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Improving product circularity through circular economy strategies for small domestic appliance design in China

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Abstract China is the world's largest home appliance producer, and the rising manufacturing of small domestic appliance (SDA) is creating high carbon emissions worldwide. Due to China's high carbon emissions, the country needs to improve its SDA design and production. This study aims to investigate the critical improvement of product circularity through circular economy strategies for SDA design. This desktop study analyses 37 journal articles from Scopus and Web of Science (WoS) databases from 2019 to 2024. This study explores the current circular economy strategies used by SDA to reduce carbon footprint and the gap in the application of circular economy strategies in SDA manufacturing. It also recommends the best circular economy strategies for SDA design to reduce carbon footprint. Key findings indicate that product disassembly, upgradability, and integrity are pivotal in extending product lifespans, reducing resource consumption, conserving materials, and reducing waste. In addition to directing future empirical and theoretical research in the circular economy, these findings can aid designers, researchers, stakeholders, and manufacturers in updating their knowledge of enhanced product circularity.

Keywords: product circularity, circular economy, product disassembly, product upgradability, product integrity

1. Introduction

China's home appliance industry started developing in the 1980s. Since then, China has become the world's largest home appliance manufacturing and exporting country, accounting for approximately 70% of the global production capacity (Fan, 2024). In the country, Guangdong's household appliance manufacturing industry accounted for more than 40% of China's total small domestic appliance (SDA) production in 2022; with its complete industrial chain, Guangdong Province boasts the world's largest and most comprehensive appliance manufacturing center (Wang, 2023). However, only 20% of electronic waste (e-waste) is formally recycled, and most of the e-waste created (80%) is transformed into rubbish (Suppipat & Hu, 2022). Approximately 4% of the rubbish was toss into home trash bins and then land-filled or burnt, and another 76% was randomly dumped or treated illegally in 2019 (Forti et al., 2020). Most of the waste flow remains unclear (Meihui et al., 2023), as shown in Figure 1.

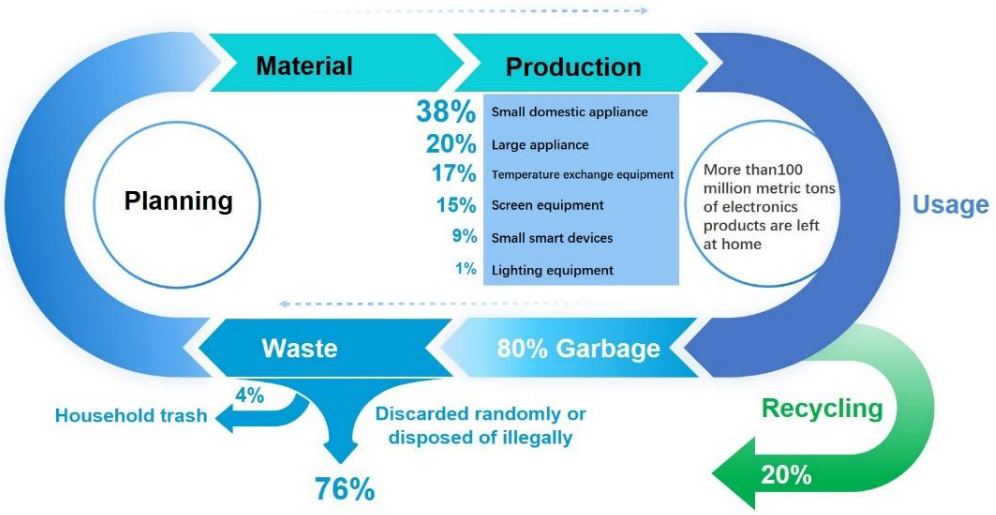

Figure 1 Global e-waste flows. *Source:* Suppipat and Hu (2022)

SDAs are typically made of durable materials such as plastics, metals, electronic components, and printed circuit boards. SDAs have relatively short lifespans before being discarded when they are no longer usable or valuable (Meihui et al., 2023). Current disposal practices result in losses of energy, resources, and values embodied in electronic products, leading to significant waste generation (Forti et al., 2020). China has surpassed the United States to become the world's largest emitter, accounting for 28% of global carbon emissions. China has pledged to reach its carbon peak by 2030 and achieve carbon neutrality by 2060 (Huaxia, 2020). The Chinese government emphasizes the need to transition to a green and low-carbon economy while promoting green recovery and development to achieve these goals.

The Circularity Gap Reporting Initiative (2021) estimates that circular economy strategies could reduce global greenhouse gas emissions by 39%. However, the global circularity rate has declined from 9.1% to 7.2% in five years (Circularity Gap Reporting Initiative, 2021). Therefore, this study aims to explore various methodologies to increase the circularity of SDA products and reclaim their inherent value, ultimately mitigating the environmental damage caused by substantial numbers of end-of-life products.

As articulated above, on the basis of the large amount of carbon emissions generated by the production and consumption of SDA in China and even though many studies have suggested the great potential of the circular economy to reduce carbon emissions, there is still a research gap on how the design of SDA can incorporate strategies of the circular economy, as well as on those product design factors that affect the circularity of SDA products. Therefore, this study aims to investigate the design factors and corresponding design parameters for SDA design to enhance product circularity.

