

A COMPARATIVE EXAMINATION OF SUSTAINABLE PRODUCT DESIGN APPROACHES THROUGH REPRESENTATIVE PRODUCTS

Ph.D. Cenk CİHANGİR¹

Istanbul Health and Technology University, Faculty of Engineering and Natural Sciences,
Department of Industrial Design Engineering, İstanbul-Türkiye

¹ORCID ID: <https://orcid.org/0000-0002-7118-6856>

cenk.cihangir@istun.edu.tr +90 554 557 06 47

ABSTRACT

Sustainable product design is a holistic product development approach that considers environmental, economic, and social impacts across the product life cycle. Within this broader framework, the present study focuses on environmental design decisions at the product level and examines how different approaches to sustainable product design are reflected in representative products through a common set of sustainable design criteria. Accordingly, Green Design, Design for X (DfX), Eco-design, Cradle to Cradle (C2C), and Life Cycle Design are examined, with a current product selected to represent each approach.

A comparative qualitative product analysis was adopted as the research method. The selected products were examined according to ten sustainable design criteria: material selection, production and resource efficiency, durability and product lifespan, repairability, disassemblability, modularity, reuse, recyclability, end-of-life strategy, and life cycle integration. Through this comparative framework, the study evaluates which design decisions are prioritized by different sustainable design approaches at the product level and how these priorities are reflected in product characteristics.

The findings indicate that the examined products address sustainable design criteria through different priorities and design decisions. While material selection and resource efficiency constitute key design considerations in some products, repairability, disassemblability, and modularity emerge through product structure and component relationships in others. Recyclability, end-of-life strategies, and life cycle integration are also significant in maintaining value at the end of use and supporting continuous material cycles. The comparative analysis demonstrates that a product's strong representation of a particular sustainable design approach does not necessarily mean that all sustainable design criteria are met to the same extent. In this context, sustainable product design should be understood not solely through specific environmental criteria, but as a design problem that requires an integrated life cycle perspective encompassing the relationships among material selection, production processes, product structure and component relationships, product lifespan, and end-of-life scenarios.

Keywords: sustainability, sustainable product design, sustainable design approaches, comparative product analysis

INTRODUCTION

The environmental impacts of products arise not only during the production phase but throughout the entire lifecycle—including raw material sourcing, production, distribution, use, maintenance, and end-of-life processes. Therefore, decisions made in product design affect not only material and production choices but also product structure, service life, repairability, and

end-of-life scenarios. Sustainable product design aims to address these relationships early in the design process to develop decisions that reduce environmental impacts throughout a product's life cycle. Current literature indicates that in sustainable product design, resource use, waste, emissions, and end-of-life management must be evaluated collectively throughout the life cycle (Mengistu et al., 2024).

However, the literature on sustainable design does not consist of a single, homogeneous method. Over time, the field of sustainable design has expanded from environmental improvements at the material and product levels to life-cycle and system-focused approaches (Ceschin & Gaziulusoy, 2016, 2020). Within this broad field, Green Design, Design for X (DfX), Eco-Design, Cradle-to-Cradle (C2C), and Life Cycle Design offer different problem focuses and design tools. Significant overlaps among these approaches necessitate the conceptual differentiation of their applications at the product level and their comparison based on common sustainable design criteria.

This study aims to examine the product-level manifestations of these five approaches and to compare a contemporary product example representing each approach based on common sustainable design criteria. The central research question is defined as follows: How do contemporary product examples representing different approaches to sustainable product design differ in terms of material selection, production and resource efficiency, durability and service life, reparability, disassemblability, modularity, reusability, recyclability, end-of-life strategy, and life cycle integrity? In line with this question, the study aims not to rank different product categories based on absolute environmental performance, but rather to comparatively highlight how sustainability goals are reflected in product design decisions.

The Concept of Sustainable Product Design

Sustainable product design is a holistic product development approach that aims to address the environmental, economic, and social impacts arising throughout a product's life cycle—along with design decisions—while meeting the product's functional requirements. This approach views life cycle stages—such as raw material and material selection, production, distribution, use, maintenance, and end-of-life—not as independent processes, but as decision areas that must be interconnected during the design phase. In this context, reducing resource consumption and environmental impacts, preserving the product's functional and technical value, extending its service life, and directing products, components, and materials toward options that can retain their value after use are among the fundamental issues of sustainable product design (Mengistu et al., 2024). Sustainable product design must address sustainability not as a feature added to the product after the fact, but as a design problem that requires the coordinated shaping of decisions regarding materials, production, product structure, use, and end-of-life throughout the product's life cycle.

Sustainable design at the product level encompasses interrelated decision areas such as resource use, material selection, production, durability, use, maintenance, repair, and end-of-life management. A comprehensive review by Mengistu and colleagues shows that factors related to sustainable product design extend across the product's entire life cycle, with resources, waste, emissions, and end-of-life management constituting key environmental themes (Mengistu et

al., 2024). Therefore, a product's sustainable design characteristics should not be evaluated based on a single material property or a single life cycle stage.

