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Current performance standard of circular product design: A systematic literature review

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ABSTRACT
The rising number of green customers has encouraged industries to assess product consequences. As a result, there has been an alignment of product development focus with regards to circular economy concepts. Consequently, several methods and tools have been developed, and thus new performance standards were introduced for product development. Nevertheless, there still exist deficiencies in industry-wide acceptance and adoption within these standards. The objective of the study aims at examining and optimizing existing standards on Circular Product Design. A systematic literature review method will be adopted with three phases: identifying research on Circular Product Design using Preferred Reporting Items for Systematic Reviews and Meta-Analyses, developing approaches on designs, and examining standards on design performance. The result shows that there are seven prevailing approaches on designs for Circular Product Design. Moreover, this study contributes an a structured classification of CPD approaches and performance standards, thus dealing with the problem of fragmented knowledge and and serves as a basis for further frameworks and research on circular product performance.

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1. INTRODUCTION

Industries require an understanding of the forces associated with consumer needs and competition for optimizing product development. Notably, there is an emerging phenomenon associated with adapting and ever-changing market demands, and that focuses on 'green' consumers. Interestingly, these 'green' consumers have demonstrating an average growth rate with a market share increase of 20.2% on average every year from 2019-2023 [1]. Although it seems negligible, it should be noted that these elements are set to continue given rising awareness among consumers about adapting sustainable consumption practices and methods [2], [3]. Green consumers refer to consumers who purchase products taking into consideration environmental impacts, ranging from raw materials to end-of-life consumption [4]. The behavior changes among these green customers intensify an importance associated with an emergent shift for green shoppers who increasingly concentrate on not only benefitting from purchases but also on associated ecological implications and impacts.

The presence associated with green and innovative products that have already managed to alter purchasing intention illustrates strengthening awareness about sustainability [5].

To address the change in consumer behavior brought about by the concern for sustainability, it began to develop eco-friendly products catering to an increasingly environmentally conscientious market. It includes considerations for environmental impact, eco-labeling, and eco-marketing perspective [6], [7]. The superiority of product quality relative to competitors remains an integral factor in influencing purchases for eco-labeled goods and services [8], [9]. Product designs are still capable of addressing and serving consumer needs and delivering benefits while serving environmental preservation goals as well [10].

Products have large effects on the environment, from start to finish in its life span [11]. Based on an analysis among various literature reviews done within 30 years, five evolutionary paradigms have emerged regarding product development, i.e. green, ecological, eco-design, sustainable, and circular [12]. At present, the continuously emerging term that topping various discussions nowadays includes circular design and the implementation of circular economy practices with a goal to better sustainability performance based on three dimensions, i.e. economic, environmental, and social.

Circular Product Design (CPD), as a design approach, uses circular economy concepts aiming at optimizing product life with a focus on product design that enables components and materials to be effectively recycled back into the material loop [13]–[16]. As a concept, there are various specific approaches within this concept that include refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover [17]. It primarily uses three specific approaches while applying various specific concepts, i.e. slowing, closing, and narrowing [13], [17], [18].

The innovation brought about in product development requires an ever-increasing amount of research work on the methods and tools employed for its implementation. The requirement for these methods and tools will soon be critical for the sector as it aims to bring about harmony between production efficiency and environmental and social factors. Some methods and tools associated with CPD include low carbon, modular designs, designs from recycling, and more [19], [20]. Moreover, there have been several methods employed for CPD concept assessment, which include life-cycle assessment methods, reuse efficiency models, and quality function-deployment models [21] – [23]. There have been tools developed related to performance measurement that emphasize product life-cycle perspective methods as a signifier for sustainability from production and usage.

Various approaches for CPD have been created, and these have caused the generation of new performance standards within the scope of product development. Although the overall sector shows low acceptance, largely in relation to environmental and societal factors that are vital for acceptance within the standard [24]. The existing literature is fragmented since it usually concentrates on certain design approaches, performance assessment techniques, and industrial application areas. Earlier conducted review studies have also concentrated on either circular design approaches or performance assessment indicators without considering their interrelation, which means that there was no sufficient information on how certain CPD approaches were connected to the performance standards of their evaluation. As a result, no systematized and holistic mapping of CPD approaches and performance standards has been produced yet.