2. Literature Review

This section discusses the circular economy strategies and the design for product circularity. First, the study conducted a thematic analysis of the literature reviewed pertaining to SDA design and circular economy strategies that support low-carbon design. The synthesized product disassembly, upgradeability, and integrity were subsequently analyzed, leading to three proposed hypotheses. Ultimately, through a series of cross-analyses, the POD tree diagram for enhancing product circularity was obtained.

2.1. Small domestic appliance (SDA) design

Product design and development are complex and dynamic processes initiated by identifying market opportunities. The processes span various stages, including planning, concept development, system-level design, detail design, testing and refinement, production, and delivery to customers. Thus, collaboration across multiple disciplines is necessary (Ulrich et al., 2020). Simon (2021) highlighted that over 70% of a product's lifecycle costs and carbon footprint are determined during its design phase. Critical decisions made during the design phase have long-lasting effects, potentially setting the parameters for a product's energy usage and carbon emissions for years. Shahbazi and Jönbrink (2020) identified a lack of knowledge and expertise among designers and a lack of incentives for companies to invest in circular product design as possible challenges in adopting a circular economy. Abdul Ghafar Maszura and Ibrahim (2018) discovered that designers must be transdisciplinary at the initial design stages to save time and reduce manufacturing waste. During the design stage, the designer makes critical decisions regarding the necessary inputs to the product's lifecycle process. Therefore, it is crucial to comprehend the essential circular economy capabilities, knowledge, and expertise that designers must possess during the design and development stage and strengthen circular economy education for designers.

Despite the fact that product design can determine the successful transition of the manufacturing industry into a circular economy, relatively few studies have been conducted on methods, strategies, and tools for the design of product circularity (Aguiar et al., 2022). Product development cannot be separated from circular economy principles (Diaz et al., 2022). Many studies have been conducted in related areas, including additive manufacturing (Tavares et al., 2023), lightweight design (König et al., 2024), generative design (Dean & Loy, 2020), reduced production steps (Diaz et al., 2022), product architecture effects (Gadam, 2023), stakeholder collaboration (Dokter et al., 2021), and consumer behavior and willingness (Triguero et al., 2023). Additionally, circular economy principles are enriched by industrial design (van Dam et al., 2020). On the basis of the above discussion, substantial contributions by additive manufacturing, lightweight design, generative design, and reduced production stages to product circularity have been demonstrated in relevant research. Consequently, a comprehensive strategy that integrates sustainable manufacturing practices, collaborative stakeholder initiatives, and advanced design techniques is a prerequisite for the establishment of a circular economy.

In summary, product design and development can determine if the transition to a circular economy is smooth. However, little research has been conducted in this field, despite various methods, tools, and frameworks that facilitate circularity design. In addition, the designer acts as a critical decision maker in the architecture, materials, and components during the product design and development phases, making it necessary to acknowledge and take advantage of the circular economy capabilities of designers and the new transdisciplinary skills associated with the design of products for circularity.

2.2. Circular economy strategies that support low-carbon design

The circular economy was put forward in the 1970s, when Kenneth Boulding (1966) proposed a circular relationship between the economy and the environment in “The Economics of the Coming Spaceship Earth. The circular economy, which is based on industrial ecological concepts, requires improved efficiency of resource utilization and waste reduction (Ghisellini et al., 2016). Özçatalbaş (2023) suggested that the old linear model of production and consumption be replaced with closed-loop systems that reuse and maintain resources in the production cycle for as long as possible. The circular economy is the opposite of the linear economy, which focuses on disposal. The circular economy stresses the extension of product and material life through remanufacturing, reusing, and recycling (Mesa et al., 2019). The circular economy is commonly defined as a restorative and regenerative framework with the maximized utilization of goods, components, and materials as the goal. Three rationales, waste and pollution reduction, product and material preservation, and natural system restoration, are the guiding principles of this economic pattern (Ellen MacArthur Foundation, 2013). Thus, the circular economy concept is based on ensuring the functioning of materials and resources in the economy for as long as feasible, boosting growth by utilizing discarded products or waste as a critical resource for production while minimizing energy and new resource consumption. Its ultimate goal is to create a closed-loop economy that balances economic development with environmental and resource protection, involving a paradigm shift toward a more sustainable and resource-efficient economic model.

Diaz et al. (2022) investigated the implications of R-strategy adoption for decision-making in sustainable product development pertaining to product materials, architecture, product services, product business models, and product ecosystems. Aguiar and Jugend (2022) highlighted that while many studies acknowledge the importance of circular product design, the gradual incorporation of circular economy practices into new product development requires further investigation. Burke et al. (2023) and Diaz et al. (2022) further explored the integration of circular product design in supply chains and strategic management, respectively. Several studies have also highlighted the systemic and methodological approaches to circular product design. Franco (2019) utilized a system dynamics model to examine the effects of combining various product design and business model strategies, demonstrating the importance of design considerations in product lifecycle stages. Hapuwatte and Jawahir (2021) propose a new methodology that integrates sustainability and circularity principles, emphasizing the inclusion of societal impacts in product evaluations. These studies have one thing in common: they indicate that circular product design involves multiple dimensions and can facilitate the fulfillment of a sustainable circular economy.

