



Review

Sustainable product design factors: A comprehensive analysis

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ARTICLE INFO

Handling Editor: Kathleen Aviso

Keywords:

Sustainable product design factor
 Product sustainability
 Sustainable product
 Industrial sustainability
 Sustainable manufacturing

ABSTRACT

Sustainable product design (SPD) is instrumental in improving the sustainability of a product throughout its entire life cycle. To attain this goal, decisions related to SPD should consider a spectrum of influential factors. Despite numerous SPD studies, a unified perspective among their findings is lacking, and comprehensive research on SPD factors is still needed. This gap in research affects the ability to comprehensively address the potential economic, environmental, and social impacts associated with each life cycle stage of a product during its design phase. The aim of this study is to provide a comprehensive analysis of the SPD factors available in the literature. To achieve this objective, the methodology involved: (1) conducting a systematic review of literature to explore SPD factors, (2) categorizing the key factors into themes related to product sustainability using an inductive approach, and (3) mapping these factors across the entire product life cycle. In the literature reviewed, a total of 297 factors pertaining to the economic, environmental, and social aspects of SPD were identified. Among these, 219 factors were mentioned only once in the articles analyzed, while 43 factors were frequently addressed by at least three papers. These frequently considered factors were categorized into nine primary themes: quality and reliability, manufacturability, costs, and financial gain under the economic aspect; resources, waste and emissions, and end-of-life (EOL) management under the environmental aspect; and functionality and usability, and social well-being under the social aspect. In light of their influence on life cycle-oriented product design, this study mapped the factors across the total product life cycle (TPLC) stages. The results of this paper provide valuable insights into SPD by addressing its impacts on sustainability throughout the life cycle of a product. Future research can capitalize on these results to comprehensively address issues concerning product sustainability.

1. Introduction

Due to dwindling natural resources, mounting environmental degradation, and significant social consequences, the notion of sustainable development has been introduced in various fields (Wang et al., 2018), including manufacturing. The manufacturing sector is widely recognized as a significant contributor to environmental degradation and social impacts (Zeng et al., 2008). To address these challenges, manufacturing companies need to adopt sustainability practices (Ahmad and Wong, 2019). Specifically, the mounting environmental and social concerns (Beekaroo et al., 2019) have led stakeholders to pressure manufacturing companies to embrace sustainability practices (Huang and Badurdeen, 2018). Moreover, it is essential for manufacturing firms to adopt sustainability practices to remain competitive (Wang et al., 2018). Industrial sustainability, which has attracted the interest of industry decision-makers, policymakers, and academics, refers to the integration of sustainability practices at the firm level (Trianni et al.,

2017). Effective management of industrial sustainability requires the adoption a comprehensive approach, such as the triple bottom line (TBL) approach (Cagno et al., 2019). The TBL approach encompasses three interconnected sustainability aspects: economic, environmental, and social (Elkington, 1997). Manufacturing companies have a significant influence on all three sustainability pillars (Ahmad et al., 2019; Ghadimi et al., 2012). Consequently, it is crucial for them to consider these aspects concurrently during the design and manufacturing of their products (Eastwood and Haapala, 2015; Lacasa et al., 2016).

Ensuring the sustainability of products is a key approach in achieving sustainable manufacturing and meeting stakeholder requirements (Hapuwatte and Jawahir, 2021). Sustainable product design (SPD) plays a key role in improving product sustainability and has received considerable attention from manufacturing companies (Ghadimi et al., 2012; Han et al., 2021). The design of sustainable products considers a comprehensive approach, aligning with the TBL approach across the total product life cycle (TPLC) (Feng and Mai, 2016; Yan and Feng, 2014). The TPLC approach primarily consists of the supply,

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Abbreviations

3R	Reduce, Reuse, Recycle
EOL	End-of-Life
GHG	Greenhouse Gas
M	Manufacturing
PSA	Product Sustainability Assessment
PU	Post-use
S	Supply
SDGs	Sustainable Development Goals
SPD	Sustainable Product Design
TPLC	Total Product Life Cycle
TBL	Triple Bottom Line
U	Use

manufacturing, use, and post-use stages (Shuaib et al., 2014). Notably, SPD impacts all stages of the product life cycle (Hosseinpour et al., 2015); and it provides a promising solution for the manufacturing of products that can satisfy different sustainability requirements (Hassan et al., 2017). The life cycle approach is essential for SPD because it provides a comprehensive view of the environmental and social impacts associated with each life cycle stage of a product (Maxwell and van der Vorst, 2003). Moreover, it helps to use resources efficiently, reduce environmental footprint, and manage end-of-life (EOL) products effectively (Hapuwatte and Jawahir, 2021). To achieve effective SPD, it is crucial to take into account a multidimensional set of factors that have an influence on the different stages of the product life cycle. This study views the SPD factor as a specific consideration incorporated during the product design phase to ensure product sustainability.

Although there are numerous studies on SPD, it is important to note that most of them have concentrated on the environmental aspect of sustainability, rather than considering the economic, environmental, and social aspects simultaneously (i.e., the TBL approach). For example, among the studies that adopted the TBL approach, Faradilla et al. (2022) developed the eco-bag concept by employing a sustainable quality function deployment technique and further evaluated this concept using SPD metrics. Soomro et al. (2021) proposed a sustainable prototyping

conceptual framework through a five-stage design thinking model. Rezaei et al. (2019) provided a multi-criteria decision analysis method for selecting a sustainable product-package design. Yan and Feng (2014) presented a methodology that emphasizes sustainable design-oriented product modularity to incorporate sustainable factors into product design process. Some studies also considered a life cycle approach, allocating a multidimensional set of factors across the life cycle of a product. For instance, Hapuwatte and Jawahir (2021) provided sustainability metrics across the life cycle stages to support SPD. Oh (2017) suggested a guideline for designing sustainable products by providing strategies to be considered across life cycle of a product. Maxwell and van der Vorst (2003) introduced a set of issues to be considered in the design and development of sustainable products following a life cycle approach. The existing literature has overlooked the simultaneous identification and categorization of the main multidimensional set of factors using the TBL approach, as well as the mapping of the identified SPD factors throughout the TPLC. Therefore, conducting the identification, categorization, and mapping of SPD factors simultaneously is crucial to address this limitation and provide a broader understanding of SPD. This will enable to comprehensively address the expected economic, environmental, and social impacts of a product across its life cycle during its design phase.

Hence, this paper holds a threefold objective. The first objective is to identify the main factors considered for SPD in the literature. This will provide valuable insights, especially concerning the frequency of use patterns of the factors, to academicians and practitioners (such as product designers, product developers, and product engineers). The second objective is to categorize the identified SPD factors into key themes or categories linked to product sustainability to provide a broader view. The third objective is to map the SPD factors across the product life cycle, considering their influence. This mapping aims to provide further insights that could be of interest to different stakeholders involved in sustainable product development and the life cycle assessment of a product. In addition, a conceptual framework for SPD is developed to provide a complete perspective of the factors. Through addressing the outlined objectives, this study provides a comprehensive and multidimensional view of SPD and product sustainability assessment (PSA) that significantly contributes to both product design research and practice.

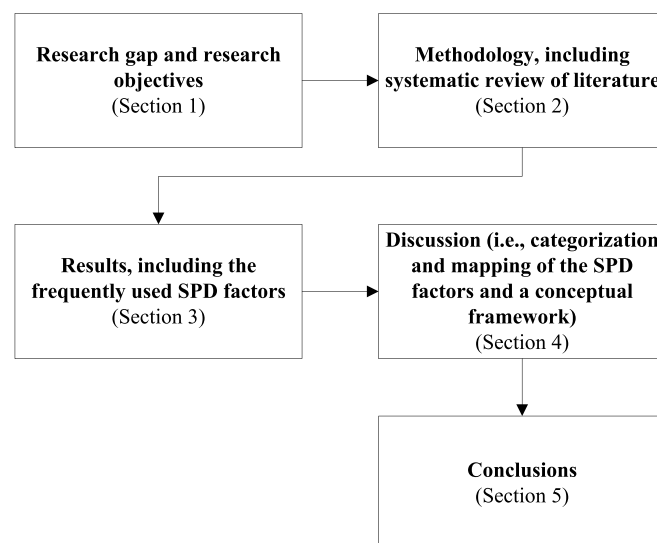


Fig. 1. Structural flow of the paper (adapted from Dieste et al., 2022).

