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Design for Low-Carbon Lifecycle (DfLCL): A conceptual framework

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Abstract

This study presents a literature review on low-carbon product design, analyzing approaches at each stage of product development: concept development, system-level design, detail design, testing and refinement, and production ramp-up. Using Scopus, 455 articles were initially screened to identify strategies that integrate lifecycle perspectives and reduce carbon emissions throughout the product lifecycle. The findings highlight existing methods, identify gaps, and propose enhancements, providing actionable propositions for each stage to align design practices with low-carbon objectives. This research offers a structured roadmap for practitioners and contributes to advancing sustainable product design in support of the global shift toward a low-carbon economy.

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Keywords: low-carbon; decarbonisation; product development; sustainability.

1. Introduction

Climate change is widely recognised as one of the most critical global challenges, largely driven by substantial CO_2 emissions from production, transportation, and consumption activities [1]. The need for decarbonisation and sustainable practices is becoming increasingly essential, and companies that continue to compete solely on cost, quality, and agility will lose competitiveness [2]. The measurement of carbon footprint in companies is usually viewed from different perspectives: the organisational level, which includes carbon emission categorisation into Scope 1 (direct emissions from owned or controlled sources), Scope 2 (indirect emissions from the generation of purchased energy), and Scope 3 (all indirect emissions not included in Scope 2 that occur both upstream and downstream in the value chain of the company), and the product level, which includes measurement from raw material to the end of life of products [1]. The design phase determines 70% of the environmental performance of the product, which covers complex life cycle information and diversified constraints [3]. Low-carbon product design is the process of creating a product with emissions considered across its complete life cycle while maximising pertinent elements of product design, manufacturing, storage and transit, distribution and use, as well as recycling and reuse, to lower greenhouse gas emissions throughout the product's life cycle [2,4]. In contrast to ecodesign, a method integrated into product design to lessen environmental impacts, low-carbon product design focuses on deploying carbon footprint models considering a range of variables to determine the best design path by assessing the product's carbon footprint [5, 2]. The result of low-carbon design is the determination of optimal design solutions, including material selection, process planning, and other factors based on the constraints of life cycle design information [3]. Two general approaches targeted at carbon footprint for sustainable design have been developed within the academic literature: design methods to reduce carbon footprint and carbon footprint modelling [5]. Existing research, nevertheless, has recognised that current low-carbon design methods tend to focus on specific stages of the design process [5], and the best

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choices are frequently overlooked when considering the complete product lifecycle [6]. Existing methods often fail to create low-carbon design solutions across the entire product lifecycle [5].

We posit that developing products fit for a low-carbon economy requires considering different aspects of the product lifecycle from the design phase (the design-for-X thinking), which includes the perspective of the entire value chain. In other words, designing for a low-carbon lifecycle ranges from using product carbon footprint assessment tools to simultaneously considering supply chain activities [5] and the perspective of multiple product lifecycles [6,7], in alignment with recent studies proposing a holistic carbon footprint assessment that encompasses the entire supply chain and is applied across all manufacturing companies and products [8-11]. In this study, we review the literature on low-carbon product design to identify actionable changes or enhancements to current design approaches to better align with low-carbon objectives.

2. Approaches to sustainable design

Various approaches to sustainable design have been discussed in the academic literature, each offering unique strategies to reduce the environmental and social impact of products and systems throughout their lifecycle. The design for environment (DfE) is a comprehensive approach that seeks to minimise environmental impacts across the entire lifecycle, from raw material extraction to end-of-life disposal or recycling [12, 13]. The core principles of DfE include [14]: material selection and resource efficiency (selecting renewable, biodegradable, or recyclable materials), efficient use of materials—often referred to as “lightweighting,” energy efficiency (prioritising manufacturing methods that consume less energy or use it more efficiently, designing products that consume less energy during their use phase), waste reduction and pollution prevention (minimising waste in production, promoting pollution prevention), design for durability and repairability, and end-of-life considerations (recycling and disposal).

The cradle-to-cradle (C2C) philosophy advocates creating products with a lifecycle that mirrors natural systems, where waste is viewed as a resource, allowing materials to be continuously cycled in closed-loop systems [15]. Unlike traditional linear models that follow a "take-make-dispose" approach, C2C envisions a circular lifecycle, where products are designed to either biodegrade safely into the environment or be reclaimed and reused indefinitely in industrial cycles [16]. C2C differentiates between two types of cycles: biological and technical. Biological cycles involve materials that can safely return to the environment as nutrients, such as biodegradable packaging or compostable materials. Technical cycles involve materials that can be perpetually circulated within industrial systems, like metals and synthetic polymers, without degradation in quality [15].

The life cycle assessment (LCA)-based design is a systematic approach to evaluating the environmental impacts of a product, process, or system across its entire lifecycle. Originating from methodologies developed in the 1960s and 1970s for energy analysis, LCA became formalised in the 1990s with the establishment of international standards, notably the ISO 14040 series [17]. LCA-based design integrates these principles into the design process, providing a framework to assess the environmental implications of every stage of a product's lifecycle, from raw material extraction to manufacturing, usage, and disposal [18]. The goal of LCA-based design is to identify "hot spots"—areas in the lifecycle with significant environmental impact—and make informed design choices to reduce these impacts [18].