Circular product design, with a focus on how to improve the product’s disassembly, integrity, and upgradability, aims to keep products, components, and materials in the loop for extended periods. Other studies in this area include “Circular Strategies Scanner Framework” (Blomsma et al., 2019), “Circular Product Design Framework” (Circle Economy, n.d.), “Circular Design of Composite Products” (Joustra et al., 2021), and “Guidelines for Circular Product Development” (CIRCit Norden, n.d.). To date, the purpose of the circular economy is to decouple economic growth from environmental degradation. However, implementing the recommendations of these studies requires specific competencies, methods, and tools. Moreover, most of these studies are theoretical and conceptual, making it challenging for designers to use them in practice. In conclusion, various circular economy strategies could keep products, components, and materials in the loop for extended periods, but current research needs empirical validation, which necessitates developing a product design framework and strengthening empirical research.

2.3. Product disassembly, upgradability and integrity

Product disassembly is an essential component of a circular economy, allowing for the recovery and reuse of materials and components at the end of a product’s lifecycle (Vanegas et al., 2018). Most of the contributions of design for disassembly (DfD) concepts derived from the literature concern disassembly in the industrial manufacturing domain. Bouyarmane and Sallaou (2020) focused on evaluating disassembly during the conceptual design phase, emphasizing criteria such as disassembly tools, accessibility, time, and end-of-life scenarios. Baazouzi et al. (2021) researched how to improve disassembly strategies and reported that it is highly important to set proper steps for disassembly. Relevant studies have focused on disassembly planning for recovery and energy conservation (Ren et al., 2020), modularity design (Cordella et al., 2021), improvements in material efficiency through recyclability (Cordella et al., 2020), design standardization (Liu et al., 2017), and access and performance models (Bocken et al., 2016). DfD techniques, which facilitate the disassembly of parts and materials that can be reused, repurposed, or remanufactured, strongly boost the transition to an industrial circular economy. Effective DfD should be implemented on the basis of practice that involves considerations of end-of-life events during the original design phase, which ensures easy disassembly with the components intact. For example, Formentini and Ramanujan (2023) studied a disassembly model as a comprehensive disassembly model, highlighting that it optimizes disassembly and supports circular design methods by considering a product’s end-of-life status.

Despite the importance of DfD, it is difficult to implement. For example, the disassembly of different product categories requires standardized methodologies and tools. Bouyarmane and Sallaou (2020) conducted a study on disassembly, emphasizing that disassembly should be assessed throughout the conceptual design phase; factors such as disassembly tools, accessibility, and time should be considered to assist in the development of easy-to-dissemble items. The aim is to increase the items’ eligibility for the circular economy. Mesa et al. (2019) conducted a relevant study and discovered that manufacturing and material consumption studies should be conducted in the design phase to ensure the flexibility of goods to circular models and thereby increase their sustainability. Effective responses to these issues cannot be separated from the collaboration of multiple entities, such as designers, producers, and legislators, to set disassembly related rules and standards. Ren et al. (2020), on the basis of disassembly sequence decisions and end-of-life techniques, examined whether good disassembly planning can help recover value and conserve energy. Companies can effectively recover valuable components and limit energy use during disassembly to save costs and increase competitiveness in a circular economy. Furthermore, Zikopoulos (2022) contends that the government can effortlessly increase the number of actions taken by enterprises to implement DfD processes through financial incentives for product updates and remanufacturing. Therefore, sustainable product design and circular economy strategies must include improvements in DfD, given its ability to promote environmental goals and its tremendous economic benefits.

In conclusion, the accessibility of product components is the basis of these strategies. As often indicated in the literature, design parameters for improving product disassembly—including material utilization, modularity, standardization, and accessibility—are highly important. The results of DfD in the industrial manufacturing sector suggest that reducing the disassembly time and costs, enhancing the disassembly procedure of items to increase their circularity and extend their use phase, and reducing the usage of materials and equipment parts are important. These circular economy strategies call for all entities, such as easier product repair, product reuse, and component harvesting, to extend product lifetimes. However, these studies should be further consolidated, given the scarcity of empirical evidence for the effectiveness of these strategies. Therefore, the following hypothesis was proposed:

H1: Enhancing product circularity at the design level of disassembly (DLD) corresponds to a decrease in carbon emissions in SDA manufacturing.

Upgradability is critical to systemic and efficient remanufacturing and recycling in terms of increasing the circularity of products. Tecchio et al. (2017) conducted a relevant study on upgradability, identifying design for upgradability (DfU) as a major component of circularity design. The aim of DfU, as per Umeda et al. (2005), is to facilitate adaptation to ever-evolving consumer needs by making products more flexible, along with some minor structural changes after manufacture. Product upgradability refers to the adaptability of a product and its long-term use in the framework of the circular economy (Triguero et al., 2023). Xing and Belusko (2008) also deeply investigated upgradability, arguing that it involves improvement in upgradability through enhanced functional and conceptual features. Thus, DfU, as a circular product design strategy, aims to increase product durability through improved functionality. The role of DfU as a catalyst for circularity relies on understand ing customer needs and assessing product durability.