Green Design

Green Design is considered one of the early approaches in the historical development of sustainable design that emphasizes environmental improvements at the product and material levels. Strategies of this approach include reducing the amount of material used, avoiding harmful substances, preferring recycled materials or those with a lower environmental impact, and reducing energy and resource consumption. However, there are no clear and universal boundaries between Green Design, eco-design, and broader sustainable design approaches. For this reason, the concept is used in this study not as an independent and standardized method, but as an analytical category that specifically highlights direct environmental improvements in material and resource inputs (Ceschin & Gaziulusoy, 2016).

Design for X – DfX

Design for X (DfX) is not a method specific to sustainability in and of itself, but rather a family of methods that enables the systematic integration of a specific design objective into the product development process. The “X” here can represent various objectives, such as manufacturability, assembly, service, disassembly, repair, recycling, or environmental performance. From the perspective of sustainable product design, sub-approaches such as Design for Repair, Design for Disassembly, Design for Recycling, and Design for Environment are particularly important. A distinctive feature of the DfX approach is its ability to translate the selected design objective into actionable design criteria, such as product structure, component interfaces, connection types, accessibility, material separation, and related product development requirements. Current DfX literature also defines Design for Recycling as a subfield of the DfX family and emphasizes that a product's recyclability must be addressed during the design phase (Wu et al., 2025).

Eco-design

Eco-design is a design approach that aims to systematically integrate environmental requirements into the product development process. Rather than focusing solely on improving a single material or environmental attribute, this approach seeks to link environmental impacts arising at different life cycle stages—such as material selection, production, distribution, use, and end-of-life—to design decisions. Systematic reviews of eco-design tools indicate that these tools are used in various product development activities, such as generating design alternatives, evaluating environmental performance, and selecting among alternatives (Lee et al., 2023).

Cradle to Cradle (C2C)

Cradle to Cradle (C2C) is a design approach that, rather than treating the end of a product's life as a linear waste stage, aims to ensure that materials can return as inputs to new production cycles. In C2C, key considerations include the preservation of material value within technical or biological cycles, material integrity, and the capacity for materials to re-enter circulation. Accordingly, the approach focuses not only on reducing the amount of waste but also on designing products in a way that ensures materials can be directed into appropriate cycles after use and that material value is preserved as much as possible (Bakker et al., 2010; Ceschin & Gaziulusoy, 2020).

Life Cycle Design

Life Cycle Design approaches the stages of a product—raw material procurement, production, distribution, use, maintenance, repair, and end-of-life—not as independent processes, but as an interconnected design system. The primary goal is to prevent improvements made in one life cycle stage from creating a greater environmental burden in another stage and to develop design decisions from a whole life cycle perspective. Developments in the literature on sustainable design indicate that life cycle thinking has become one of the fundamental evaluation frameworks in product design (Ceschin & Gaziulusoy, 2016).

Life Cycle Design and Life Cycle Assessment must be conceptually distinguished. Life Cycle Design refers to an approach that incorporates life cycle stages into design decisions; LCA, on the other hand, refers to the quantitative calculation of environmental impacts at these stages under defined methodological conditions. In this study, Life Cycle Design is used as an analytical approach that evaluates how a product's environmental outcomes are addressed collectively, from raw material selection through distribution and end-of-use.

Conceptual Distinction Between Approaches and Their Use in Research

The five approaches addressed in this study are not mutually exclusive categories. The same design decision can serve different functions within multiple approaches. For example, disassemblability can be a direct design goal within DfX, a strategy that improves end-of-life outcomes within eco-design, and a product feature that supports the separation and re-circulation of technical materials within C2C. Similarly, the life cycle perspective supports the integrated assessment of the outcomes of eco-design decisions across different life cycle stages. The sustainable design literature also demonstrates that these approaches can establish overlapping and complementary relationships (Ceschin & Gaziulusoy, 2016).

These five approaches have been considered together because they highlight different yet interrelated design logics in sustainable product design: Green Design focuses on direct environmental improvements in material and resource inputs; DfX involves translating specific objectives into product structure and component relationships; Eco-Design emphasizes the systematic integration of environmental requirements into the product development process; C2C focuses on material cycles and end-of-life recovery; and Life Cycle Design highlights the relationships between decisions across different life cycle stages. This selection was made not to treat the approaches as equivalent in terms of theoretical scope and methodological characteristics, but to enable a comparison of the different design decisions they emphasize in sustainable product design at the product level.

For this reason, the product examples in the study were not placed into definitive, mutually exclusive categories. For each approach, a product example was selected that clearly demonstrated the fundamental design logic of that approach at the product level and could be analyzed using product-specific technical or academic data and documentation. The selected products were then compared based on the same ten sustainable design criteria, independent of the approach they represented (Table 1). This comparative framework prevents the assumption that a product's strong representation of a particular approach automatically means it meets all

sustainable design criteria to the same degree, and ensures that the comparison is conducted based on product design decisions.

Table 1. Conceptual distinction among the five sustainable product design approaches used in the study.