The remaining content of this paper is structured as follows. Section 2 focuses on the methodology considered for conducting this study. In Section 3, the paper presents the results of the analyses. Section 4 provides a discussion on the categorization and mapping of the SPD factors, along with the conceptual framework for SPD. Lastly, the conclusions, including implications and future research agendas are presented in Section 5. The overall structure of the paper is shown in Fig. 1.

2. Methodology

This section provides a concise description of the methodology applied to address the research objectives mentioned in the introduction section. It includes an overview of the methodology, a description of the data collection process, and an explanation of the approaches used for data analysis.

2.1. Overview of the methodology

The increasing focus on SPD and the lack of studies with comprehensive literature analyses of SPD factors have prompted the authors' interest. To provide a broader understanding of SPD considerations, a systematic review of relevant literature was conducted to identify SPD factors, as shown in Fig. 2. The identified SPD factors were then categorized into themes or categories related to product sustainability. In addition, the identified SPD factors were mapped across the product life cycle. Scopus and Web of Science were used as academic research databases for the systematic review due to their extensive coverage of peer-reviewed articles. This paper focuses on academic literature due to its analytical advantage over grey or non-academic literature. Unlike grey literature such as sustainability standards and guidelines, academic literature provides regularly updated information on SPD factors, which enable the identification and mapping the frequently considered factors in the literature over a specific period. The systematic review in this paper followed a series of steps adapted from Tranfield et al. (2003): (a) defining the review's objective, (b) selecting appropriate keywords and databases, (c) screening and selecting papers for collecting data, (d) coding and analysis of the data, and (e) presenting the results deriving from the systematic review. To categorize the factors, an inductive approach was applied (Braun and Clarke, 2006; Thomas, 2006). The factors were then mapped according to the TPLC approach, consisting of

the supply, manufacturing, use, and post-use stages (Shuaib et al., 2014). As a result, a conceptual framework for SPD was developed.

2.2. Data collection

In order to explore SPD factors, an extensive search of the literature was conducted with a focus on SPD and/or PSA. Specific keywords related to SPD and/or PSA were applied in this search. As depicted in Fig. 3, a total of 6402 papers published till 2023 were found. Out of these papers, a combined total of 2879 reviews, book chapters, conference papers, and other document types were excluded. After this exclusion, 3523 peer-reviewed articles remained for further consideration. During this process, 1152 articles were identified as duplicates and subsequently removed, leaving 2371 unique articles for further analysis. After reading the abstracts, 2099 articles were excluded because they did not address SPD and/or PSA for manufacturing companies and/or lacked a comprehensive approach like the TBL approach. The online sources did not provide access to 8 articles, which were consequently excluded. The full texts of the remaining 264 papers were thoroughly examined, resulting in the exclusion of 207 papers that lacked factor-based SPD and/or did not provide relevant SPD factors. Finally, after this rigorous filtering process, 57 papers were identified as meeting the criteria and were selected for further analysis to identify SPD factors.

2.3. Data analysis

The identification of SPD factors and their frequency of use in the reviewed literature was conducted through content analysis. This process involved the recording and coding of data, including the SPD factors mentioned in the selected papers. To determine the frequency of use of the factors (i.e., by how many papers a factor was considered), phrase-by-phrase and word-by-word analyses were conducted, taking into account their context and intended purpose (Hsieh and Shannon, 2005). Accordingly, SPD factors with similar meanings were grouped together, while unique or dissimilar factors were analyzed individually. The frequently used SPD factors were subsequently categorized into themes or categories associated with product sustainability using an inductive approach. Specifically, these factors were coded into a set of themes based on their meaning, significance, and relevance to the theme (Braun and Clarke, 2006; Thomas, 2006). In addition, the factors were mapped

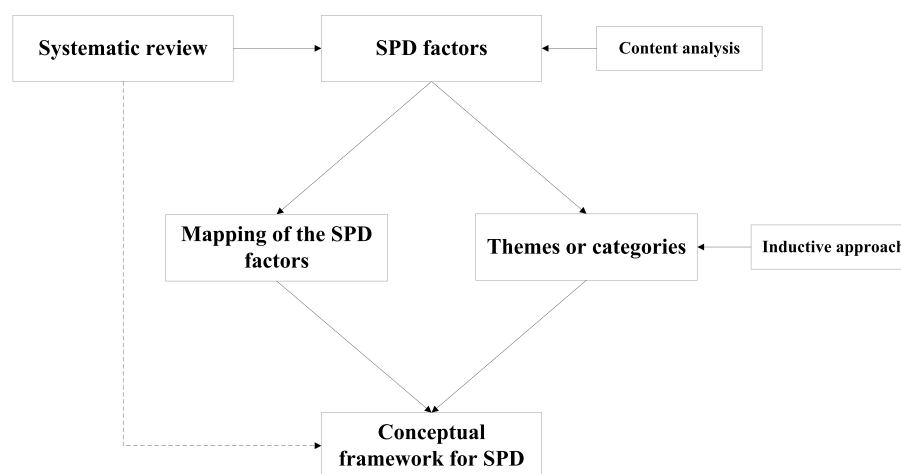


Fig. 2. The methodology employed to conduct the study.

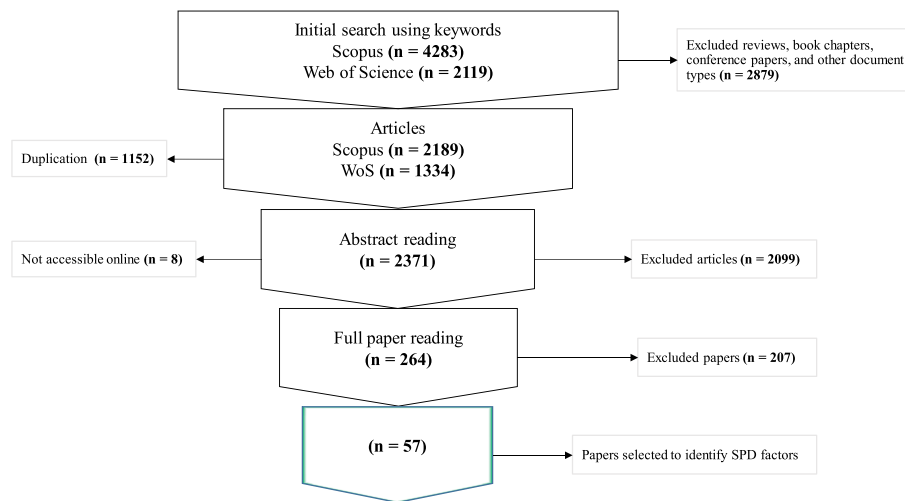


Fig. 3. Approach applied for screening and selecting papers (adapted from Mengistu and Panizzolo, 2023).

across the TPLC stages to provide a broader view of SPD.

The literature review was conducted in a systematic and structured manner to ensure objectivity (Durach et al., 2017; Tranfield et al., 2003). The research group also engaged in multiple rounds of discussion to evaluate the coding process, address any disagreements that emerged, and refine the inclusion of each factor identified in the literature (Seuring and Gold, 2012). Finally, following the guidelines of Seuring and Müller (2008), another means of ensuring validity was to present this research at an international conference, allowing other researchers and practitioners to provide feedback and suggest further improvements.