The enhancement of product circularity and company performance in the circular economy context rests upon whether upgradability and redesign are included in product design (Triguero et al., 2023). Ganter et al. (2021) conducted studies on component upgrading and discussed how to upgrade components in refurbishment processes, emphasizing that components should be modified before being upgraded to state-of-the-art or adapted to changing requirements. Schischke et al. (2021) conducted a study on circularity, discussing the circularity of modularity approaches, suggesting that the adoption of repair, upgrade, customization, reuse, and repurposing of modules can help eliminate overspecification. Royo et al. (2024) present a framework in which questions are guided for the generation of product ideas that meet evolving needs to enhance product adaptability for improved upgradability. The inclusion of adaptability in the design process facilitates product upgrading, which, in turn, contributes to customer satisfaction and product durability, as well as the resolution of changing requirements. Saidani et al. (2020) conducted a study on product-centric circularity indicators; their study was based on the context of product design, highlighting improved product maintainability as a prerequisite for the implementation of circular economy principles. Their research suggested that eco-design tools and circularity indicators are positively correlated with the circularity performance of industrial products. These findings are in line with the principle of the circular economy that advocates product maintainability. Thus, increased product upgradability, specifically compatibility, adaptability, and maintainability, is positively correlated with increased product circularity and performance. This effect is achieved through better adaptation to new requirements and technologies. However, tremendous amounts of time are needed to maintain compatibility, and this process requires strict standards and design beforehand. These technologies should be applied on the basis of a rigorous framework and industry-wide collaboration to comply with circular economy principles.

Overall, the circular economy can be better implemented through product upgradability and design parameters for improving product upgradability—including adaptability, maintainability and compatibility. This aspect has been widely regarded as critical to circular product design and development and is positively correlated with product durability, reduced waste, and resource conservation. However, product upgradability is difficult, and this process involves trade-offs. Designers who seek to upgrade products must strike a balance between modularity and standardization and the limits of cost, performance, and aesthetics. Furthermore, there is a need for an interdisciplinary and systematic perspective. The resulting complexity and compatibility concerns limit product ease of use and reliability. Therefore, this study proposed the following hypothesis:

H2**:** Enhancing product circularity at the design level of upgradability (DLU) corresponds to a decrease in carbon emissions in SDA manufacturing.

Product integrity is the ability of a product to meet or exceed a customer's expectations for performance, quality and durability throughout the life of the product (Bakker et al., 2021). According to Evans and Evans (2001), product integrity includes performance, quality, reliability, and durability factors. van Dam et al. (2020) researched the significance of product durability. Their studies are based on the circular economy context and seek to determine what design techniques can increase product longevity and maximize consumer durable use rates. Mesa et al. (2022) stated that the inclusion of durability in product design involves changes in a system-based design approach. This method, with a focus on the entire product lifecycle and system interactions, improves product longevity and integrity. Circular product design requires an increase in product durability (Aguiar et al., 2022). Strategies such as emotional durability, multiple usage cycles, and biomimicry all contribute to the development of products in the circular economy framework. Munten et al. (2021) explored whether product-oriented product-service systems (PSSs) can contribute to the management of obsolescence issues and reported that increased durability can address obsolescence and maintain product integrity. Thus, durability, modularization, and other criteria can transform items into more sustainable, reusable, and recyclable items, as their integrity is ensured during several usage cycles. The extension of product lifespans enables various circularity tactics, such as reuse, repair, refurbishment, and remanufacturing, making it essential for product durability. However, theoretical approaches to increasing durability—such as designing for emotional and physical durability, maintaining, upgrading, and repairing and remanufacturing facilities—frequently overlap. Addressing this overlap and research gaps in understanding how to execute these solutions best is critical for addressing product durability concerns and promoting sustainable development goals in a circular economy. Additionally, Wang et al. (2023) highlighted that it is crucial for the design of low-carbon product families to include component reliability and warranty duration. González-Domínguez et al. (2020) emphasized that the inclusion of reliability considerations in product design can increase durability and repeatability, thus increasing circularity. Wallat et al. (2022) indicated that the development of reliable products can enhance circularity and knowledge-based product design in the circular economy, making it easier to create products through circular economy principles. Thus, the alignment of product design with consumer expectations for long-lasting, dependable products and progress may facilitate the achievement of a circular economy and reduce the carbon footprint.

In conclusion, improved design for product integrity can, to some degree, determine if circularity can be increased and carbon emissions can be reduced in the manufacturing industry. The aim of integrity design is to preserve or improve economic value. Manufacturers can mitigate the negative environmental impacts associated with e-waste disposal by emphasizing product durability and reliability. Consequently, incorporating durability as a critical factor in product design aligns with sustainable development and circular economy goals, benefiting both consumers and manufacturers alike. Thus, promoting the design of more durable products can substantially extend product lifetimes, reduce resource consumption, conserve materials, and minimize waste production. On this basis, the following hypothesis was formed:

H3: Enhancing product circularity at the design level of integrity (DLI) leads to a decrease in carbon emissions in SDA manufacturing.

Advancing product circularity through disassembly, upgradability, and integrity is essential for achieving a circular economy in the manufacturing industry. Material utilization, modularity, standardization, accessibility, adaptability, maintainability, compatibility, durability, and reliability are latent variables of this conceptual circular product framework. These strategies not only support environmental goals but also provide significant economic benefits, making them crucial components of sustainable product design and circular economy strategies. By improving the design levels of disassembly, upgradability, and integrity, manufacturers can achieve significant reductions in carbon emissions in SDA manufacturing, thus supporting a more sustainable and circular economy. The theoretically related constructs and latent variables of the circular product design framework for SDA design are shown in Figure 2.