Approach	Main objective	Level of fundamental analysis	The fundamental question	Role in the research
Green Design	Reducing certain environmental impacts	Material / Product	What direct design decisions can be made to reduce the environmental impact?	It represents environmental improvements focused on the use of materials and resources.
Design for X (DfX)	Incorporating specific design objectives into the product structure	Component / product connection / structure	How can goals such as repair, disassembly, or recycling be incorporated into a product's design?	It represents goal-oriented decisions such as reparability, disassemblability, and modularity.
Eco-Design	Systematic integration of environmental requirements into product development	Product Development / Life Cycle	How are environmental requirements systematically integrated into design decisions?	It represents the consideration of multiple environmental criteria together in the product development process.
Cradle-to-Cradle Design (C2C)	The preservation of the value of materials in technical or biological cycles	Material cycle / end-of-use system	How can materials be reintroduced into the production cycle after use?	It represents the concept of the material cycle and producer-controlled recycling.
Life Cycle Design	Managing design decisions throughout their entire life cycle	Raw materials–production–distribution–use–end of life	How can environmental impacts be addressed holistically throughout the entire life cycle?	It highlights the interactions and transfer of loads between the stages of the life cycle.

RESEARCH AND FINDINGS

In this study, a comparative qualitative product analysis was adopted to answer the research question defined in the introduction. The Green Design, Design for X (DfX), Eco-Design, Cradle-to-Cradle (C2C), and Life Cycle Design approaches were examined through the Emeco 111 Navy Chair, Fairphone Gen. 6, Herman Miller Mirra 2, Shaw EcoWorx, and Muebles LUFÉ – LORE Litera 90, respectively. Rather than directly ranking environmental performance across different product categories, the study investigated which design decisions in each product reflect sustainable design principles. Accordingly, the products were evaluated based on ten common sustainable design criteria: material selection, production and resource efficiency, durability and service life, reparability, disassemblability, modularity, reusability, recyclability, end-of-life strategy, and life cycle integrity. These criteria align with the multidimensional structure of sustainable product design, which encompasses interrelated design decisions spanning the various stages of the product life cycle (Mengistu et al., 2024).

The analysis, conducted while defining individual products as units of analysis, focused on the products' material systems, product structure, and interrelationships among components; characteristics related to production and resource use; design decisions supporting product lifespan; and end-of-life options. Thus, the analysis was not limited to identifying individual characteristics associated with sustainability in products; it also examined how these characteristics relate to the product's service life, maintenance and repair capabilities, the separability of components, and options for preserving value after use.

The sources used in the assessment varied depending on the nature of the design feature under examination. Literature reviews, product-specific life cycle assessments, and environmental product declarations were used to examine information related to life cycle and environmental performance; manufacturer technical documents, material information, repair and disassembly documents, warranty and spare parts information, and certification documents were used to evaluate the technical and structural characteristics of the products. Thus, rather than ranking products' overall sustainability levels with a single score, the comparison was structured to reveal how and to what extent common design criteria are met across different products.

Evaluation of Sustainable Design Criteria at the Product Level

The common ground for this comparison is based on the recognition that sustainable product design should not be reduced to a single environmental performance indicator. The literature shows that sustainable product design is addressed using multidimensional criteria that encompass different life cycle stages, such as materials, production, use, and end-of-life. Han, Jiang, and Childs (2021) define materials, production, use, and end-of-life as separate measurement areas in the evaluation of sustainable product design concepts; meanwhile, Mengistu et al. (2024) demonstrate that factors related to sustainable product design are distributed across the entire life cycle under themes such as resources, waste and emissions, quality and reliability, and end-of-life management. The ten criteria used in this study have been organized in a manner consistent with the literature to highlight design decisions at the product level; in addition to material selection and production decisions, durability, reparability, disassemblability, modularity, reusability, recyclability, end-of-life strategy, and life cycle integrity have been addressed as separate evaluation areas (Han et al., 2021; Mengistu et al., 2024). These ten criteria were not taken from a ready-made set presented in the literature as a single standardized scale; rather, they were synthesized from life cycle and sustainable product design criteria in the literature to make design decisions at the product level comparable, in line with the research question (Table 2). Therefore, "life cycle integrity," in particular, is not a standardized, independent index; rather, it is a

study-specific, integrative evaluation area that examines whether product-specific life cycle data, measures to extend service life, opportunities for maintenance, repair, and reuse, and end-of-life scenarios are considered collectively.

product level; in addition to material selection and production decisions, durability, reparability, disassemblability, modularity, reusability, recyclability, end-of-life strategy, and life cycle integrity have been addressed as separate evaluation areas (Han et al., 2021; Mengistu et al., 2024). These ten criteria were not taken from a ready-made set presented in the literature as a single standardized scale; rather, they were synthesized from life cycle and sustainable product design criteria in the literature to make design decisions at the product level comparable, in line with the research question (Table 2). Therefore, “life cycle integrity,” in particular, is not a standardized, independent index; rather, it is a study-specific, integrative evaluation area that examines whether product-specific life cycle data, measures to extend service life, opportunities for maintenance, repair, and reuse, and end-of-life scenarios are considered collectively.

Table 2. Definitions and indicators used in the evaluation of sustainable design criteria at the product level.

