of those methods. As such, the findings from this work contribute to further the theoretical understanding of CPs, enabling the development of product circularity assessment methods that will ultimately benefit the industry. The CP attributes identified through this work can also facilitate developing an articulate definition for CPs that is currently lacking in the literature.

The CP attributes presented in this paper primarily focused on the environmental and economic aspects. The evolving discourse around CE (Padilla-Rivera et al., 2020; Walker et al., 2021) in general and CPs, as well as the authors' extensive interactions with the industry for ongoing research on CPD and product circularity assessment, underscore the critical importance of considering the social dimension and the potential benefits toward the society resulting from the environmental and economic benefits derived by CE and CP. Future research should, therefore, endeavour to integrate social considerations more explicitly into CE-related research, particularly in the assessment of indirect benefits derived from CP. Based on the identified attributes, a review of existing product circularity assessment methods was conducted. The results demonstrate areas for reconciliation of the current methods. Exploring the integration of these methods also presents a potential avenue for future research. The findings underscore the need for future work towards evaluating the different approaches in terms of effectiveness and moving towards comprehensive product circularity assessment methods that can be agreed upon and widely deployed in the industry.

To complete the suggested future work, firstly, a more in-depth analysis is needed to further refine the CP attributes identified and validate them with industry stakeholder engagement. As discussed previously, not all the attributes identified in current literature as CP attributes are features of the products. Some items classified as attributes in the literature are in fact characteristics that can be considered enablers or drivers for CPs while others are benefits (e.g., economic benefits) and implications derived as a result of the circular flow of resources in the CPs. As such, it is also necessary to differentiate all the compiled attributes into different groups such as CP drivers/enablers, features of CPs themselves, and benefits/implications of CPs in future work in order to facilitate better decision-making during CP design and assessment. This process also requires engaging industry stakeholders to ensure all relevant attributes are accurately identified to establish a concrete foundation of what characterizes CPs. This paper's authors are also working to identify a comprehensive set of indicators and metrics that can aid the evaluation of the identified CP attributes and implementation levels of CPD principles. The establishment of standardized CPD principles and evaluation methods will support the transition toward a CE at all levels. Developing relevant standards is also crucial, as the process of standards development can facilitate the engagement of various stakeholders and build consensus on fundamental concepts, terminology definitions, and guidelines on design and manufacturing practices. Towards this end, many authors of this paper are engaged in ASTM International's Work Item titled "New Guide for Principles for Circular Product Design" (ASTM WK83603, 2022). The collaboration team developing the new standard seeks to identify standardization needs, review existing literature to identify principles and build consensus on generally applicable principles that can aid the CPD process. The collaboration team has also benefitted from the findings of this paper, enabling a more concrete understanding of the core constitutive characteristics of CPs to be considered during standard development.

Official position disclaimer

The opinions, recommendations, findings, and conclusions addressed in this paper do not necessarily reflect the views or policies of NIST or the United States Government.

CRediT authorship contribution statement

Junwon Ko: Writing – original draft, Methodology, Conceptualization. **Gisele Bortolaz Guedes:** Writing – review & editing, Methodology, Conceptualization. **Fazleena Badurdeen:** Writing – review & editing, Methodology, Conceptualization. **I.S. Jawahir:** Writing – review & editing, Conceptualization. **K.C. Morris:** Writing – review & editing, Supervision. **Vincenzo Ferrero:** Writing – review & editing, Supervision. **Buddhika Hapuwatte:** Writing – review & editing, Supervision. **Ryan Bradley:** Writing – review & editing, Supervision. **Ardeshir Raihanian:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Fazleena Badurdeen reports financial support was provided by National Institute of Standards and Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix

Identified attributes (References)	Consolidated attributes
	Value recovery strategies
• Designed for reuse (EMF, 2013)	
• Keep materials in use for as long as possible (Circular Tayside, 2017)	

(continued on next page)

(*continued*)