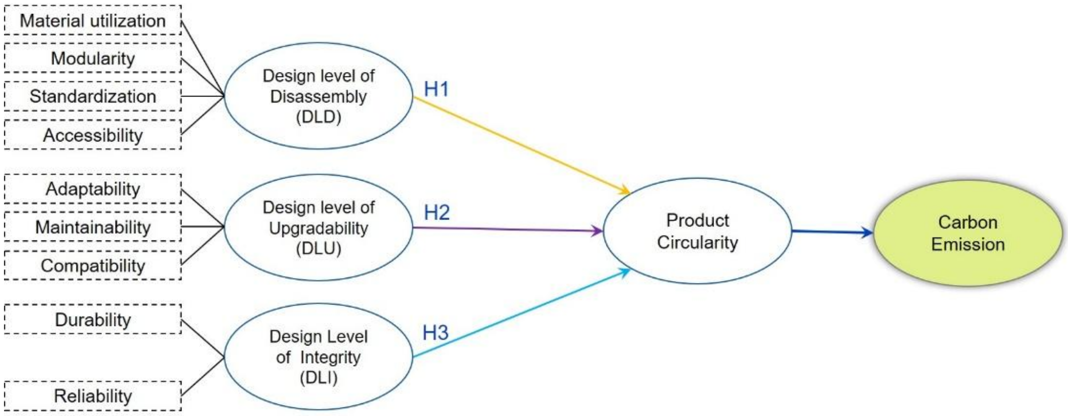

Figure 2 Theoretical relating constructs and latent variables of the circular product design framework for SDA design.

2.4. POD tree diagram for enhancing product circularity

On the basis of the preceding literature review, this study created POD1, POD2, and POD3, adapted from Ibrahim and Mustafa Kamal (2018). Then, through a series of cross-analyses, the POD tree diagram (refer to Figure 3) was synthesized. POD9 was the final theoretical proposition: "Improving product integrity, disassembly, and upgradability is vital for enhancing product circularity and preserving product value to reduce carbon emissions."

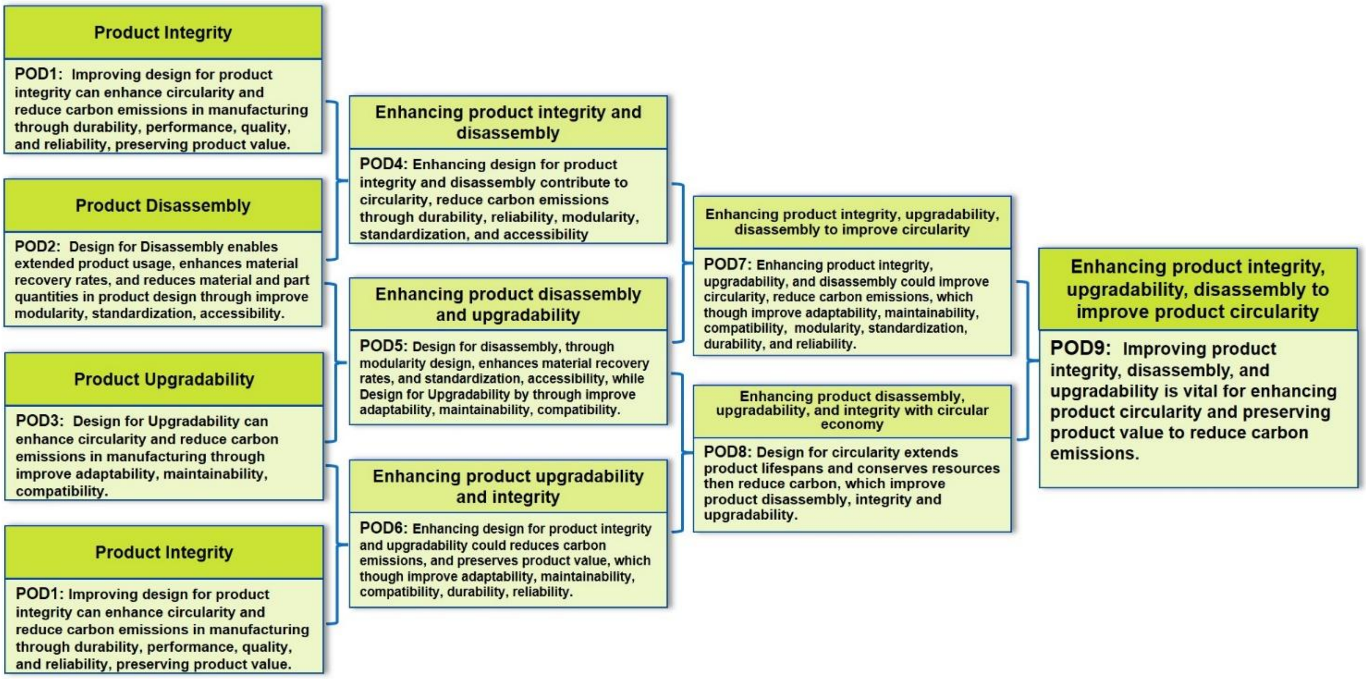

Figure 3 POD tree diagram for enhancing product circularity.