Sustainable Design Criterion	Scope Of Evaluation in Terms Of Product Design	Observable Indicators at The Product Level
Material Selection	Alignment of material composition with the principles of resource efficiency and circularity. (Han et al., 2021; Mengistu et al., 2024)	Recycled/renewable content; material reduction; reduction or traceability of critical/hazardous materials; material selection that supports separation.
Production / Resource Efficiency	The extent to which production and assembly decisions take into account energy, resource, and waste efficiency. (Han et al., 2021; Mengistu et al., 2024)	Product-specific energy/emissions data; use of low-carbon/renewable energy; reduction/recovery of production waste; resource efficiency through assembly and component standardization.
Durability / Service Life	Design features that help the product maintain its functional and technical value over the long term. (Cordella et al., 2021; Mesa et al., 2022)	Durability testing or extended warranty; serviceability; replaceability of wear-and-tear components; support for updates and upgrades in technological products.
Repairability	Restoring a faulty component to full functionality through diagnosis, access, disassembly, and replacement or repair. (Cordella et al., 2021; Ruiz-Pastor & Mesa, 2023)	Access to critical components and reversible connections; requirement for standard or accessible tools; availability of replacement parts; repair/disassembly documentation.
Removability	The ability to disassemble a product in a controlled and non-destructive manner for the purposes of maintenance, repair, reuse, or recycling. (Assyiraq Ibrahim & Putri, 2025; Inselmann et al., 2025)	Disassembly sequence/depth; required tool type; reusability and reversibility of fasteners; disassembly time/accessibility.

Sustainable Design Criterion	Scope Of Evaluation in Terms Of Product Design	Observable Indicators at The Product Level
Modularity	The organization of functional subsystems into separable, replaceable, or upgradeable modules. (Amend et al., 2022; Inselmann et al., 2025)	Functional module separation; well-defined/reusable interfaces; the ability to modify a module independently; cross-generation compatibility or the ability to upgrade.
Reuse	The ability of a product or its components to be reused while retaining their functional value after initial use. (Cordella et al., 2020; Assyraq Ibrahim & Putri, 2025)	Second-use/refurbishment support for the entire product; reuse of components/modules; take-back/refurbishment channel; the ability to reuse without destructive processing.
Recyclability	Ensuring that components and materials can be disassembled and directed into recycling streams at the end of their useful life. (Cordella et al., 2020; He et al., 2021)	Material traceability; separability of material types; limitations on permanent bonds; take-back/recycling infrastructure; or a product-specific recyclability statement.
End-of-life strategy	Defining, at the design and system levels, which value preservation or recovery pathway a product will follow at the end of its life. (Cordella et al., 2020; Mengistu et al., 2024)	Channel for open take-back/return; reuse/refurbishment pathway; recycling/recovery pathway; documented end-of-life instructions or responsibility.
Life cycle integrity	Considering the raw material, production, use, maintenance, and end-of-life stages collectively in design decisions. (Han et al., 2021; Mengistu et al., 2024)	Product-specific LCA/EPD or life cycle data; strategy for extending the product's service life; maintenance/repair/reuse system; end-of-life take-back/reuse/recycling scenario.

The indicators in this study are based not only on general sustainability statements but also on product-specific design characteristics such as the product's material system, connection types, component accessibility, and end-of-life infrastructure. A three-level qualitative assessment system specific to this study was used to interpret product-criterion matches; these levels are not presented in the literature as universal or standard thresholds. "Sufficient" refers to situations where the core indicators of the relevant criterion are clearly met with product-specific information and there is no critical design barrier that invalidates the assessment; "Limited" refers to situations where, although direct product information supporting the criterion exists, only a portion of the indicators is met or there is a significant design, implementation, or infrastructure limitation; "Insufficient" refers to situations where the product's structure or design feature directly prevents the application of the relevant criterion or where the criterion's fundamental conditions are not met. These determinations do not assign a score to the overall sustainability level of products; they merely indicate the extent to which the relevant criterion is reflected in the product design based on the available information. For this reason, different product categories are not reduced to a single total score. It has also been demonstrated in the literature that the results of repairability assessment methods can vary depending on the criteria used and methodological choices (Bracquené et al., 2021; Dangal et al., 2022).

In the evaluation, repairability, disassemblability, and modularity are specifically distinguished from one another. Repairability refers to the diagnosis, access, removal, and restoration of a faulty or worn-out component; disassemblability refers to the ability to separate target components in a controlled and, as far as possible, non-destructive manner; and modularity refers to the ability to independently replace or upgrade functional subsystems via defined interfaces. This distinction prevents every disassemblable product from being considered repairable or modular. The literature also emphasizes that product structure affects different stages of the life cycle and that modularity gains meaning when linked to specific design objectives (Bonvoisin et al., 2016). In disassembly evaluations, the sequence and depth of disassembly, the type of tools used, the reversibility of fasteners, and the disassembly time are among the key parameters (De Fazio et al., 2021).