While other literature review studies concentrate only on the discussion of certain circular design strategies or assessment tools independently, this study analyzes both CPD approaches and performance standards simultaneously. The study reveals the popular CPD approaches, evaluates the performance assessment indicators, and evaluates the relations between the approaches and the performance indicators for various circular approaches. The key contribution of the research paper is the development of a structured knowledge base.

2. MATERIALS AND METHODS

In this research, we have adopted the Systematic Literature Review Method for examining and analyzing 59 relevant articles. The Systematic Literature Review Method aids greatly in the systematic search and analysis of CPD methods and associated performance standards. The Systematic Literature Review Methodologies include three main steps: planning, criteria screening, and literature analysis. All these steps are done within the Preferred Reporting Items for Systematic Reviews and Meta-Analyses model flowchart [25]. As shown in Figure 1, at stage planning, articles for literature review were searched for availability via the Scopus database with search terms "Circular Economy" AND "Product Design" OR "Circular Product

Design" and obtained 795 articles. All these articles were then summarized and filtered appropriately for suitability and relevance within the research aims. Article criteria included filters on language, type, and date of publishing, and keywords. A total of 642 articles were discarded because they were not published in English (NE=6), were not within Engineering submissions (N.Eng.=362), not within document type criteria (ND=212), were not published as Journal articles (NJ=2), were not completed work articles (NF=6), were not within 2018-2024 date criteria (NY=24), and were not among product design keyword submissions (NP=30). A secondary testing stage was conducted on 153 article abstracts on suitability and relevance within research aims, more specifically on relevance within performance standards on CPD. From here, 62 articles were discarded as they were not about CPD performance standards but were about general Circular Economy concepts, businesses, and supply chain concepts, production, and chemicals materials concepts and articles (not related, NR=62). A third level elimination stage conducted on articles selected eliminated 32 articles as they were vaguely related to research aims and topics as they contained subjects and concepts on Circular Economy practice, consumption behavior, Chemicals, Circular Supply Chain concepts, and Circular Economy practices as vaguely related articles (VR=32). Articles cleared and passed all three testing and removal steps were analyzed at an illustrative and detailed manner by Affinity diagrams and Heat Maps for research aims on CPD practice and associated standards and processes. The coding and classification process was conducted through a collaborative review by the author team using NVIVO. In each selected paper, the performance indicators mentioned were determined and categorized into either the environmental, economic, or social dimensions depending on what the measurement of each indicator entailed. Collection rate and number of reuse cycles were some of the indicators that were classified under the environmental dimension due to its focus on materials recycling and extending product life. The CPD strategy used in each paper was then identified, and those that shared similar goals and design features were grouped together.