3. Materials and Methods

The research methodology outlined in this literature review is based on the Eagle research methodology coined by Ibrahim in 2011 and later elaborated on by Ibrahim and Mustafa Kamal in 2018. Using this approach, the study developed a taxonomy of research question constructs to distinguish the thematic aspects of "who", "what", and "how" when three distinct research objective constructs were designed. These constructs collectively address the overarching research question. While the "who" is defined as the element affected by the investigation, the "what" construct represents the knowledge required to resolve the specified issue, and the "how" construct is the action of the study. The synthesis of these elements is visually represented in the point of departure (POD) tree diagram, adapted from the work of Ibrahim and Mustafa Kamal (2018). Figure 4 provides a flowchart that succinctly illustrates this review methodology, detailing the structured data synthesis and analysis process.

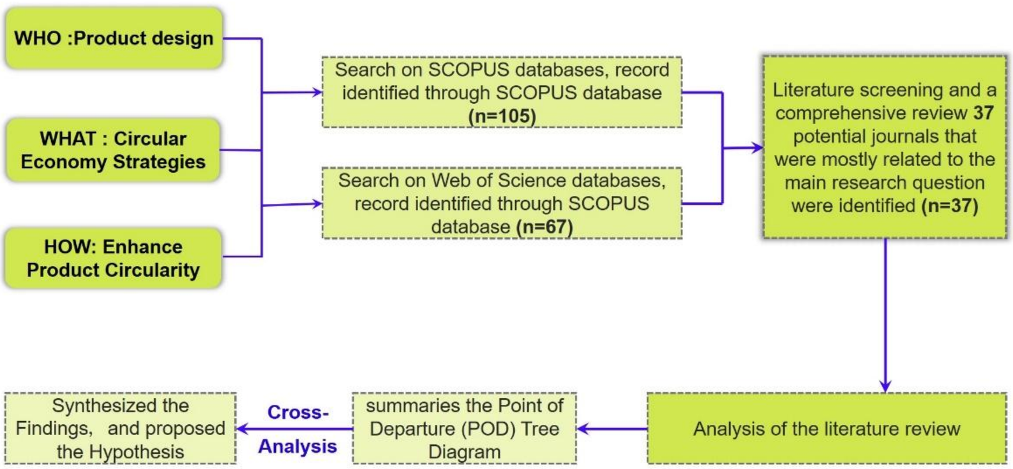

Figure 4 Workflow of the systematic literature review and synthesis process.

A comprehensive literature search was performed in the Scopus and WoS databases. Keywords consisting of the constructs of the target research question (RQ) (Waddington et al., 2012) were used. Specifically, this study used search terms related to product circularity, namely, “Product design” OR “Circularity” OR “Product disassembly” OR “Product upgradability” OR “Product integrity” AND “Circular economy”. After the literature screening and comprehensive review, 37 potential journals that were related mostly to the main research question were found. The findings of the selected potential articles were analyzed in greater detail, and the research problems to be solved in the future were identified. The systematic review resulted in research findings consisting of synthesized topics, which were then cross-analyzed. Finally, the potential operational procedures were associated with and prioritized on how they might improve product circularity from the perspective of a circular economy. The outcomes are depicted in the POD tree diagram.

4. Results and Discussion

This section discusses improving the SDA lifecycle through the circularity of product design and improving the design levels of disassembly, upgradability, and integrity. Second, variables and parameters are used to develop a circular product design framework, and implications for SDA design are recommended. Finally, it highlights the best practices in SDA design and manufacturing.

4.1. Improving the SDA lifecycle through the circularity of product design

According to circular economy principles, items are used longer, resources are constantly recirculated, and environmental impacts are minimized (Mesa et al., 2019). Material utilization, modularity, standardization, and accessibility are important factors for enhancing the design level of disassembly (DLD) (Ren et al., 2020; Cordella et al., 2021; Cordella et al., 2020; Liu et al., 2017). Products designed with these factors taken into account normally last longer, these products also involve less waste and feature resource efficiency, with fewer negative impacts generated on the environment (Vanegas et al., 2018). To reduce raw material use, designers should account for modularity, standardization, and accessibility in SDA design and development. For example, design evaluations can be conducted via disassembly and circularity indicators, and product manufacturing can be completed via the R method. However, these factors intersect in product design, requiring designers to improve them through effective strategies, especially for product circularity enhancement.

Adaptability, maintainability, and compatibility can significantly enhance the design level of upgradability (DLU) (Aguiar et al., 2022). The design level of upgradability considerations needs to be improved to fit with such principles (Tecchio et al., 2017). Adaptable, maintainable products interconnected with other products or systems enable manufacturers to minimize waste, conserve resources, and deliver more value (Triguero et al., 2023). Therefore, SDA designers must consider how to enhance these factors during the product development process, such as incorporating design indicators for subsequent product updates and upgrades so that products can be updated without replacing them with new products. At the same time, improving the maintainability of products makes them easier to maintain, which extends their lifecycle. The design also considers product compatibility, so the products are better compatible with multiple functions, replacing or reducing the number of similar product development categories.