Selection of Sample Products and Analysis Design

The products to which this evaluation framework will be applied were selected through a targeted selection process. Four criteria were considered together in the selection process: (1) the product must visibly demonstrate the fundamental design logic of one of the five sustainable design approaches outlined in the introduction at the product level; (2) the product must be current or still accessible and available for examination; (3) technical, environmental, or academic information specific to the product must be accessible; (4) the selection must not be based solely on the manufacturer's general sustainability narrative. This selection does not rest on the assumption that the five approaches constitute mutually exclusive categories. The sustainable design literature demonstrates that product-level approaches have historically evolved from different priorities, yet there are significant overlaps and complementarities among them (Ceschin & Gaziulusoy, 2016; Ceschin & Gaziulusoy, 2020). Therefore, each product was selected not merely because it belongs to a single approach, but because the relevant approach makes its defining design logic more clearly visible compared to the product's other characteristics. The purpose of the product selection is not to achieve statistical representation or to generalize to the entire product market, but to comparatively highlight the distinct design logics of the five approaches at the product level.

Green Design: Emeco 111 Navy Chair

The Emeco 111 Navy Chair is a seating element that incorporates recycled PET as a core material in its design (Figure 1). The fact that the product contains 90% recycled PET and utilizes waste material equivalent to approximately 170 plastic bottles in its production highlights a design approach aimed at reducing environmental impact, particularly through material selection (Emeco, n.d.-a; Emeco, n.d.-b). In furniture design, material selection, reducing resource use, and extending product lifespan are considered key areas for life-cycle-focused environmental improvements (Yang & Vezzoli, 2024). However, the limited product-level information regarding the repair, disassembly, and reuse of components for the 111 Navy Chair necessitates that the product's sustainable design characteristics be evaluated primarily through the lens of material selection and durability.



Figure 1. Emeco 111 Navy Chair, (Emeco, n.d.-a)

Design for X: Fairphone Gen. 6

The Fairphone Gen. 6 is a modular smartphone designed to facilitate maintenance, repair, and component replacement (Figure 2). User-replaceable parts, spare parts support, long-term software support, and a product design that facilitates repair enable users to address malfunctioning components rather than replacing the entire device (Fairphone, n.d.; Fairphone, 2026). Academic literature also demonstrates that modularity in smartphones can support repairability, upgradability, and extended product lifespan (Schischke et al., 2019). The Fairphone Gen. 6 is therefore a strong example of how the DfX approach can be incorporated into product design, particularly through repairability, disassemblability, and modularity.



Figure 2. Fairphone Gen. 6, (Fairphone, n.d.)

Eco-design: Herman Miller Mirra 2

The Herman Miller Mirra 2 is an office chair designed with a holistic approach that considers material usage, product weight, component structure, and long-term use (Figure 3). The reduction in product weight compared to the previous Mirra model, the use of recycled materials in certain components, and the 12-year warranty demonstrate that resource use and product lifespan were considered together during

the product development process (Herman Miller, n.d.-a; Herman Miller, n.d.-b). The disassembly instructions published by the manufacturer indicate that there is a defined procedure for separating the product's components for recycling (Herman Miller, 2013). Studies on furniture design also show that environmental impact can be reduced not only through material selection but also by addressing production, service life, and end-of-life decisions collectively (Yang & Vezzoli, 2024). In this regard, the Mirra 2 has been evaluated within the framework of the Eco-Design approach, where environmental criteria are systematically incorporated into product development decisions.



Figure 3. Herman Miller Mirra 2, (Herman Miller, n.d.-a)

Cradle to Cradle (C2C): Shaw EcoWorx

Shaw EcoWorx is a tile-based flooring system that incorporates end-of-life material flow as an integral part of product design (Figure 4). Its PVC-free material composition, the ability to replace individual tile units as needed, and the manufacturer's take-back program support the product's transition into the recovery process after use (Shaw Contract, n.d.-a; Shaw Contract, n.d.-b). An academic evaluation of EcoWorx identifies the transfer of recovered technical materials into the remanufacturing cycle as one of the product system's key features (Segars et al., 2003). Therefore, EcoWorx's distinctive feature from a C2C perspective is not merely the recyclability of the material, but the fact that the end-of-life process is linked to a defined take-back and material cycle.

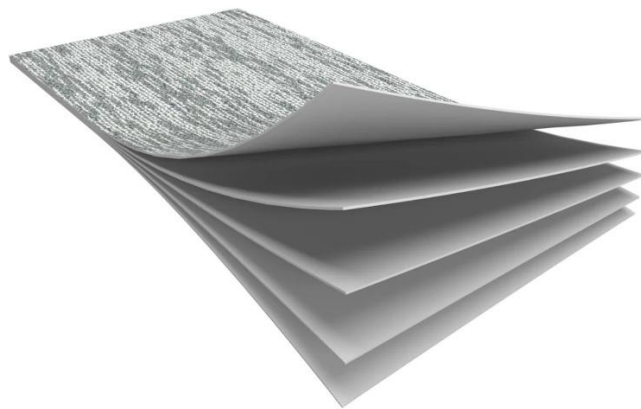


Figure 4. Shaw EcoWorx, (Shaw Contract, n.d.-a)

Life Cycle Design: Muebles LUFE – LORE Litera 90

Muebles LUFE – LORE Litera 90 is an example of wooden furniture that allows for the joint assessment of material sourcing, production, and distribution decisions throughout its life cycle (Figure 5). The use of PEFC-certified solid pine, a local raw material and production approach, and a product design based on user assembly constitute the key features of this framework (Muebles LUFE, n.d.). In a life-cycle assessment that directly examined the product, a cradle-to-grave carbon footprint of 1.71 kg CO₂e/kg was calculated; it was shown that transportation to the end user was a key factor in total greenhouse gas emissions and that a local sales scenario could reduce emissions by approximately 40% (Coloma-Jiménez et al., 2022). This result demonstrates that the product's environmental performance depends not only on material selection but also on the interplay of supply, production, and distribution decisions throughout its life cycle.