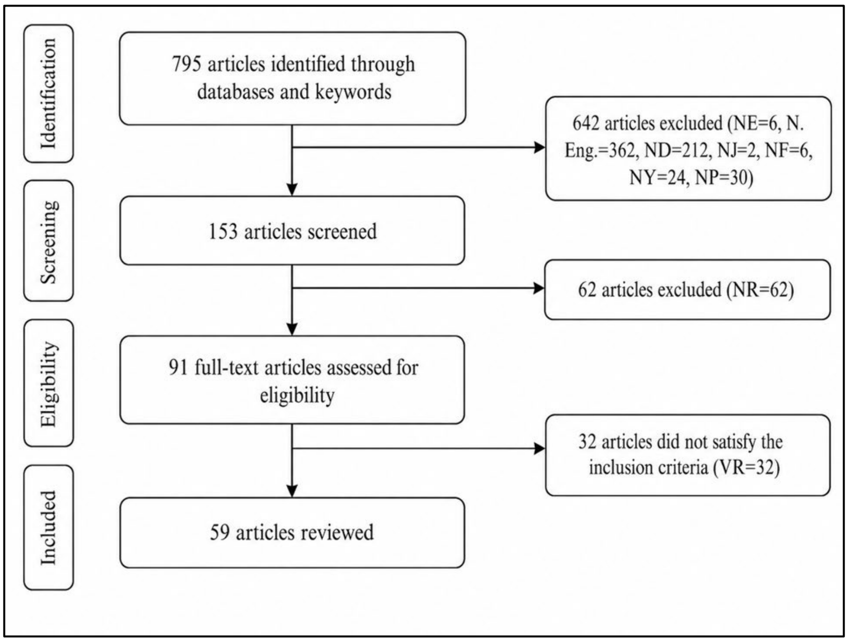

Figure 1. Research method based on PRISMA

3. RESULTS

CPD integrates three essential strategies to improve product sustainability: narrowing, slowing, and closing. The narrowing strategy optimizes the use of resources with low-impact, lightweight, and energy-efficient designs [13], [25]. The Slowing strategy focuses on extending the life of the product through reliability, reusability, ease of repair, and technological adaptation [13], [25], [26]. Meanwhile, the closing strategy emphasizes recycling both technologically and naturally to close the resource cycle [13], [25], [27].

The number of CPD-related studies in Scopus has increased by an average of 31% each year as seen in Figure 2. Studies in this domain reached its peak in 2023, with projections for 2024 indicating that it will closely approach these levels. This trend suggests a potential sustained escalation in study within this field. Most of the study analyzed: 66.2% or around 49 articles, came from developed countries. Meanwhile, around 33.8% of the studies was implemented in developing countries, including Brazil, China, Columbia, and Turkey. As much as 67.5% of the study came from the European continent, 16.3% from Asia, 13.5% from America, and 2.7% from Australia. Studies from the Asian continent uses case studies from China, India, Iran, South Korea, Singapore, Taiwan, and Thailand.

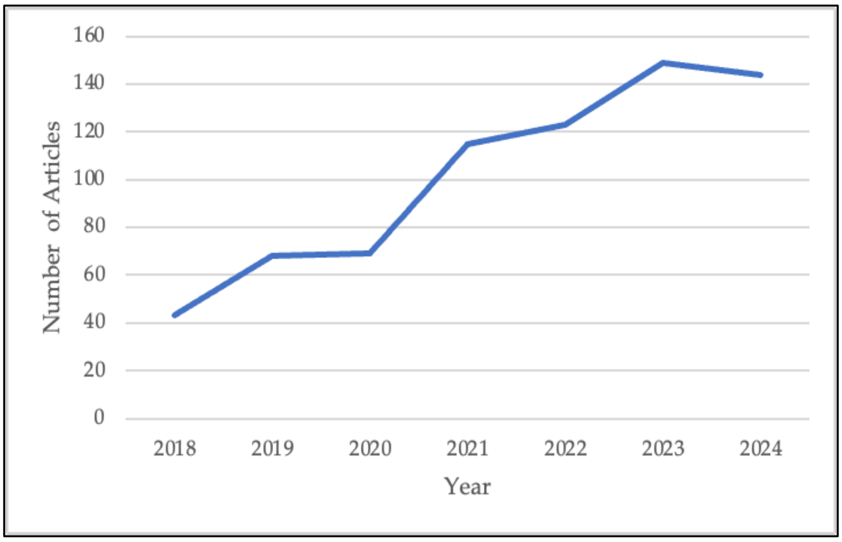

Figure 2. Number of studies on circular product design in Scopus

In product development, several critical stages play a role in achieving effective product design, i.e., planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up [28]. The CPD literature emphasizes the importance of planning and concept development, as seen in the dominance of the planning (34%) and concept development (19%) stages in existing studies, as seen in Figure 3. However, the testing and refinement stage, which is very crucial in evaluating product performance, only covers 24% of the total literature. The lack of studies in this stage indicates that performance evaluation, which is essential for ensuring the sustainability and effectiveness of product design, needs to receive adequate attention in CPD studies.