Identified attributes (References)	Consolidated attributes
• No mixture of biological and technological materials (Romero and Rossi, 2017) • Designed for reuse, remanufacture (Hansen and Revellio, 2020) • Designed for reuse, remanufacture, refurbish (Pretner et al., 2021) • High utilization of products (Boyer et al., 2021) • Designed for remanufacture, refurbish, and recycle (EMF, 2022) • Closed-loop products (Bressanelli et al., 2020; ISS, 2022) • Designed for recycle (Van der Berg and Baker, 2015; Suppipat and Hu, 2022) • Designed for reuse, remanufacture, recycle, recover (Vimal et al., 2021; Saidani and Kim, 2021) • Recyclable materials (Mestre and Copper, 2017; Nag et al., 2022; Gossen and Kropfeld, 2022) • Designed for reuse, remanufacture, recycle (Linder et al., 2017; Mestre and Copper, 2017; Bressanelli et al., 2020)	
• Long-lasting use of components (EMF, 2013) • Long-lasting use of products (Van der Berg and Baker 2015) • Lifecycle extension (Romero and Rossi, 2017) • Keep products in use for as long as possible (Circular Tayside, 2017) • Extended product lifetime (Bressanelli et al., 2020) • Product life extension (Hansen and Revellio, 2020) • Extended lifecycle of products (Pretner et al., 2021) • High endurance (Boyer et al., 2021) • Product longevity (Hapuwatte and Jawahir, 2021) • Designed for maintenance, longevity, and durability (EMF, 2022) • Product life extension with upgrade (Nag et al., 2022) • Prolonging the use phase (ISS, 2022) • Designed for reliability and durability (Mestre and Copper, 2017; Suppipat and Hu, 2022)	**Lifecycle extension**
• No toxic materials (EMF, 2013) • Reduced or no virgin resource use (Circular Tayside, 2017) • Use of recycled resources (Romero and Rossi, 2017) • Materials management (Conte and Brogna, 2019) • Cleaner, renewable, lower energy materials (Mestre and Cooper, 2017) • No harmful materials (EMF, 2020) • Optimized resource efficiency (Pretner et al., 2021) • Efficient usage of materials (Vimal et al., 2021) • Use of renewable energy (EMF, 2022) • Recyclable materials (Mestre and Copper, 2017; Nag et al., 2022; Gossen and Kropfeld, 2022) • Use of recycled or upcycled materials (Gossen and Kropfeld, 2022) • Use of recycled materials (Suppipat and Hu, 2022)	**Effective resource selection**
• Closed-loop material flow (Romero and Rossi, 2017) • Closed-loop products, components, and materials (Bressanelli et al., 2020) • Material recovery (Hansen and Revellio, 2020)	**Closed-loop resource flow**

(*continued on next page*)

(*continued*)

Identified attributes (References)	Consolidated attributes
• Closed-loop materials (Pretner et al., 2021) • Material recovery and recirculation (Boyer et al., 2021) • Closed-loop products (ISS, 2022) • Closed-loop cycles (Linder et al., 2017; Hapuwatte and Jawahir, 2021) • Designed for multiple lifecycles of products (Vimal et al., 2021; EMF, 2022) • Recyclable materials (Mestre and Copper, 2017; Nag et al., 2022; Gossen and Kropfeld, 2022)	
• Stakeholder involvement (Conte and Brogna, 2019) • Stakeholder consideration (Bressanelli et al., 2020) • Coordination of multiple stakeholders (Hansen and Revellio, 2020) • Stakeholder consideration and engagement (Hapuwatte and Jawahir, 2021) • Customer involvement (Nag et al., 2022) • Collaborative community design (Suppipat and Hu, 2022)	**Stakeholder collaboration and engagement**
• Materials management (Conte and Brogna, 2019) • Environmental benefits (Bressanelli et al., 2020) • Minimal harm to the environment (Vimal et al., 2021) • Environmental savings (Saidani and Kim, 2021) • Reduced waste and pollution (EMF, 2022) • Biodegradable products (Gossen and Kropfeld, 2022)	**Provide environmental benefits**
• Designed with consideration of EoL (Circular Tayside, 2017) • Consideration of lifecycle stages (manufacture, use, post-use) (Cayzer et al., 2017) • Consideration of all lifecycle stages (Vimal et al., 2021) • Engagement with stakeholders across the total lifecycle (Hapuwatte and Jawahir, 2021) • Consideration of the product's next life (ISS, 2022)	**Consideration of total lifecycle stages**
• Recirculation of economic value (Hapuwatte and Jawahir, 2021) • Economic profits (Gossen and Kropfeld, 2022) • Economic benefits (Bressanelli et al., 2020; PLI, 2023)	**Provide economic benefits**
• Designed for disassembly (Van der Berg and Bakker, 2015; EMF, 2022) • Easy disassembly (EMF, 2013; Nag et al., 2022)	**Designed for disassembly**
• Modularization (EMF, 2013; Nag et al., 2022) • Modular design (Suppipat and Hu, 2022)	**Modularization**
• Designed for remake (Van der Berg and Baker, 2015) • Designed for servitization (Romero and Rossi, 2017) • Use of renewable energy (Mestre and Cooper, 2017) • Optimized production technique (Mestre and Cooper, 2017) • Energy-efficient transport mode (Mestre and Cooper, 2017) • Operate within the CE (Circular Tayside, 2017) • Enabled by technological revolution (Conte and Brogna, 2019) • Societal benefits (Hapuwatte and Jawahir, 2021)	**Others**

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(*continued*)

Identified attributes (References)	Consolidated attributes
• Standardized components (Hapuwatte and Jawahir, 2021)	
• Scalable design (Suppipat and Hu, 2022)	
• Classic design (Suppipat and Hu, 2022)	
• Product multifunctionality (Suppipat and Hu, 2022)	
• Simplified product structure (Suppipat and Hu, 2022)	
• Simplified manufacturing process (Suppipat and Hu, 2022)	
• Dematerialization (Suppipat and Hu, 2022)	
• Customization (Suppipat and Hu, 2022)	
• Designed for attachment and trust (Suppipat and Hu, 2022)	

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