Figure 5. Muebles LUFE – LORE Litera 90, (Muebles LUFE, n.d.)

Five product reviews demonstrate that sustainable design approaches are realized at the product level through various design decisions. Key features include material selection at Emeco; a product structure at Fairphone that supports repair and component replacement; the integration of multiple environmental design criteria in Mirra 2; the material cycle between the product and the take-back system at EcoWorx; and the consideration of life cycle stages alongside product-specific environmental data in LORE Litera 90. For this reason, the products were not ranked in terms of overall environmental performance; instead, they were compared based on the common sustainable design criteria defined in the methods section (Mengistu et al., 2024). Table 3 summarizes the 50 product–criterion pairings evaluated based on the criteria defined in the methods section and the observable indicators at the product level. Decisions are not based on a mechanical scoring system or an equally weighted sum of indicators; instead, the product-specific nature of the information used, its direct relevance to the criterion, whether it is supported by multiple indicators, and the presence or absence of a design feature that limits the outcome were evaluated collectively. Therefore, “Sufficient” does not indicate that a product is generally sustainable, but rather that multiple key indicators for the relevant criterion are consistently and directly supported by product information; “Limited,” on the other hand, indicates that while positive information exists, the scope of the information or the design/implementation conditions are insufficient to fully meet the criterion. In this way, different product categories were compared without being reduced to an artificial total score (Han et al., 2021; Mengistu et al., 2024). The comparative evaluation shows that the products under review meet sustainable design criteria in line with different design priorities. While the Fairphone Gen. 6 exhibits a more integrated structure in criteria aimed at extending the product's lifespan—particularly reparability, disassemblability, and modularity—the EcoWorx stands out for its end-of-life

strategy and defined take-back system. While the use of recycled materials and durability are prominent features of the Emeco 111 Navy Chair, the Mirra 2 combines design decisions related to disassembly with those regarding material and resource use. The LORE Litera 90, on the other hand, is evaluated based on life cycle data and a local materials and production approach; however, the scope of product-level information regarding repairability, modularity, and end-of-life practices remains more limited. This distribution indicates that while the products excel in certain criteria, they do not address all dimensions of sustainable product design to the same extent (Table 3).

When these criteria are evaluated together, it becomes evident that differentiation in sustainable product design does not stem solely from the environmental qualities of the materials used; rather, it is shaped by the relationships among product structure, interactions between components, design decisions that support the product's lifespan, and end-of-life options. While decisions regarding material selection and resource efficiency influence the pre-production and production phases of a product, repairability, disassemblability, and modularity support the preservation of the product's functional value during its use phase. Reusability, recyclability, and end-of-life strategies, in turn, determine the possibilities for preserving the value of products and materials after their use. From this perspective, the key finding of the comparison is that individual design features—such as the use of recycled materials, a long service life, replaceable components, or a take-back system—do not, on their own, result in a holistic sustainable product design. A more comprehensive approach requires that these decisions be linked in a way that supports one another across the different stages of the product's life cycle.

Table 3. Comparative findings for the five products based on common sustainable design criteria.

Criterion	Emeco 111 Navy	Fairphone Gen. 6	Mirra 2	EcoWorx	LORE Litera 90
Material selection	Sufficient	Sufficient	Limited	Sufficient	Sufficient
Production / Resource Efficiency	Limited	Limited	Sufficient	Limited	Sufficient
Durability / service life	Sufficient	Sufficient	Sufficient	Sufficient	Limited
Repairability	Limited	Sufficient	Limited	Limited	Sufficient
Removability	Insufficient	Sufficient	Sufficient	Limited	Sufficient
Modularity	Insufficient	Sufficient	Limited	Limited	Limited
Reuse	Limited	Limited	Limited	Limited	Limited
Recyclability	Sufficient	Limited	Sufficient	Sufficient	Sufficient
End-of-use strategy	Limited	Sufficient	Limited	Sufficient	Limited
Life Cycle Integrity	Limited	Sufficient	Sufficient	Sufficient	Sufficient

A comparative analysis reveals that sustainable product design should be evaluated not based on the presence of individual environmental characteristics, but rather on the integrity of design decisions that interact with one another throughout the product's life cycle. While material selection and production decisions shape a product's initial resource and environmental

impacts, product structure, intercomponent relationships, reparability, disassemblability, and modularity can influence the extension of its service life and the preservation of the functional value of its components. End-of-life strategies, in turn, determine the extent to which the product, its components, and materials can be directed toward reuse, recovery, or recycling options. Therefore, features such as the use of recycled materials, long warranty periods, replaceable components, or take-back programs do not, on their own, demonstrate a holistic sustainable design approach. The key factor is establishing continuity among these design decisions throughout the life cycle and ensuring that not only the product's functional value but also the value of its components and materials is preserved as much as possible

CONCLUSION

This study compared the product-level implementations of Green Design, Design for X (DfX), Eco-Design, Cradle-to-Cradle (C2C), and Life Cycle Design approaches based on ten common sustainable design criteria. The findings indicate that sustainable product design cannot be explained by a single material property, product structure decision, or end-of-life solution; rather, decisions regarding materials, production, service life, product structure, and end-of-life must be evaluated collectively throughout the life cycle.