3. Results

This section presents and explains the results of the descriptive and content analyses, including the economic, environmental, and social factors identified in the literature and their frequency of use.

3.1. Trend analysis of the literature reviewed

Fig. 4 illustrates the journals that contributed at least two papers, which together contributed 26 papers. The remaining 31 papers were sourced from 31 different journals, each contributing one paper. This underscores the wide distribution of the selected papers across various fields, including sustainability, business and management, and engineering, indicating that SPD is a topic of interest across a range of academic disciplines.

The publication trend shown in Fig. 5 indicates an increase in research interest regarding SPD and PSA. Notably, a wide spectrum of factors have been considered by prior research. Most of the factors are applicable both in the design phase of a product and in the assessment of product sustainability performance. Among the SPD factors identified in the literature reviewed, a few were frequently appeared in multiple papers. This implies that the factors that were considered in previously published papers have remained relevant to recent ones. For instance, durability/lifespan is a frequently used factor, considered by Maxwell

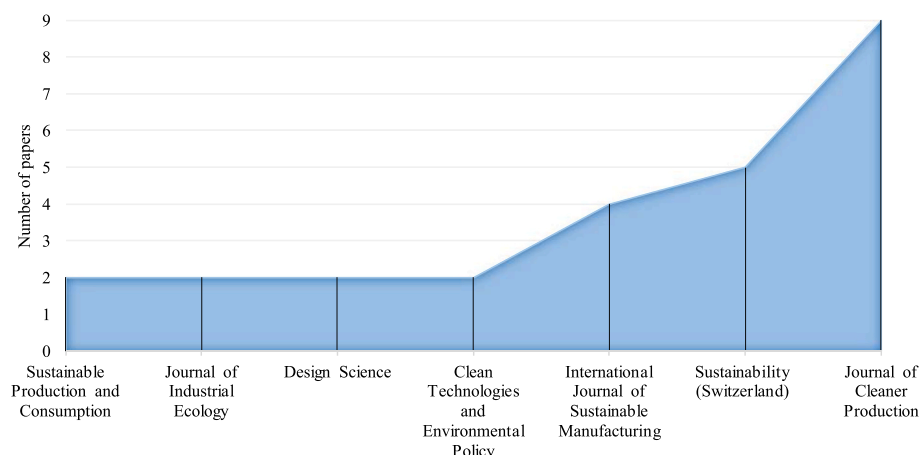


Fig. 4. Distribution of the papers by journal type.

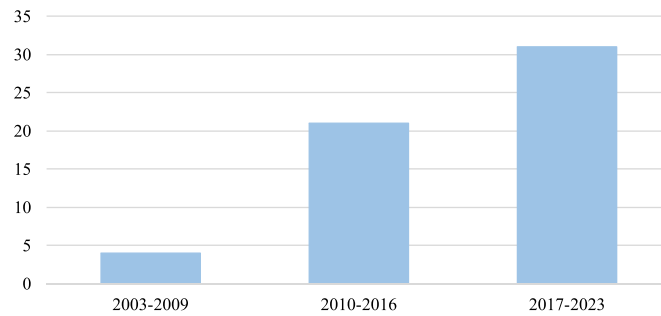


Fig. 5. Distribution of the papers over the publication years.

and van der Vorst (2003) and later by Chipambwa et al. (2023). Likewise, there are other factors that have been frequently considered in the literature reviewed, as presented in Subsection 3.2.

3.2. SPD factors identified in the literature

Aligned with the outlined objective, this paper identified 297 SPD factors from the literature reviewed using a content analysis stated in Subsection 2.3. Among these factors, 69 are associated with the economic aspect, 132 with the environmental aspect, and 96 with the social aspect of SPD, as shown in Table 1.

Table 1 reveals that the majority of identified SPD factors (i.e., 219 factors) were considered only once in the literature reviewed, highlighting a wide range of factors being considered for SPD. Indeed, the considerations for SPD are heavily influenced by the specific context of a product. Specifically, the use of SPD factors varies depending on the product, as each has its own requirements, challenges, and opportunities that demand a tailored approach to sustainability. For instance, the factors taken into account for designing a portable blender (Han et al., 2021) were notably different from those considered for the design of a wheelchair (Hosseinpour et al., 2015). While the remaining 78 factors were used frequently, appearing in multiple papers within the literature reviewed. Of these, 43 factors were identified as the most frequently used and were considered for further analysis, with 15 pertaining to the economic aspect, 14 to the environmental aspect, and 14 to the social aspect.

Fig. 6 shows the economic factors frequently considered in the literature reviewed, providing valuable perspectives on product design considerations for achieving economic sustainability. Notably, 22 papers considered durability/lifespan as a crucial factor in SPD. The

Table 1

The number of identified SPD factors along with their respective frequency of use.

Frequency of use	Identified factors (#)	Identified factors based on TBL
1	219	Economic factors (#) 69
2	31	
3	7	
4	5	
5	11	
6	4	Environmental factors (#) 132
7	6	
8	2	
9	4	
10	1	
11	1	Social factors (#) 96
12	1	
16	1	
20	1	
22	2	
24	1	
Total	297	297

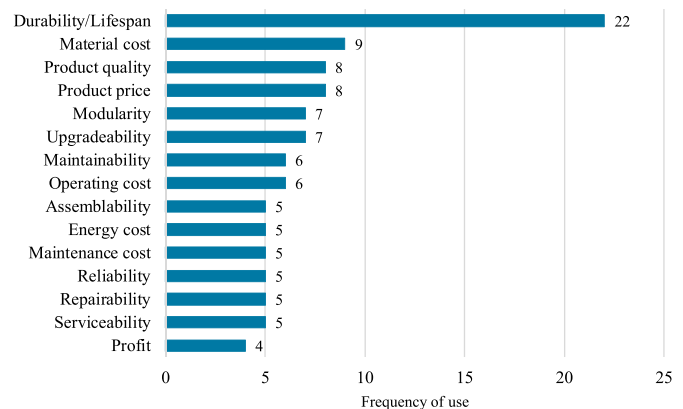


Fig. 6. Frequently used economic factors.

extended lifespan of a product serves multiple sustainability goals, as it reduces resource consumption by postponing replacement, minimizes waste, and often leads to cost savings for the user. This, in turn, leads to increased customer satisfaction and loyalty. This underscores the economic reality that durable products, despite potentially higher production costs, often generate long-term benefits that exceed their initial investment, both from economic and environmental perspectives. *Material cost* and *product price*, mentioned in 9 and 8 papers respectively, underscore the importance of cost-effectiveness in SPD. In a competitive marketplace, the sustainability of a product is closely tied to its economic viability. Accordingly, manufacturing companies should procure materials cost-effectively to offer competitively priced products. Moreover, if customers perceive the price of a sustainable product as reasonable, they are more likely to choose it over less sustainable alternatives, thereby contributing to its market success. *Product quality* and *modularity*, appeared in 8 and 7 papers respectively, highlight the changing dynamics of product development. This indicates a growing demand for products that offer superior quality and flexibility. *Modularity*, in particular, facilitates the upgrading, repairing, and recycling of a product. *Upgradeability*, *maintainability*, and other factors such as *operating cost*, *reliability*, and *serviceability* further emphasize the significance of considering the total cost of ownership in SPD. A product characterized by lower operating costs, easy of upgrades and repairs, and appropriate service provisions promotes economic sustainability by reducing overall expenses and enhancing long-term value. In addition, the consideration of *energy cost*, *maintenance cost*, and factors related to assembly and repair in multiple studies indicates that product design is moving towards a more comprehensive view of economic sustainability. *Profit*, often viewed as the ultimate measure of economic sustainability for manufacturing firms, was considered by 4 papers. Despite its lower frequency of use, *profit* remains a critical factor in SPD. It underscores the reality that manufacturing companies need to ensure their products

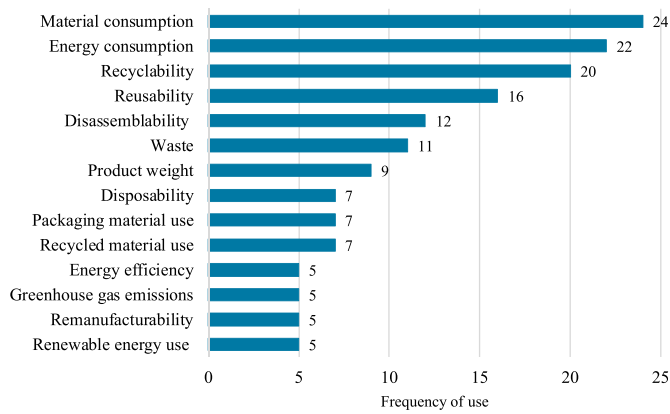


Fig. 7. Frequently used environmental factors.

generate sufficient revenue to cover production costs and deliver a return on investment, thus sustaining their operations.