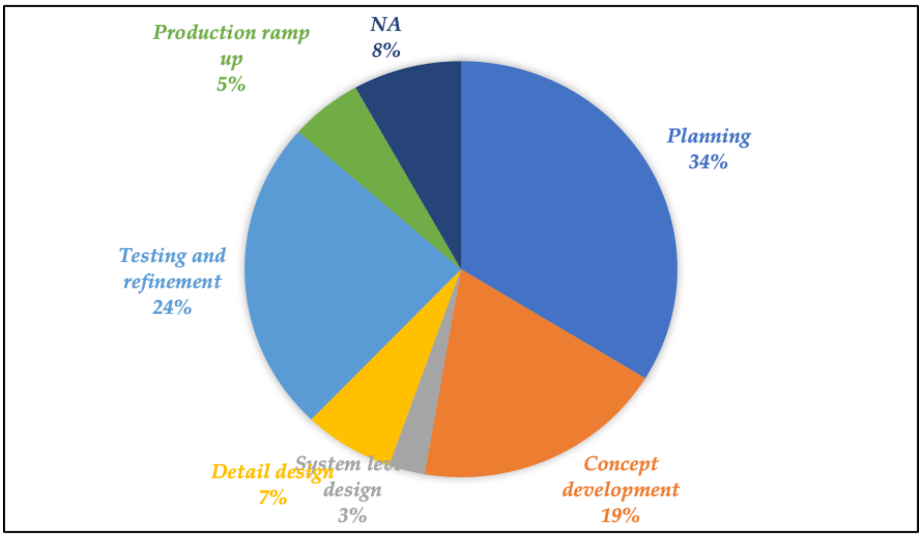

Figure 3. CPD studies based on product development stages

3.1. Circular Product Design Approach

The analysis of CPD approaches in the literature, including related terms such as eco-design, design for reuse, and design for recycling when they are explicitly linked to circular economy principles, aimed to offer an alternative perspective on design guidelines and examples of design practices suitable for implementing the concept. Approaches that share the same intents and design concepts were then grouped together. This led to the identification of seven major CPD approach categories, which give a holistic view of the design methods employed to minimize the impacts on the environment, increase the lifespan of the product, recycle the products and materials, and achieve product functionality through new business models. However, studies focusing on industrial practices to decelerate and close the material cycle remains incomplete [29]. Therefore, in this study, we consider seven main approaches in CPD that are widely discussed in the literature, as seen in Table 1. These approaches include product design that not only aims to reduce negative iconsequences on the environment but also supports sustainability through reusability, recyclability, manufacturability, and new business models such as product service systems (PSS).

Table 1 Circular product design approach

Design Approach	Brief Definition	Authors
Eco design	Consider environmental impacts throughout the product lifecycle, including a focus on energy efficiency and low impact.	[20], [30], [31], [32], [33]
Design for reuse	Create reusable products, including considering durability and repairability to extend product life.	[16], [21], [29], [34], [35], [36], [37], [38], [39], [40]
Modular design	Increase product flexibility and customization, facilitate upgrades, and extend product life by replacing or upgrading individual modules without replacing the entire product.	[35], [41], [42], [43], [44]
Design for disassembly	Prioritize easy separation of product components at end-of-life.	[45], [46], [47], [48], [49]
Design for remanufacturing	Allow products to be refurbished or restored to like-new condition through repair and component replacement processes.	[50], [51], [52], [53], [54], [55], [56], [57]
Design for/ from recycling	Allow products to be easily recycled or made from recycled materials, to reduce the use of new resources and waste.	[14], [22], [23], [26], [58], [59], [60], [61], [62], [63], [64]
Product service system	Design products integrated with a service to be shared, reducing the need for individual ownership.	[65], [66], [67], [68]

These seven categories constitute different, but complimentary, methods of achieving circularity. Eco-design utilizes a wide scope of the life cycle of the product through the reduction of material and energy usage, emissions, and waste at the initial phase of product production. This method can be effectively used in energy-efficient household products, low-impact packaging products, and products that require lower or hazardous materials during manufacture [20], [30], [31]. Reuse design and modular design focus on product-life extension. For instance, clothes, furniture, and jewelry could be made for reuse through methods of repairing, upgrading, replaceable parts, and long-term warranties of spare parts [29]. Similarly, modular design may be used in electronic products, furniture, and industrial machinery through repairing, replacing or upgrading of modular parts without disposal of the whole product [35], [41], [42].