The study's key finding is that just because a product strongly embodies a particular sustainable design approach does not mean it performs equally well across all common metrics. The use of recycled materials in Emeco, the product design that supports repair and component replacement in Fairphone, and the combined focus on material reduction and disassembly in Mirra 2, the take-back and remanufacturing cycle at EcoWorx, and the user-assembly-based product design with lifecycle data at LORE Litera 90—have highlighted different design priorities. These differences were used not to establish a general sustainability ranking among the products, but to explain how sustainability goals translate into different design decisions.

The comparison revealed that recycled content is not the same design attribute as recyclability, nor is disassemblability the same as reparability, nor is component separability the same as functional modularity. Extending a product's service life is linked to value-preservation strategies such as maintenance, repair, and reuse; whereas the environmental benefit of modularity is associated with actual usage outcomes such as part replacement, repair, or upgrades. Similarly, recyclability does not, on its own, constitute a comprehensive end-of-life strategy when there are no defined take-back, separation, or recovery pathways.

The study's key contribution lies in comparing the design decisions highlighted at the product level by different sustainable product design approaches within a common evaluation framework, rather than explaining them solely through their theoretical characteristics. However, the fact that the products belong to different categories and that the scope of product-specific academic studies, LCA/EPD, technical documentation, repair, and end-of-life information varies across products constitutes the main limitations of the comparison. Therefore, the evaluations do not indicate the products' absolute environmental performance or overall level of sustainability, but rather demonstrate the extent to which the criteria defined based on the available product-specific information are reflected in the product design. In future studies, it would be beneficial to test the framework on broader sample groups within similar functional and product categories, using data on physical disassembly, repair, access to replacement parts, reuse, and recovery.

In conclusion, sustainable product design should be approached not merely as the combination of individual environmental characteristics, but as the integrity of design decisions that support the preservation of a product's functional, component, and material value throughout its life

cycle. Material selection, production methods, product structure, maintenance and repair options, and end-of-life scenarios are not independent of one another; a decision made at one stage can either expand or limit subsequent life-cycle options. Therefore, the fundamental design question is not merely “How can a product with a lower environmental impact be designed?” but also “How can the value of the product, its components, and its materials be preserved throughout the life cycle through design?”

REFERENCES

- Amend, C., Revellio, F., Tenner, I., & Schaltegger, S. (2022). The potential of modular product design on repair behavior and user experience – Evidence from the smartphone industry. *Journal of Cleaner Production*, 367, 132770. <https://doi.org/10.1016/j.jclepro.2022.132770>
- Assyraq Ibrahim, N., & Putri, S. A. (2025). Integration of design for disassembly method using recycled mahogany material in modular furniture. *Mobilya ve Ahşap Malzeme Araştırmaları Dergisi*, 8(1), 88–99. <https://doi.org/10.33725/mamad.1674449>
- Bakker, C., Wever, R., Teoh, C., & De Clercq, S. (2010). Designing cradle-to-cradle products: A reality check. *International Journal of Sustainable Engineering*, 3(1), 2–8. <https://doi.org/10.1080/19397030903395166>
- Bonvoisin, J., Halstenberg, F. A., Buchert, T., & Stark, R. (2016). A systematic literature review on modular product design. *Journal of Engineering Design*, 27(7), 488–514. <https://doi.org/10.1080/09544828.2016.1166482>
- Bracquen , E., Peeters, J., Alfieri, F., Sanfelix, J., Duflou, J., Dewulf, W., & Cordella, M. (2021). Analysis of evaluation systems for product repairability: A case study for washing machines. *Journal of Cleaner Production*, 281, 125122. <https://doi.org/10.1016/j.jclepro.2020.125122>
- Ceschin, F., & Gaziulusoy,  . (2016). Evolution of design for sustainability: From product design to design for system innovations and transitions. *Design Studies*, 47, 118–163. <https://doi.org/10.1016/j.destud.2016.09.002>
- Ceschin, F., & Gaziulusoy,  . (2020). Design for sustainability: A multi-level framework from products to socio-technical systems. Routledge. <https://doi.org/10.4324/9780429456510>
- Coloma-Jim nez, M., Akizu-Gardoki, O., & Lizundia, E. (2022). Beyond ecodesign, internationalized markets enhance the global warming potential in the wood furniture sector. *Journal of Cleaner Production*, 379, 134795. <https://doi.org/10.1016/j.jclepro.2022.134795>
- Cordella, M., Alfieri, F., Clemm, C., & Berwald, A. (2021). Durability of smartphones: A technical analysis of reliability and repairability aspects. *Journal of Cleaner Production*, 286, 125388. <https://doi.org/10.1016/j.jclepro.2020.125388>
- Cordella, M., Alfieri, F., Sanfelix, J., Donatello, S., Kaps, R., & Wolf, O. (2020). Improving material efficiency in the life cycle of products: A review of EU Ecolabel criteria. *The International Journal of Life Cycle Assessment*, 25, 921–935. <https://doi.org/10.1007/s11367-019-01608-8>
- Dangal, S., Faludi, J., & Balkenende, R. (2022). Design aspects in repairability scoring systems: Comparing their objectivity and completeness. *Sustainability*, 14(14), 8634. <https://doi.org/10.3390/su14148634>
- De Fazio, F., Bakker, C., Flipsen, B., & Balkenende, R. (2021). The Disassembly Map: A new method to enhance design for product repairability. *Journal of Cleaner Production*, 320, 128552. <https://doi.org/10.1016/j.jclepro.2021.128552>
- Emeco. (n.d.-a). 111 Navy Chair. <https://www.emeco.net/products/111-navy-chair-dark-blue>
- Emeco. (n.d.-b). Recycled PET. <https://www.emeco.net/about/sustainability/recycled-pet>
- Fairphone. (n.d.). The Fairphone (Gen. 6). <https://www.fairphone.com/the-fairphone-gen-6>
- Fairphone. (2026). Impact report 2025. <https://www.fairphone.com/impact-report>