Fig. 7 presents the frequently used environmental factors that are central to the design of sustainable products. It is noteworthy that *material consumption* and *energy consumption*, appearing in 24 and 22 papers respectively, emerge as primary considerations. The prominence of these factors can be attributed to their direct impact on natural resource depletion and environmental footprint. High material consumption and energy consumption not only indicate the potential overexploitation of resources but can also lead to higher production costs, affecting both economic and environmental sustainability. *Recyclability* and *reusability*, with 20 and 16 frequencies of use respectively, underscore the importance of a circular economy in SPD. These factors demonstrate a product’s potential to reduce waste by either re-entering the production cycle or extending its life cycle through reuse. The high frequency of use of these factors highlights a growing commitment to the principles of 3R (i.e., reduce, reuse, and recycle), aimed at minimizing the adverse environmental impact of a product. *Disassemblability* and *waste*, in conjunction with the previously stated factors, emphasize the significance of EOL management in SPD. Products that are easily disassembled often lead to higher rates of recyclability and reusability, thus reducing waste and conserving resources. *Product weight*, *packaging material use*, and *disposability* are crucial factors associated with resource utilization and waste management. Lighter products typically require fewer materials and less energy, leading to reduced production costs. Meanwhile, *packaging material use* and *disposability* underscore the impact of packaging, secondary materials, and EOL management practices on product sustainability. The use of *recycled materials* and *renewable energy* can significantly mitigate the negative environmental impact of manufacturing companies. Additionally, extant research indicates that improving *energy efficiency* can reduce a product’s environmental

footprint, specifically its carbon footprint. The inclusion of *GHG emissions* as a factor indicates the growing awareness of climate change and SPD’s role in reducing it. Furthermore, *remanufacturability* reflects the concept of a circular economy, offering an additional opportunity for resource conservation.

Fig. 8 reveals the key social factors considered when designing sustainable products. The factor *product safety*, mentioned by 10 studies, underscores the paramount importance attributed to the well-being of users. Products that pose potential harm to users are neither desirable nor sustainable. *Functionality* and *usability*, each considered by 9 papers, highlight the importance of how effectively a product fulfills its intended purpose and how intuitive it is for the user, respectively. A product that excels in both functionality and usability is more likely to satisfy consumers, thereby reducing the need for product replacement and ultimately contributing to sustainability. *Health and safety*, *aesthetic*, and *ergonomics*, each appeared in 7, 6, and 6 papers respectively. *Health and safety* underscores the importance of promoting the well-being of all individuals involved in the product life cycle, including employees engaged in product manufacturing. *Aesthetic* plays a crucial role in customer preference and can significantly influence the life cycle of a product. A product that appeals to a user’s senses is more likely to be used and retained for an extended period. *Ergonomics* emphasizes the design of products that seamlessly suits the user, improving usability, comfort, and satisfaction. The remaining social factors further enrich the landscape of social sustainability in product design. In particular, factors such as *health and wellness*, *ethical responsibility*, and *employee satisfaction* underline the importance of SPD in addressing broader social implications of manufacturing practices, including labor conditions and fair trade issues.

In Subsection 3.2, the main factors considered for SPD in the literature were identified, aligning with the first objective outlined in the introduction section. In Section 4, these factors were categorized into key themes linked to product sustainability, meeting the second objective, and systematically mapped across the entire product life cycle to achieve the third objective. Furthermore, a conceptual framework was introduced based on the categorization and mapping of the factors. The aim is to provide a comprehensive view and understanding of SPD.

4. Discussion

Besides identifying the main factors considered for SPD in the literature, this paper took a step further by categorizing and mapping the identified factors to provide a more comprehensive discussion and insights. As shown in Fig. 9, the identified factors were categorized into themes or categories relevant to product sustainability using an inductive approach described in Subsection 2.3. Most of the categories outlined in this study were adapted from Joung et al. (2013), which is based on the widely recognized sustainability indicators categorization by the National Institute of Standards and Technology. Accordingly, the economic factors were categorized into quality and reliability, manufacturability, costs, and financial gain. Meanwhile, the environmental factors were classified into resources, waste and emissions, and EOL management. In addition, the social factors were grouped into functionality and usability, as well as social well-being, with a primary focus on the well-being of stakeholders such as employees, customers, and the community. This systematic categorization of the SPD factors provides a structured approach to comprehensively examine the diverse aspects of sustainability within the context of product design and development.

The economic aspect of SPD focuses on enhancing *quality and reliability*, which involves improving the durability, quality, maintainability, reliability, repairability, and serviceability of a product. Soota (2017) underlined the importance of considering durability and maintainability attributes in sustainable product development, while Lin et al. (2019) identified product quality, reliability, repairability, and serviceability as factors for evaluating product sustainability. Increasing *product manufacturability* is another key consideration in the economic

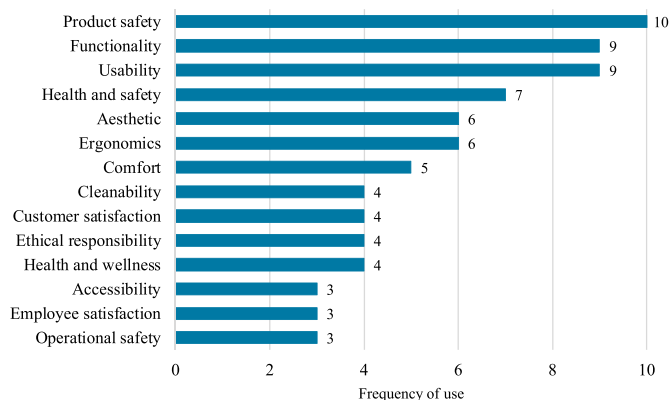


Fig. 8. Frequently used social factors.