Disassembly design is aimed at separating product components for further reuse, remanufacture or recycling. This type of design applies to various products, like electronics, batteries, appliances, vehicles, where fasteners, joints and materials can be designed in such a way as to facilitate disassembling and sorting of materials [45], [46]. Remanufacturing design is associated with repairing a product or a component so that it could meet specific functional requirements through inspecting, cleaning, repairing, reprocessing and component substitution. Common applications of remanufacture design are auto parts, machines, industrial equipment and electric goods, which high value components can be reused [51].

Design for reuse forms 20.3% of all the identified articles, showing that much attention is paid to extending the life of products and components through the process of repeated use, durability, maintenance, repair and updating. For instance, such goods as clothing, furniture and jewellery will be able to preserve their functionality and economic value when they are designed in such a way that they can be updated or repaired in any moment thanks to their replaceable parts and joints [29].

Remanufacturing design is 15.6% of the articles discussed and deals with keeping the value contained in products through the process of reusing parts that can be recovered. This kind of design includes automotive engines, gearboxes, machine tools, and industrial equipment due to the fact that their cores and valuable parts can be inspected, refurbished and reused rather than scrapped [29]. The eco-design, modular design, and design for disassembly designs all occupy 10.2% of the studied literature. The eco-design literature addresses issues relating to the reduction of environmental impact of products such as packaging, home appliances, and consumer goods [20], [30]. Modular design allows for the maintenance and upgrade of electronic products, configurable furniture, and industrial equipment [41], [42]. The design for disassembly literature deals with the recovery of parts and materials of electronic products, home appliances, and automobiles [45], [46].

Product–service systems form the smallest percentage, being only 7%. This includes product leasing, bicycle/vehicle sharing, equipment renting, and pay-per-use service for home appliances and industrial machinery [65], [66]. While it is not so popular among the approaches to CPD, it is still very significant as it combines physical product design with the whole cycle of ownership, maintenance, return, and recovery of the products. Products provided in the form of service can be controlled by manufacturers or service providers, thus increasing the motivations for longevity, repairability, upgradability, take-back, and recovery. Research on CPD is predominantly focused on material recovery and product-life extension. Recycling-oriented design is one of the most popular strategies as it can be implemented in the current waste collection and recycling system, while others, such as product-service systems and others, are paid much less attention.

The implementation of CPD can be done by combining several design approaches systematically according to the characteristics of the product and the business context. Industries can start with a conceptualization involving recycling to ensure that products are readily disassembled and recycled, then enhance these products by designing for reuse and remanufacture through durable material choices, component standardization, and designing products that allows for upgrade and repairs. The modular design and design for disassembly approach acts as a technical enabler so that the process of disassembly, component replacement, and product life extension can be carried out efficiently, while the eco-design principle ensures that the use of resources and energy remains optimal from the design stage. To maximize the impact of circularity, such design approaches need to be supported by business model innovations, such as Product-Service Systems, so that the industry not only manages the product lifecycle technically, but also creates economic mechanisms that encourage reuse, product returns, and product value optimization throughout its lifecycle.

3.2. Performance Standard

The literature has presented various performance standards for evaluating CPD. Overall, the CPD performance standard indicators that have been developed cover economic, social, and environmental aspects. However, the large and diverse number of indicators will increase the complexity of problems in product development. Therefore, some indicators can be proposed as the primary indicators using heat map analysis as seen in Figure 4. The determination of the main indicators is based on the frequency of the indicators' appearance in all the literature analyzed.

In the case of the environmental dimension, the indicators associated with waste production, land use avoidance, carbon footprint, rate of recycling, number of reuse cycles, and resource use efficiency are those that are reported most often. Waste production and land use related indicators are useful for evaluating how well CPD strategies prevent items and materials from going into final disposal [46], [69], [70]. The carbon footprint indicator has been widely utilized for emissions resulting from manufacturing, repairing, refurbishing, recycling, and recovering materials [35], [58], [64]. Indicators related to recycling and reuse include the recycling rate, collection rate, reuse rate, and reuse cycle numbers [21], [38]. Resource efficiency and dematerialization indicators are used to measure reductions in the use of virgin materials and resources.