Additionally, the design level of integrity (DLI) involves eliminating obsolescence and developing items that can be restored to their highest value by taking into account performance, quality, reliability, and durability (Bakker et al., 2021). Reliable items require fewer replacements, so less waste is caused, with more resources conserved (Wang et al., 2023). Durable items usually last longer than less durable items do, so they consume fewer new resources, and their manufacturing and disposal cause less environmental harm (van Dam et al., 2020). This, in turn, contributes to the promotion of the items' long-term viability and social acceptance. However, these elements may make products more complex, and there will be concerns about whether they are compatible with other components (Schickel et al., 2021). Thus, designers should consider the negative impact during design and turn to an interdisciplinary and systemic approach to implement the circular economy effectively. Furthermore, other stages of product development can suffer during the implementation of a circular product design strategy. Concerns include increased costs, among other problems. Therefore, these circular design approaches should be evaluated in terms of their feasibility.

In summary, the design level of disassembly (DLD), and design level of upgradability (DLU), design level of integrity (DLI) in product design matter for circularity, which can generate long-term economic value and contribute to a circular economy. Although many design concerns exist for integrity, upgradability, and disassembly. SDA manufacturers need to consider these three factors from the product development and design stage throughout the product life cycle to enhance its circularity and reduce carbon emissions.

4.2. Variables and parameters for the circular product design

Most circular product design frameworks are built on established notions such as R strategies, sustainable design, and eco-design (Aguiar & Jugend, 2022; Blomsma et al., 2019; Joustra et al., 2021). An example is the R strategies of reduce, recycle, and reuse. In addition, eco-design plays a vital role in sustainable manufacturing by minimizing the environmental footprint of products and processes from their inception to disposal (Diaz et al., 2022). Frameworks built in this way can enhance product circularity and reduce carbon emissions (Hapuwatte & Jawahir, 2021). However, these strategies also have limitations. Theoretically, the definition and scope of the circular economy are unclear, resulting in overly broad applications and boundaries of these R strategies. For example, the reuse strategy can be implemented from a macro-industrial development perspective or at the individual product level, but this undoubtedly increases the complexity of the strategy.

From an implementation perspective, these strategies are challenging to apply in the production and manufacturing of SDAs, and manufacturers often lack expertise in the circular economy (Aguiar & Jugend, 2022). SDA designers have strong experience in product development design and business model innovation but lack circular economy skills (Shahbazi & Jönbrink, 2020). For example, designers aiming for commercial value might consider how to design more styles and functions for products. However, from the perspective of the circular economy, this approach hinders the transition to a circular economy. Therefore, when developing circular product design frameworks, designers need to integrate circular economy assessment goals and incorporate circular economy strategies and theories into the product design and development process (Diaz et al., 2022). Additionally, the functionality and aesthetics of the product need to be evaluated, and the circular economy aspects need to be assessed after product development (Aguiar et al., 2022). Systematically developing a circular product design framework in this way is conducive to implementing and realizing the circular economy. Figure 5 below shows the proposed key parameters in developing a circular product design framework.