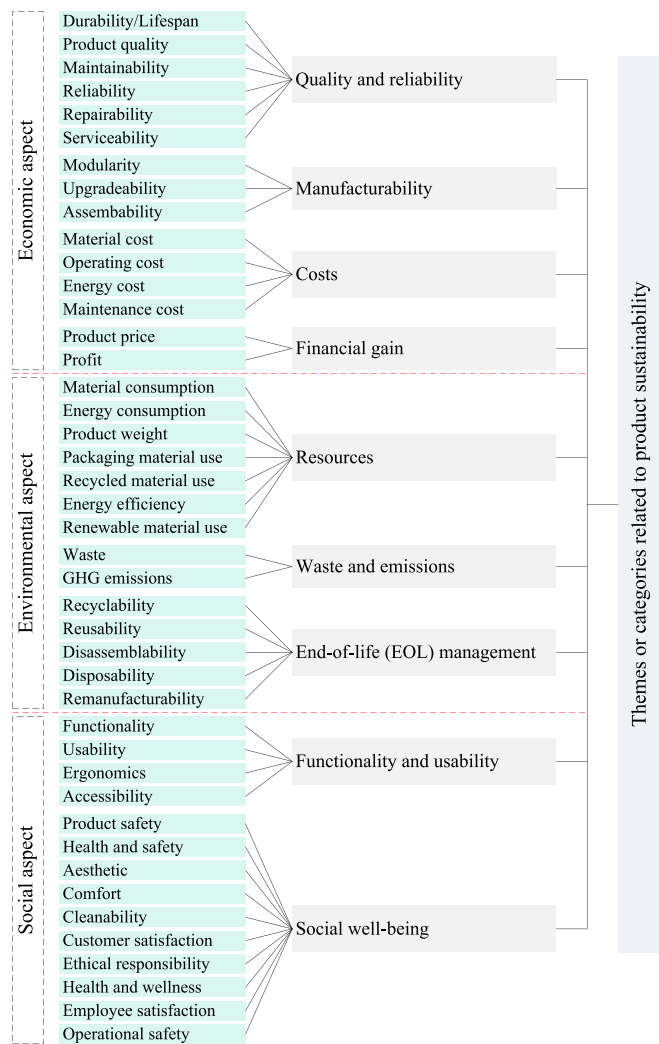


Fig. 9. Categorization of SPD factors into relevant themes.

aspect of SPD, which can be achieved by improving the modularity, upgradeability, and assemblability of a product. Chunhua et al. (2020) used these factors for group decision making in designing sustainable products. The economic aspect of SPD also stresses the reduction of costs such as material, operating, energy, and maintenance costs. In their work, Zolfani and Chatterjee (2019) incorporated most of these cost considerations for sustainable material selection in household furnishing. Furthermore, the economic aspect of SPD aims to attain an increased financial gain by increasing the profitability of a product, as indicated by Rezaei et al. (2019), while maintaining a reasonable price, as highlighted by Horani (2020).

On the other hand, the environmental aspect of SPD underscores the importance of improving resource utilization effectiveness. This requires a focus on reducing material consumption, energy consumption, product weight, and minimizing the use of packaging materials. Moreover, it involves increasing the use of recycled materials and renewable energy, as well as improving efficiency. In their study, Gholami et al. (2022) mentioned material consumption and energy consumption as major

criteria affecting sustainable product development. Meanwhile, Oh (2017) considered recycled material use and renewable energy use as crucial strategy items for the design of sustainable products. The environmental aspect of SPD also encompasses the reduction of waste, as highlighted by Kuo and Wang (2019), and the reduction of GHG emissions, as outlined by Vink (2020). Effective EOL management is another critical focus within the environmental aspect of SPD. This entails improving the recyclability, reusability, disassemblability, disposability, and remanufacturability of a product. In their work, Yan and Feng (2014) considered these factors for sustainable design.

Meanwhile, the social aspect of SPD place its emphasis on enhancing functionality and usability. This encompasses improving the functionality, usability, ergonomics, and accessibility of a product. Hassan et al. (2017) used functionality and ergonomics as a criteria for the sustainability assessment of a product during its design phase. Similarly, Soomro et al. (2021) considered usability and accessibility of a product for their sustainable prototyping conceptual framework. Furthermore, the social aspect of SPD contributes to promoting social well-being by improving product safety, aesthetic, health and safety, product comfort, and the cleanability of a product. In their study, Pan and Nguyen (2015) took customer satisfaction and employee satisfaction as performance criteria for assessing product-service system, while Faradilla et al. (2022) incorporated the aesthetic and comfort of a product into their SPD concept.

To provide additional insights, the SPD factors were mapped across the TPLC stages, as shown in Table 2. For instance, during the supply stage of the product life cycle, some of the key factors to consider include type of raw materials, type of packaging materials, and material cost. In their study, Kolling et al. (2022) presented sustainable packaging materials as one of the main elements of cosmetic product life cycle. Seyajah et al. (2016) considered material cost as one of the sustainability criteria in the supply stage for the design of sustainable office furniture. In the manufacturing stage, sustainability can be ensured by considering SPD factors such as material consumption, energy consumption, GHG emissions, and occupational health and safety. Hapuwatte and Jawahir (2021) identified material consumption as one of the sustainability metrics for SPD in the manufacturing stage. Maxwell and van der Vorst (2003) included energy consumption in the manufacturing stage as one of the issues for the development of sustainable products and services. Roy et al. (2014) used GHG emission as one of the metrics to assess the sustainability of an automotive component. Bertoni et al. (2020) identified health and safety as one of the sustainability criteria in the manufacturing stage for sustainable product development. During the use stage of the product life cycle, some of the crucial SPD factors to consider are the durability of a product, product safety, the functionality of a product, and ergonomics. In their work, Chatty et al. (2022) included durability in the use stage as one of the sustainable design strategies. Hassan et al. (2016) considered functionality and ergonomics as sustainability criteria in the use stage. Moreover, SPD should consider factors that contribute to effective EOL management during the post-use stage of a product's life cycle. These considerations include the recyclability, reusability, and disposability of a product, as stated by Schöggel et al. (2017); the disassemblability of a product, as mentioned by Hassan et al. (2022), and the remanufacturability of a product, as presented by Yan et al. (2012).

The mapping presented in Table 2 emphasizes that designing sustainable products requires adopting a life cycle-oriented approach that

Table 2
Mapping the SPD factors across the TPLC.

Sustainability aspects	SPD factors	TPLC stages			
		Supply (S)	Manufacturing (M)	Use (U)	Post-use (PU)
Economical	Durability/Lifespan	X		X	
	Material cost	X			
	Product quality	X	X	X	
	Product price	X	X	X	
	Modularity	X	X	X	X
	Upgradeability		X	X	
	Maintainability			X	
	Operating cost			X	
	Assemblability		X		
	Energy cost		X	X	
	Maintenance cost			X	
	Reliability	X		X	
	Repairability			X	
	Serviceability			X	
Profit	X	X	X		
Subtotal		7	7	13	1
Environmental	Material consumption	X	X		
	Energy consumption	X	X	X	
	Recyclability				X
	Reusability				X
	Disassemblability				X
	Waste	X	X		X
	Product weight	X	X		
	Disposability				X
	Packaging material use	X	X		
	Recycled material use	X	X		
	Energy efficiency		X	X	
	GHG emissions		X	X	
	Remanufacturability				X
	Renewable energy use	X	X	X	
Subtotal		7	9	4	6
Social	Product safety			X	
	Functionality			X	
	Usability			X	
	Health and safety		X	X	X
	Aesthetic			X	
	Ergonomics			X	
	Comfort			X	
	Cleanability			X	
	Customer satisfaction	X	X	X	X
	Ethical responsibility	X	X	X	X
	Health and wellness		X	X	X
	Accessibility			X	
	Employee satisfaction		X		
Operational safety			X		
Subtotal		2	5	13	4
Total		16	21	30	11

extends beyond the manufacturing stage, encompassing all stages of the product's life cycle. It stresses the importance of considering a multi-dimensional set of SPD factors for each stage of the product life cycle. This paper reveals that most of the SPD factors are linked to the use stage of a product, followed by the manufacturing-stage. This underscores the significance of prioritizing the use and manufacturing stages to effectively design, manufacture, and offer products with the required level of sustainability that meet stakeholder demands (customer demands in particular). Several SPD factors such as durability/lifespan, product price, modularity, material consumption, energy consumption, waste, health and safety, customer satisfaction, ethical responsibility, and others are indeed relevant across multiple life cycle stages of a product. Notably, modularity, customer satisfaction, and ethical responsibility emerge as key factors that maintain significance across all stages of the product life cycle.