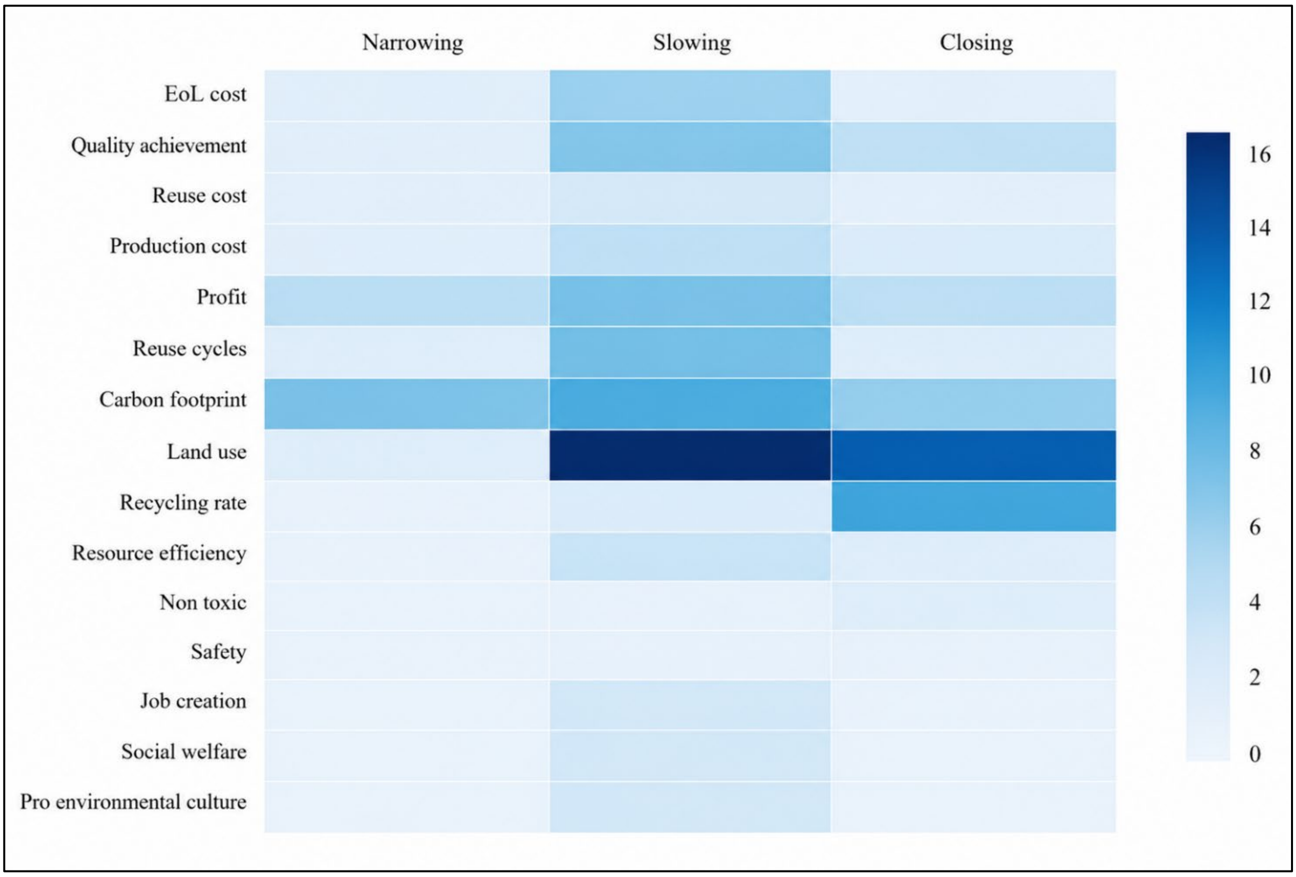

Figure 4 Heat map CPD performance standard

In terms of economic indicators, the main indicators are profitability, production or product cost, quality achievement, end-of-life cost, and reuse cost. Profitability is used to evaluate whether the circular strategies provide adequate economic benefits through recovery of products, parts, or materials [23], [60]. The production and product costs are used to compare the economic impact of different scenarios including manufacturing, repairing, refurbishing, and recycling [35], [45]. Quality indicators are always taken into consideration as the reused, refurbished, and remanufactured items have to meet the required functionality and technicality [20], [63]. Costs associated with end-of-life consist of collection costs, disposal costs, repair costs, refurbishing costs, recycling costs, and recovery costs [38], [69].