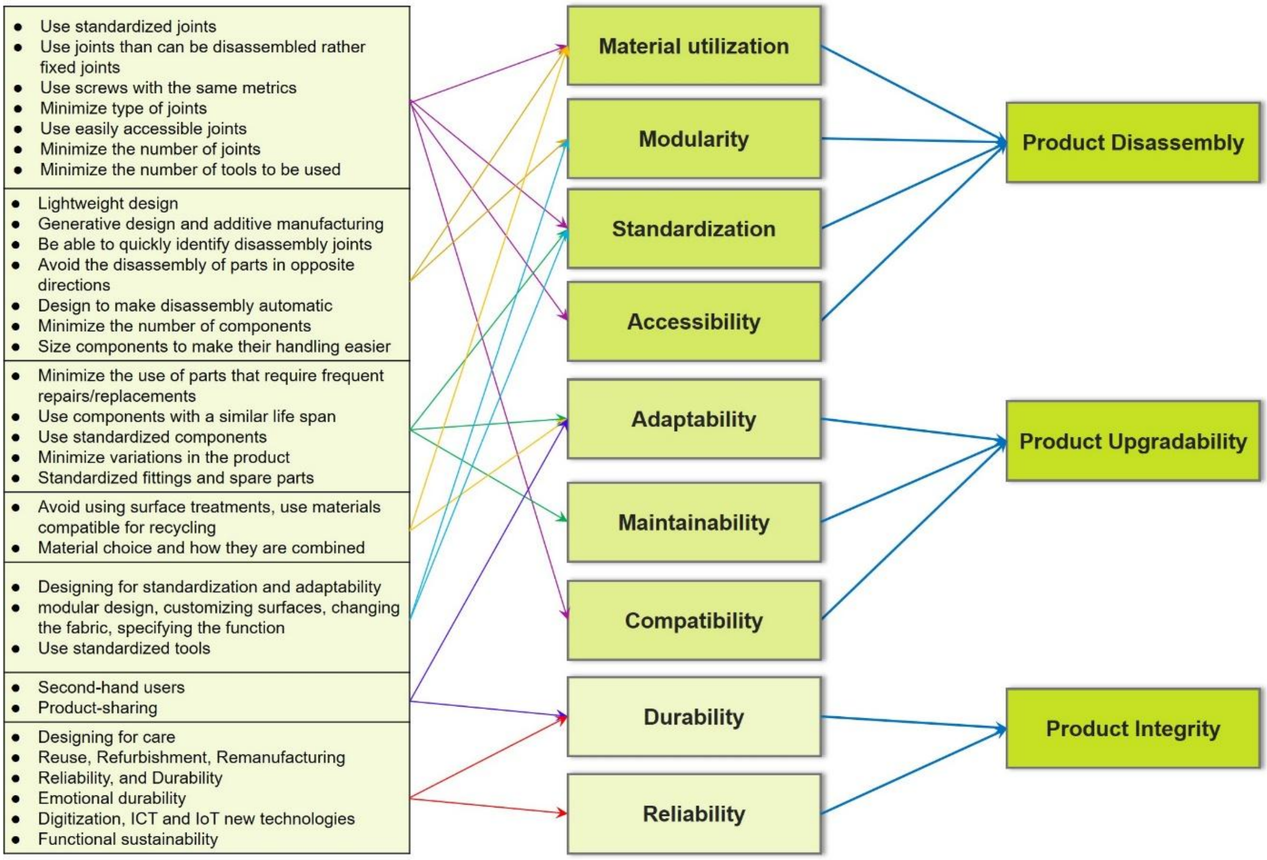

Figure 5 Circular product design parameters.

In summary, the key parameters for developing a circular product design framework are proposed in Figure 5 above, considering the practical knowledge and skills of the SDA designer, the circular economy theory, and the actual product design and development phases. Add a circularity index evaluation stage to evaluate the design effect regarding product function and circularity comprehensively. The ultimate goal of the circular economy for products is achieved by integrating circularity indicators into the entire product process, including product planning, concept development, industrial design, product detail design, product testing, product production, and product end-of-life recycling.

4.3. Circular economy best practices in SDA design and manufacturing

Design is critical in the manufacturing industry's transition to a circular economy (Aguiar et al., 2022). In general, product disassembly, upgradability, and integrity have significant potential to extend product lifespans, reduce waste, and conserve resources (Vanegas et al., 2018; Tecchio et al., 2017; Bakker et al., 2021). Achieving this purpose is an enormous task and is possible only through collaboration among multiple stakeholders, including government policymakers, designers, suppliers, and consumers (Ulrich et al., 2020; Dokter et al., 2021; Diaz et al., 2022). Thus, a comprehensive consideration of both circular economy barriers and drivers is crucial for effectively implementing circular economy principles (Tura et al., 2019). Designers face numerous challenges within this paradigm, necessitating a deep understanding of specific knowledge, strategic approaches, and circular design metrics (Shahbazi & Jönbrink, 2020). They must also acquire practical strategies aligning with their design capabilities and expertise (van Dam et al., 2020). To date, the majority of studies on designing for the circular economy have been theoretical and conceptual, with few delving into the practical implications. There is a notable gap in knowledge regarding how design practitioners actualize the concept of circularity. Given this context, empirical validation of circular product design strategies is essential, particularly to mitigate potential negative rebound effects. The manufacturing activity needs to incorporate circular economy strategies for reuse, refurbishment, remanufacturing, and recycling starting from the product development phase to optimize value retention and prolong the life cycle of resources, products, components, and materials.

5. Final Considerations

This study highlights the importance of enhancing product integrity, disassembly, and upgradability to improve circularity, optimize resource utilization, extend product lifespan, maintain product value, and conserve resources, resulting in lower carbon emissions. Most research on circular economy strategies are theoretical and conceptual. As a result, for SDA designers, the circular economy introduces numerous new issues that necessitate specialized knowledge, techniques, and resources. On the basis of the abovementioned extensive literature search and cross-analysis, three prospective circular product design elements are proposed: product disassembly, upgradability, and integrity. Product disassembly, upgradability, and integrity are crucial factors for increasing a product's circularity, helping to extend the product's lifetime, reducing resource use, saving materials, and reducing waste production. This research proposes key parameters for circular product design related to various circularity characteristics (Figure 5). The results show that the key parameters for improving circularity for SDA are material utilization, standardization, accessibility, adaptability, maintainability, compatibility, durability, and reliability. These factors should be incorporated into the circular product design framework of SDA.

Furthermore, when developing a circular product design framework, one needs to consider the perspectives of relevant stakeholders and clarify how the government, manufacturers, supply chains, industrial parks, consumers, and other collaborators achieve circular economy transition while also proposing countermeasures for implementation. Manufacturing industries develop and implement circular economy strategies that are either too broad or too narrow in scope, making them unsuitable for the shift to circular economy. Although this study is limited by the subjectivity inherent in keywords screening and sample selection, it offers valuable insights for manufacturers and designers eager to embark on the journey toward circular product design and development circular economy strategies. This can be used as a practical reference for business decision-makers, designers, engineers, and other manufacturers who need to implement circular economy. The guidelines have been found to help with decision-making and improve product circularity. Future research needs to concentrate on the boundaries of the circular economy in the SDA industry and aim to deepen the theoretical exploration of design strategies that enhance product circularity.

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Ethical Considerations

Not applicable.

Conflict of Interest

The authors declare that they have no conflicts of interest.

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