To provide a comprehensive understanding of the SPD impact, a conceptual framework was developed on the basis of the categorization and mapping of the factors, as depicted in Fig. 10. The framework take

into account both the TBL and the TPLC approaches. Specifically, it underscores that the design of sustainable products should holistically consider the economic, environmental, and social aspects throughout the whole life cycle of a product (Hapuwatte and Jawahir, 2021). In developing the framework, the SPD factors corresponding to each stage of the product life cycle (referring to Table 2) were counted and visually represented in different colors for each category (referring to Fig. 9). For example, all six factors categorized under quality and reliability are linked to the use (U) stage, representing the highest number of factors compared to the other stages of the product life cycle. From these six factors, two factors (2nd highest number) are associated with the supply (S) stage, one factor (3rd highest number) with the manufacturing (M) stage, and none are linked to the post-use (PU) stage. This approach was similarly applied to count and visually represent the SPD factors associated with each product life cycle stage for the remaining categories to provide a complete view.

The framework highlights that to ensure sustainability during the use stage of a product, the highest number of SPD factors are linked to

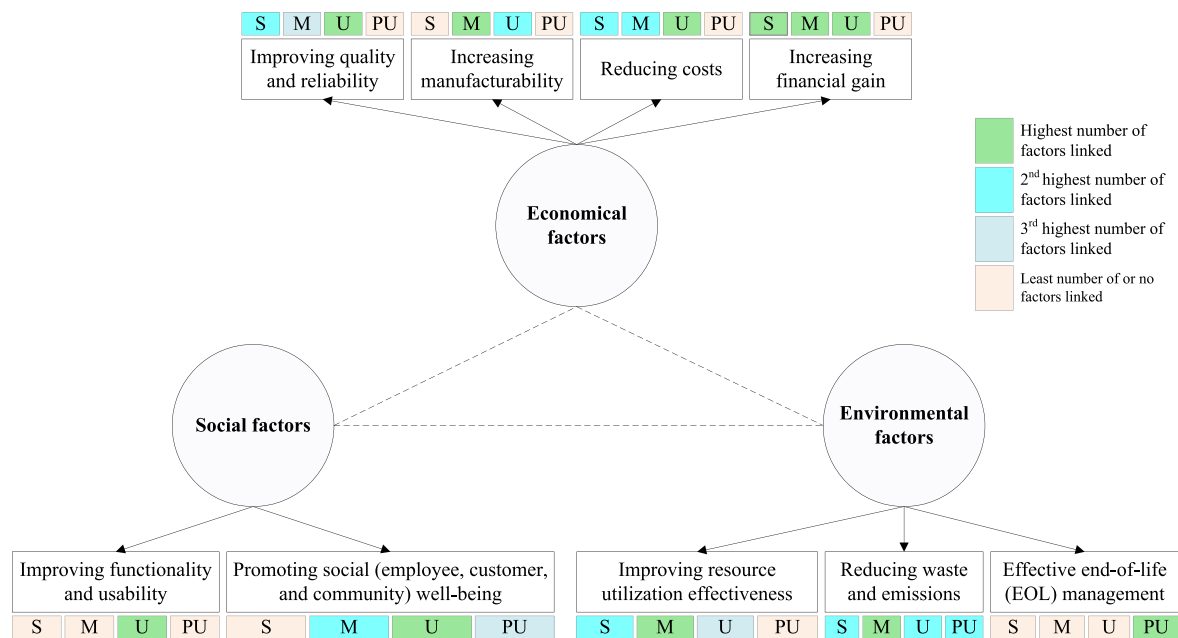


Fig. 10. Conceptual framework for SPD.

quality and reliability, costs, financial gain, functionality and usability, and social well-being, when compared to other stages. This underscores the importance of paying more attention to improving quality and reliability, functionality and usability, and social well-being to satisfy customers during this stage. Meanwhile, the manufacturing stage demands the highest consideration of factors related to product manufacturability, resources, and waste and emissions. Consequently, more emphasis is required to increase product manufacturability, improve resource utilization effectiveness, and reduce waste and emissions during this stage. Additionally, the post-use stage incorporated the highest number of factors pertaining to EOL management, suggesting that more weight should be given to ensuring effective EOL management during this stage. Therefore, when designing a sustainable product, it is logical to prioritize the life cycle stages of a product based on the considered factors and their respective categories or themes.

By achieving its objectives, this paper provides a broader view of SPD by providing valuable insights that significantly contribute to the existing knowledge in the field of SPD and PSA. Finally, this study concludes by summarizing its findings, presenting implications, and providing potential future research directions in Section 5.

5. Conclusions

This paper conducted a thorough analysis of the factors pertinent to SPD in the literature, considering two key approaches to product sustainability: (1) the triple bottom line (TBL) and (2) the total product life cycle (TPLC). The findings of the paper indicate that most of the factors identified in the reviewed literature were considered only once. This highlights that a wide array of SPD factors have been considered across different products. Consequently, understanding the specific context of a product is essential to effectively implement SPD factors. On the contrary, a few SPD factors were appeared frequently across multiple papers, providing visible patterns and valuable insights. These frequently used factors underscore various crucial aspects of product sustainability. This includes quality and reliability, manufacturability, costs, and financial gain within the economic aspect of SPD; resources, waste and emission, and EOL management within environmental aspect; and functionality and usability, and social well-being within the social

aspect. The framework presented in this paper emphasizes the importance of considering a multidimensional set of factors, based on the TBL approach, when designing sustainable products. This encompasses considerations ranging from the sourcing of raw materials to the EOL of a product. It can serve as a guide for designing sustainable products with the aim of achieving various product sustainability goals. These goals include improving quality and reliability, increasing product manufacturability, reducing costs, and increasing financial gain, improving resource utilization effectiveness, reducing waste and emissions, ensuring effective EOL management, improving functional and usability, and promoting social well-being. This study emphasizes the importance of considering waste and emissions reduction, reusability, and recyclability. These considerations promote the principles of 3R and circular economy.

5.1. Implications of the paper

This paper holds relevant implications for academics, managers, as well as policymakers. Academically, it constitutes a valuable contribution for future research on SPD and PSA. Certainly, researchers can use the findings of this paper as a basis for exploring product sustainability and related issues. Additionally, they can leverage the outlined themes or categories of the factors to direct their research towards key focus areas of SPD. The framework provided by this paper will assist researchers in integrating the TBL approach across the product life cycle in their research activities. This paper underscores the significance of ensuring environmental sustainability through resource efficiency, the use of recycled materials and renewable energy, the reduction of waste and emissions, and effective EOL management. These aspects are in line with the aim of advancing cleaner production technologies, emphasizing that the SPD factors presented in this paper will play a crucial role in the development and adoption of cleaner production technologies. This involves applying these factors for assessing the sustainability impacts of these technologies, identifying the most suitable technologies from multiple alternatives, and implementing the optimal technologies. In addition, this paper can serve as a crucial reference for developing educational materials on sustainable manufacturing that include SPD and PSA. Accordingly, universities, colleges, research institutes, as well

as training centers could expand their teaching and research initiatives concerning SPD and PSA. Furthermore, this study is intended to stimulate further discussion on the research agendas presented in [Subsection 5.2](#).

From a managerial perspective, the findings of this paper can serve as a valuable operational tool for designing sustainable products and assessing the sustainability of products in manufacturing companies. This can be achieved through a multidimensional set of SPD factors along with their corresponding themes or categories, and a comprehensive framework for SPD. Thus, the results of this paper will help managers in achieving sustainable manufacturing and meeting stakeholder requirements. With stakeholders placing emphasis on sustainable manufacturing, it is imperative for managers to take a leading role in enhancing their companies' product sustainability. This can be achieved through the adoption of the TBL approach throughout the life cycle of a product during its design and development process. Eventually, this can enable manufacturing companies to build a strong trust with their stakeholders, enhance their corporate image, and sustain their competitiveness in a market, where sustainability is increasingly relevant. By implementing the framework presented in this paper, manufacturing companies can improve the sustainability of their products across the TPLC. This, in turn, will enable them to achieve the product sustainability goals mentioned in the first paragraph of Section 5. Consequently, they can make valuable contributions to the achievement of the Sustainable Development Goals (SDGs) established by the United Nations in the long run. Specifically, this study can contribute to improving health and well-being (SDG 3), ensuring sustainable economic growth, productive employment, and decent work (SDG 8), promoting sustainable consumption and production (SDG 12), and tackling climate change and reducing its impacts (SDG 13).