The social indicators are not as commonly cited as environmental and economic indicators. These indicators comprise primarily safety, creation of jobs, social welfare, and the environmental corporate culture [57], [67], [71]. The social welfare or social surplus is one of the social indicators used in the evaluation of circular business/product strategy [30], [72].

This integrated approach reveals that the various CPD approaches correspond to different types of strategies, which includes narrowing (less), slowing (longer), and closing (new cycle). Eco-design corresponds to the narrowing approach in terms of reducing the use of materials, energy, and carbon footprint. The approaches of design for reuse/repair, modularity, disassembly, and remanufacturing have been identified mostly as slowing approaches due to their effect on prolonging the life of the product and its components and performance in terms of number of reuse cycles, durability, quality, cost of production, and end-of-life cost. Design for/from recycling is mostly a closing approach in terms of collection, recycling, and material recovery. The recycling rate, recovered material usage, carbon footprint, and recovery cost are used as performance indicators.

4. DISCUSSION

The findings indicate that CPD should be undertaken through a combination of design techniques depending on the nature of the product, circular aims, stakeholder needs, and the industrial setting. This is consistent with the literature that presented CPD as a relatively new and complex field of study where the links between design variables, stakeholders, and circular approaches are inadequately clear [14]. They found out that circular design can adopt biological cycle approaches involving use of renewable materials as well as technical cycle approaches like reuse, repair, remanufacture, and recycling. This means that CPD considerations should be made not only of technical aspects of the products but also the needs of various stakeholders involved in the process.

Slowing strategies rely heavily on product durability, modularity, reparability, and reuse capacity. Modularity was one of the most crucial product features contributing to the repair process, as it makes the process of disassembly and assembly more manageable [42]. The modular design of smartphones enables not only professional repair but also self-repairing and increases the lifetime of products by decreasing unnecessary replacements. On the other hand, products as reusable glass bottles need to be designed in such a way to survive multiple processes of collection, reuse, and remanufacturing without losing its functionality [21]. Hence, it is possible to conclude that the effectiveness of slowing strategies should not be estimated only based on the lifetime of the product, but also on the rates of collection, reuse cycle, reparability, product quality, and cost of reuse.

Modularity and design for disassembly are relevant both for slowing and closing approaches. For instance, modular furniture was analyzed by using computational multi-objective optimization, and different product designs were compared based on their global warming potential [19]. This clearly shows that such factors as material choice, amount of material used, modular system, and disassembly properties have to be analyzed together because design choices which would enable parts replacement and material recovery might also have environmental impact. Therefore, modularity is not only a product property but also enables repair, reuse, remanufacturing, and recycling.

The prevalence of the design for/from recycling concept in the literature under analysis is another proof of the significance of material properties. Both the durability and recyclability of products are strongly dependent on the materials used, while a mono-material approach can enhance product recyclability [26]. This means that the closure approach requires designers to take into account the compatibility of materials, the separability, contamination, and recoverability of post-consumer materials. Nonetheless, it is necessary to remember that recycling cannot be viewed in isolation.

Moreover, the examined studies reveal that the role of economic factors is considerable in terms of the implementation of CPD approaches. It is common for profitability to play an important role when decisions on repair, refurbishment, repurposing, reuse, recycling, and recovery are made in the industrial setting [23]. Environmental and social factors were often considered the constraints that needed to meet certain criteria and standards while not being the key goals to be achieved. The discussed findings allow making a conclusion about the reason behind the high relevance of profitability, product costs, end-of-life costs, and quality among the reviewed performance measures.

Reuse and take-back policies can be enhanced by business model configurations. Examples include lifetime free replacement and trade-ins, which create incentives for consumers to return or replace the product through a controlled process [47]. These business model configurations can facilitate product collection, reuse, repair, and recycling while sustaining a relationship between the service provider and the consumer. This further enhances the importance of product-service system and take-back mechanisms in linking product design with economic mechanisms to keep products and material flows in circular loops.