- Han, J., Jiang, P., & Childs, P. R. N. (2021). Metrics for measuring sustainable product design concepts. *Energies*, 14(12), 3469. <https://doi.org/10.3390/en14123469>
- He, X., Su, D., Cai, W., Pehlken, A., Zhang, G., Wang, A., & Xiao, J. (2021). Influence of material selection and product design on automotive vehicle recyclability. *Sustainability*, 13(6), 3407. <https://doi.org/10.3390/su13063407>
- Herman Miller. (2013). Mirra 2 disassembly for recycling. https://www.hermanmiller.com/content/dam/hermanmiller/documents/environmental/recycling/Mirra_2_Chairs_Recycling_Instructions.pdf
- Herman Miller. (n.d.-a). Mirra 2 chair: Design story. <https://www.hermanmiller.com/products/seating/office-chairs/mirra-2-chair/design-story/>
- Herman Miller. (n.d.-b). Mirra 2 chair: Specifications. <https://www.hermanmiller.com/products/seating/office-chairs/mirra-2-chair/specs/>
- Inselmann, P., Deutschmann, T., & Krause, D. (2025). Enhancing end-of-life sustainability through modularity and interface design in product development. *Proceedings of the Design Society*, 5, 1525–1534. <https://doi.org/10.1017/pds.2025.10166>
- Lee, A. W. L., Chung, S. Y., Tan, Y. S., Koh, S. M. H., Lu, W. F., & Low, J. S. C. (2023). Enhancing the environmental sustainability of product through ecodesign: A systematic review. *Journal of Engineering Design*, 34(10), 814–843. <https://doi.org/10.1080/09544828.2023.2261094>
- Mengistu, A. T., Dieste, M., Panizzolo, R., & Biazzo, S. (2024). Sustainable product design factors: A comprehensive analysis. *Journal of Cleaner Production*, 463, 142260. <https://doi.org/10.1016/j.jclepro.2024.142260>
- Mesa, J. A., González-Quiroga, A., Aguiar, M. F., & Jugend, D. (2022). Linking product design and durability: A review and research agenda. *Heliyon*, 8(9), e10734. <https://doi.org/10.1016/j.heliyon.2022.e10734>
- Muebles LUFÉ. (n.d.). LORE litera 90. <https://muebleslufe.com/literas-infantiles-y-adultos/litera-90>
- Ruiz-Pastor, L., & Mesa, J. A. (2023). Proposing an integrated indicator to measure product repairability. *Journal of Cleaner Production*, 395, 136434. <https://doi.org/10.1016/j.jclepro.2023.136434>
- Schischke, K., Proske, M., Nissen, N. F., & Schneider-Ramelow, M. (2019). Impact of modularity as a circular design strategy on materials use for smart mobile devices. *MRS Energy & Sustainability*, 6, E16. <https://doi.org/10.1557/mre.2019.17>
- Segars, J. W., Bradfield, S. L., Wright, J. J., & Realff, M. J. (2003). EcoWorx, green engineering principles in practice. *Environmental Science & Technology*, 37(23), 5269–5277. <https://doi.org/10.1021/es034576a>
- Shaw Contract. (n.d.-a). EcoWorx. <https://www.shawcontract.com/en-us/technicalpage/ecoworx-%281%29>
- Shaw Contract. (n.d.-b). re[TURN] recycling program. <https://www.shawcontract.com/en-us/sustainability/commercial-flooring-recycle-program>
- Wu, X., Gao, Q., & Li, W. (2025). Design for recycling: A systematic review of approaches for enhancing product recyclability. *Sustainability*, 17(5), 1790. <https://doi.org/10.3390/su17051790>
- Yang, D., & Vezzoli, C. (2024). Designing environmentally sustainable furniture products: Furniture-specific life cycle design guidelines and a toolkit to promote environmental performance. *Sustainability*, 16(7), 2628. <https://doi.org/10.3390/su16072628>