From a policy viewpoint, this paper offers valuable insights for formulating and implementing policies and regulations concerning product sustainability across the TPLC. This study comprehensively addresses SPD, making it relevant for policies concerning the environment, socio-economic, and social responsibility. Specifically, it can influence environmental policy by exploring SPD factors related to resource utilization, waste, emissions, and EOL product management. In addition, this paper addresses factors associated with quality, reliability, costs and financial gain, which can influence policies pertaining to socio-economic aspects. Furthermore, the identification of factors linked to the social well-being can contribute to the formulation policies associated with social responsibility.

5.2. Limitations and future research directions

While acknowledging its contributions and limitations, this paper offers avenues that have paved the way for future research to further enrich the existing knowledge in the domain of sustainable product design (SPD) and product sustainability assessment (PSA). The suggested future research directions mentioned below require comprehensive consideration, aligning with the TBL approach across the total life cycle of a product.

- This paper focused on SPD factors published in the academic literature. However, future research could expand its scope by exploring SPD factors from other types of publications such as technical reports or standards. This will provide additional insights derived from the practices of organizations engaged in designing sustainable products and assessing product sustainability.
- Future research could apply the SPD factors in real-time design of sustainable products in different manufacturing companies and conduct comparative analysis of the factors from the perspective different contexts, including product type and industry type. This will enable the identification of core SPD factors (i.e., those applied across different product types) and product-specific factors. Longitudinal studies could be effective for this purpose.
- This paper has laid the foundation for future research to conduct an empirical study aimed at linking the factors to the product design and development practices of manufacturing firms. Case studies and action research can be useful for this purpose.
- Future research could capitalize on the results of this paper to conduct an empirical study, including statistical analysis of data collected from manufacturing companies engaged in SPD and PSA, to empirically test and validate the SPD factors.
- While this paper focused on proposing a conceptual framework to assist manufacturing companies in designing sustainable products and assessing product sustainability, future research could aim to test and validate the framework through an empirical study. In this regard, Delphi method, case studies, and action research can be applied by researchers.
- In light of the framework presented, the SPD factors have significant implications for life cycle assessment, 3R initiative, and circular economy. Therefore, future research could expand the application of these factors by integrating them into various life cycle assessment tools and circular economy models. Literature reviews, along with case studies can play a crucial role in developing, testing, and validating the framework for integrating these factors.
- In future research, empirical analyses could focus on examining the relationship between the factors and the themes, as well as the relationship between the factors and the product life cycle stages. Structural equation modeling can be useful for conducting such empirical analysis.
- Finally, future research could expand the application of the SPD factors in assessing the performance of various cleaner production technologies and in identifying and adopting the most appropriate technologies. Case studies could provide valuable insights into these aspects.

As a final point, it is imperative that a promising sustainable product design integrates eco-friendly resources, technologies, policies, and practices to effectively address environmental and social impacts. Embracing the triple bottom line (TBL) and the total product life cycle (TPLC) approaches in design cultivates a more sustainable and socially responsible product landscape. Collaborative efforts among stakeholders, including academia, industries, and policymakers, are crucial for driving innovation and ensuring product sustainability.

CRedit authorship contribution statement

Azemeraw Tadesse Mengistu: Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Writing – review & editing, Conceptualization. **Marcos Dieste:** Writing – review & editing, Visualization, Methodology, Funding acquisition, Conceptualization. **Roberto Panizzolo:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Stefano Biazzo:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

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

Marcos Dieste reports financial support was provided by Next-Generation EU (Italian PNRR – MICS Extended Partnership). Azemeraw Tadesse Mengistu reports financial support was provided by University of Padova, Department of Management and Engineering.

Data availability

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

Acknowledgements

Marcos Dieste conducted this study as part of the MICS (Made in Italy – Circular and Sustainable) Extended Partnership and received funding from Next-Generation EU (Italian PNRR – M4 C2, Invest 1.3 – D.D.

1551.11-10-2022, PE00000004). CUP MICS C93C220052800.

Azemeraw Tadesse Mengistu conducted this research as part of the "Product Design in the Perspective of Industrial Sustainability" project and received funding from the University of Padova – Department of Management and Engineering with grant number BOLI_BIRD2121_01.

Appendix

Summary of the reviewed papers.

No.	Author(s)	Objective	Methodology/Approach
1	Calik (2024)	To create a validated scale for assessing the performance of sustainable product innovation	Literature review; Questionnaire; Exploratory factor analysis (EFA); Confirmatory factor analysis (CFA)
2	Hallstedt et al. (2023)	To explore and review methods for anticipating new products' sustainability performance in early design stage	Literature review; Action research; Semi-structured interviews
3	Chipambwa et al. (2023)	To investigate sustainability in the perspective of design in SME furniture manufacturing enterprises in Zimbabwe	Interview; On-site observation; Sustainable design matrix
4	Zhang et al. (2023)	To propose the Psycho-Sustainable Design (PSD) technique, intended to improve product sustainability	Analysis of consumers; PSD
5	Fan and Chang (2023)	To explore the key criteria for sustainable design from the viewpoint of social responsibility, the TBL approach, and the cradle-to-cradle concept	Literature review; Questionnaire; Delphi method; Interview; Analytic network process (ANP)
6	Gholami et al. (2022)	To investigate I4.0 technologies applicability based on the TBL approach at the product level and assess the technologies using sustainability criteria	Literature review; Survey; Fuzzy TOPSIS; Case study at Automotive Industry (Malaysia)
7	Chatty et al. (2022)	To identify the considerations that have impact on sustainable design practices integration into real-world product development practices	Literature review; Case study at Engineering Consultancy Firm
8	Kolling et al. (2022)	To identify the barriers, drivers, and good sustainable practices existing in the cosmetics industry from the corporate social responsibility perspective	Literature review; Case study at Cosmetics Industry
9	Hassan et al. (2022)	To propose a study on how crusher design concepts are selected from a sustainable perspective	Weighted decision matrix (WDM); Case study of Crusher Design
10	Faradilla et al. (2022)	To formulate the eco-bag concept and assess the concept using SPD metrics	Quality function deployment (QFD); Case study of Eco-Bag from Pineapple Leaf Fiber
11	Trojanowski (2022)	To determine the development level of sustainable confectionery products in the companies that were studied	Computer-assisted web interview method; Computer-assisted telephone interview method; Case study of Confectionery Industry (Food Industry)
12	Hapuwatte and Jawahir (2021)	To explore product design in the context of sustainability and circularity principles and present a new methodology for incorporating these two principles	Literature review; Developing an evaluation method for SPD; Proposing a conceptual framework for modeling product sustainability
13	Rausch et al. (2021)	To identify specific sustainable clothing attributes for consumers and analyze consumers' readiness to pay for the attributes	Best-worst scaling (BWS) method; Case study of Apparel
14	Fetanat and Tayebi (2021)	To examine the sustainability indicators associated with the household water treatment system design	Fuzzy QFD-LINMAP; Case study of Household Water Treatment System
15	Han et al. (2021)	To explore the key elements of sustainable design and suggest a set of metrics to measure SPD concepts	Case study of Portable Blenders Design
16	Enyoghasi and Badurdeen (2021)	To examine Industry 4.0 technologies' impact on sustainable manufacturing using a comparative analysis	Comparative analysis
17	Soomro et al. (2021)	To propose a sustainable prototyping conceptual framework on the basis of a five-stage design thinking model	Literature review; Digital fabrication; Proposing a conceptual framework; Case study of Alarm Clock, Smart Blinds, and Catapult
18	Horani (2020)	To identify target customers for sustainable designs and provide a method for profiling the eco-friendly customers on the basis of sustainable consumer behavior	Interview and questionnaire; Process macro and two-way interaction effect method; CFA
19	Bertoni et al. (2020)	To propose an approach that integrates value-driven design with sustainable product development models	Participatory action research; Machine learning; Case study of Turbine Rear Structure (Aerospace Application)
20	Bataglin and Ferreira (2020)	To propose a novel method for product modularization with a focus on the TBL	Literature review; proposing modularization method; Kano model; Case study of Hydraulic Product
21	Vink (2020)	To assess the awareness of material scientists regarding the sustainable life cycle aspects of materials	Literature review; Questionnaire; Interview
22	Chunhua et al. (2020)	To evaluate conceptual schemes taking into account sustainability attributes through group decision-making method	Literature review; Morphological matrix; Intuitionistic fuzzy preference relations; Case of Spindle System of CNC
23	Lin et al. (2019)	To establish ergonomics-based criteria for assessing product sustainability	Fuzzy Delphi method (FDM)
24	Kuo and Wang (2019)	To integrate robust design and axiomatic design method for SPD	Literature review; Axiomatic design and robust design method; Case of Baby Pram
25	Rezaei et al. (2019)	To present a multi-criteria decision analysis method for selecting a sustainable product-package design	Literature review; Best worst method (BWM); Case study at Food Industry
26	Mattson et al. (2019)	To introduce a quantified trade-off space between economic, environmental, and social sustainability	Literature review; Multi-objective optimization; Case of Borehole Drill Machine
27	Zolfani and Chatterjee (2019)	To compute criteria weights for selecting sustainable housing materials	Literature review; Step-wise weight assessment ratio analysis (SWARA); BMW; Case study of Household Furnishing Materials
28	Huang and Badurdeen (2017)	To evaluate the performance of sustainable manufacturing at the enterprise level	Literature review; Case study at Consumer Electronics Industry