On the whole, from the above discussion, it becomes clear that the effectiveness of various CPD methods has to be determined based on the appropriate set of indicators, which should correspond to a particular circular strategy used. Indicators for narrowing include indicators like material intensity, energy intensity, carbon footprint, and production efficiency. Slowing strategies imply the use of durability, modularity, repairability, collection rate, reuse frequency, quality, and cost of reuse. Closing implies such indicators as recyclability, material recoverability, recycling rate, waste generated, global warming potential, and end-of-life cost. Social aspects such as safety, job creation, social welfare, and pro-environmental culture are the least used compared to other aspects. In accordance with previous studies, the social aspect of sustainable products has received different levels of attention compared to other aspects [47]. In fact, the impact of products on social and economic aspects such as health, welfare, and quality of life needs to be considered to expand the benefits of sustainable design [30], [57].

Methods that include life cycle assessment (LCA), life cycle costing (LCC), and material flow analysis (MFA) could facilitate the evaluation process in that they measure environmental impact, life-cycle cost, and material flow, respectively. In this particular study, LCA, LCC, and MFA help evaluate the performance of CPD from environmental, economic, and material flow perspectives. The insufficient presence of these methods in reviewed literature also suggests the necessity for future research in terms of integrating these analytical methods with CPD.

The results reveal that different CPD approaches facilitate different circular strategies and properties of products. Designers could utilize reuse, repair, remanufacturing, modularity and disassembly for slowing resource loops, whereas designers could employ design for recycling for closing resource loops. Businesses could implement these approaches through replaceable parts, easy-to-access fasteners, modular construction, durable materials and mono-material packaging. They must evaluate the performance of each CPD approach using corresponding indicators in accordance with the targeted circular strategy, including resource and energy use for narrowing, durability and repairability for slowing, recyclability and material recovery for closing. Even though the study does not propose any CPD framework, it provides a holistic integration of the three concepts.

There are several limitations to the current study. First, it is worth mentioning that the literature review has been carried out using only one database and predefined keywords, publication years, document types, and language criteria. Second, despite the fact that all the included studies have been systematically screened and classified in accordance with the research methods used by them, results, and product development phases, no methodological quality appraisal has been performed. This means that the presented frequencies do not show any methodological quality of the literature. In addition, differences in terminology, industrial context, and research methodology have made it difficult to compare the findings of the included studies. Further research is needed to expand the range of the literature search and verify the suggested relationships with the help of case studies and methodological quality of the literature appraisal.

5. CONCLUSION

Studies on performance standards in circular product design is exhibiting a positive trend, indicating that this area remains engaging and continues to evolve. Developed countries have predominantly led these studies, highlighting significant opportunities for similar studies in developing nations. This literature study was conducted system-atically using the PRISMA flowchart for relevant studies articles in the 2018-2024 period. The results show that seven design approach options in CPD are most widely discussed: eco-design, design for reuse, modular design, design for disassembly, design for remanufacturing, design for/from recycling, and product service system. The design approach is evaluated for performance within the framework of the CPD strategy: narrowing (less), slowing (longer), and closing (new cycle). Several performance standards that dominate CPD studies include economic aspects (profit, production cost, quality achievement, environmental aspects (reuse cycles, carbon footprint, land use, recycling rate), and social aspects (job creation, social welfare, pro-environmental culture). This study provides an integrative synthesis that connects CPD strategies, design approaches, and performance indicators related to them. By systematically consolidating these previously fragmented concepts, this study is able to directly fill the knowledge gap that was identified in the introduction. This classification will therefore provide a basis for understanding how various industries choose and evaluate the CPD options available in relation to the circular goals. However, this study is limited by the use of the Scopus database, predefined search terms, period of publication criteria, article types, and English language articles. Different terms, industry settings, and evaluation techniques prevented direct comparison of the articles considered. Further studies is recommended to develop a methodology that integrates actual industry practices, thereby enhancing understanding of CPD performance standards. Future research should further expand the literature search and verify the established relationships via industrial case studies or through expert opinions. This might assist in developing an adaptive model suitable for various industries.

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DECRLARATION OF AI-TOOL USAGE

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