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No.	Author(s)	Objective	Methodology/Approach
29	Hassan et al. (2017)	To assess the sustainability of a product during the design phase	Literature review; Product sustainability evaluation tool; Case study of Car Seat Design (Car Manufacturer)
30	Oh (2017)	To propose a new guideline for sustainable design, complementing social aspects	Case study of Eco-friendly Toys (Green Toys) and the 606 Shelving System
31	Soota (2017)	To provide a novel and deeper insight into how companies can manage iterative and integrative approaches for product development	ANP; QFD; Case study of Hypothetical Writing Instrument
32	Schöggel et al. (2017)	To develop a new checklist for developing sustainable products	Literature review; Interview; Case study of Automotive Lightweight Technologies
33	Mayyas et al. (2016)	To propose an approach for the selection of eco-material for the body panels of automobile	Fuzzy TOPSIS; Case study of Automotive Body-in-White (BIW) design
34	Feng and Mai (2016)	To introduce a novel assessment methodology for product sustainability performance evaluation using quantitative and qualitative information	Fuzzy multi-criteria decision analysis; Case study of Milling Machine Tool
35	Go et al. (2016)	To present a comprehensive framework to identify and evaluate design elements when developing multiple life-cycle products	Literature review; Analytical hierarchy process (AHP); Case study of Automobile Engine
36	Seyajah et al. (2016)	To provide a method to determine the significance of assessment criteria in office furniture sustainable design	Literature review; AHP; Case study of Office Furniture
37	Hassan et al. (2016)	To propose a systematic approach for evaluating the sustainability of different alternative configurations in product design	AHP; WDM; Artificial neural network (ANN); Case study of Armed Chair
38	Pan and Nguyen (2015)	To assist manufacturing companies in identifying the essential performance assessment criteria to achieve customer satisfaction	Balanced scorecard (BSC); DEMATEL; ANP; Delphi method; A questionnaire survey; Case study at manufacturing firms from Taiwan, Thailand, and Vietnam
39	Hosseinpour et al. (2015)	To develop an approach for deciding design details through benchmarking that contains the existing sustainable design practice	Literature review; QFD; Case study of Wheelchair Design
40	Romli et al. (2014)	To propose a conceptual model for supporting SPD	QFD; Case study of a Medical Forceps
41	Fargnoli et al. (2014)	To develop a design management framework for sustainable product development	QFD; Case study of Trimmer Design (Italian Gardening Equipment Manufacturer)
42	Shuaib et al. (2014)	To present product sustainability index (ProdSI) methodology for assessing product sustainability	Literature review; ProdSI method; Case study of Consumer Electronics Product
43	Roy et al. (2014)	To discuss an integrated product information model development that will facilitate the process of product sustainability index assessment	Core Product Model; Information model development; Case study of Automotive Component
44	Vinodh et al. (2014)	To propose a model for innovative and sustainable product development	Literature review; ECQFD; AHP; Theory of inventive problem-solving (TRIZ); Case study of Overflow Valve (Automotive Parts Company)
45	Yan and Feng (2014)	To propose a methodology for sustainable design-oriented product modularity for incorporating sustainable factors into product design process	Relationship matrix; Case study of Rotor Laboratory Bench
46	Bereketli and Erol Genevois (2013)	To identify sustainable product development improvement strategies	Literature review; QFD for environment (QFDE); Fuzzy AHP; Case study of Hand Blender (Kitchen Appliance)
47	Mayyas et al. (2013)	To suggest an eco-material selection approach through quantifiable measures, aiming at creating a sustainability model applicable for an automobile body	PSI; PCA; Case study of Automotive BIW design
48	Yan et al. (2012)	To propose a modular design methodology to achieve sustainable design	Kernel-based fuzzy c-means algorithm; Case study of Reduction Gear
49	Ghadimi et al. (2012)	To devise a weighted fuzzy evaluation method for assessing product sustainability	Fuzzy AHP; Weighted fuzzy assessment method (WFAM); Case study of Fuel Filter (Iranian Automotive Components Manufacturing Company)
50	Mayyas and Omar (2012)	To suggest an eco-material selection approach for the sustainability aspects of designing an automobile structure	AHP; QFD; Case study of Automotive BIW design
51	Mayyas et al. (2012)	To propose a set of metrics for selecting materials that consider all aspects of sustainability	Life cycle analysis (LCA); Case study of Automotive BIW design
52	Hassan et al. (2012)	To integrate morphological analysis theory (MAT) with artificial neural network (ANN) approach for designing sustainable products	MAT; ANN approach; Case study of Portable Vacuum Cleaner
53	Azkarate et al. (2011)	To propose specific methods for future machine tools' sustainable design	Literature review; Multi-criteria analysis theory; Case study of Machine Tools
54	Jin Gam et al. (2009)	To create and implement a new model for designing and producing sustainable apparel, cradle-to-cradle apparel design (C2CAD)	Developing C2CAD model; Case study of Children Knitwear (Apparel Design and Production)
55	Lindgreen et al. (2009)	To examine the challenge organizations face in understanding how customers perceive the environmental and social sustainability aspects	Literature review; Interview; Case study of High-Tech Medical Equipment
56	De Silva et al. (2009)	To provide quantifiable elements of sustainability in consumer electronic products	Proposing product sustainability scoring methodology; Case study of Laser Printer (Lexmark International)
57	Maxwell and van der Vorst (2003)	To present a sustainable product and/or service development (SPSD) method for developing sustainable products and services	Developing (SPSD) method; Case study of Electronic Automotive Components and Personal Computer

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