Ecodesign incorporates environmental considerations into the earliest stages of product development to reduce the environmental impacts across a product's lifecycle—from raw material extraction to end-of-life disposal or recycling [19, 20]. A fundamental principle of ecodesign is the minimisation of resource consumption, which encourages designers to reduce the use of raw materials and natural resources wherever possible. Research demonstrates that lightweighting, a common strategy in ecodesign, is especially effective in industries such as automotive and aerospace, where reducing material use can significantly improve fuel efficiency and lower emissions [21]. Another critical principle in ecodesign is the selection of environmentally friendly materials. By opting for materials that are non-toxic, biodegradable, or recyclable, designers can reduce potential health hazards and minimise harm to ecosystems [22]. Energy efficiency is also a central focus of ecodesign, particularly for products with high energy demand during their operational phase. The product’s end-of-life phase is also crucial in ecodesign, which involves designing products that are easier to recycle, disassemble, or dispose of safely, promoting a circular economy.

Biomimicry draws inspiration from nature to address human challenges by emulating biological forms, processes, and ecosystems [23]. This principle is based on the observation that organisms and ecosystems have evolved highly efficient strategies for survival, optimised for resource use, resilience, and sustainability [24]. These evolved strategies enable organisms to thrive within ecological niches with minimal environmental impact, providing a model for human designs that prioritise environmental compatibility [25]. A central concept in biomimicry is closed-loop systems, a defining characteristic of natural ecosystems where waste generated by one organism serves as a resource for another, maintaining balance and minimising resource depletion [26]. By adopting closed-loop principles, biomimetic designs aim to minimise waste and maximise material efficiency, a concept gaining traction in industrial ecology and sustainable manufacturing [27].

Circular economy design (CED) shifts away from the "take-make-dispose" model of production towards a regenerative system where resources are continually cycled back into the economy [27]. CED promotes designing products with circularity, extending product lifespans, encouraging reuse, and facilitating end-of-life recycling to reduce waste and conserve resources [28]. This concept, rooted in industrial ecology and systems thinking, designs products to function within closed-loop systems where waste from one process becomes the input for another [29]. CED emphasises designing for durability, repairability, and recyclability, making products easier to disassemble, upgrade, and refurbish. These strategies help reduce the need for virgin materials [27].

Green design focuses on reducing environmental impacts by prioritising resource efficiency, pollution reduction, and sustainable material use. Unlike CED, which encompasses the entire lifecycle and resource regeneration, green design often centres on specific lifecycle stages, like material sourcing, manufacturing, and usage, to minimise environmental impacts [30, 31].

Socially responsible design extends beyond environmental concerns, incorporating social and ethical dimensions. This philosophy, sometimes referred to as "design for social good," acknowledges that design decisions profoundly impact individuals and communities and seeks to ensure these impacts are positive [32]. Socially responsible design focuses on creating products and systems that meet the needs of underserved populations, support inclusive development, and contribute to a fairer and more equitable society [33]. Table 1 summarises the key features of the sustainable design approaches.

Despite significant advancements in sustainable design, gaps remain that could hinder the development of products fit for a low-carbon economy. One main issue is the lack of explicit carbon emission prioritisation in many sustainable design approaches. While frameworks such as ecodesign and cradle-to-cradle emphasise broad environmental impacts, they often lack a focused approach to directly reducing carbon emissions. Another gap is the integration of renewable energy within product life cycles. Most current sustainable design models do not explicitly incorporate renewable energy sources, especially in energy-intensive products. Scalability and economic feasibility present additional challenges, particularly for approaches promoting closed-loop systems. For products with multiple lifecycles, it is also necessary to account for carbon emissions across lifecycles to support design decisions [6]. Emissions should be assessed holistically, considering the whole value chain involved in the multiple lifecycles. Social equity in carbon reduction is another critical aspect often overlooked. Integrating social equity with carbon reduction strategies ensures that the shift to a low-carbon economy is inclusive, addressing social disparities while promoting environmental goals. Furthermore, the lack of cross-disciplinary tools and standardised frameworks creates inconsistencies across industries, limiting the scalability and effectiveness of sustainable design practices. Developing a unified framework could provide industries with a consistent foundation for aligning sustainable design practices across sectors, enabling a more coherent and scalable transition to a low-carbon economy.

Table 1. Sustainable design approaches.

Approach	Key focus & principles	Unique features
Design for Environment (DfE)	Minimize environmental impact from material extraction to disposal; prioritize sustainable material use, energy efficiency, waste reduction [12, 13, 14]	Full lifecycle approach; aligns with environmental regulations
Cradle-to-Cradle (C2C)	Closed-loop systems, biological/technical cycles to reuse materials indefinitely [15, 16]	Distinguishes between biodegradable (biological) and recyclable (technical) cycles
Life Cycle Assessment (LCA)-based Design	Uses LCA to quantify environmental impacts; targets "hot spots" for design improvements [17, 18]	Analytical, data-driven; formalized through ISO standards
Ecodesign	Incorporates environmental impact from development stages; emphasizes resource and energy efficiency, recyclable design [19, 20, 21, 22]	Focus on reducing raw material use and creating energy-efficient designs
Biomimicry	Emulates nature's efficient and resilient systems; adopts closed-loop principles [23, 24, 25, 26]	Inspired by biological models; promotes harmony with ecosystems
Circular Economy Design (CED)	Designs for product longevity, reusability, and recyclability; aims for regenerative systems [27, 28, 29]	Strong focus on durability, repairability, and closed-loop systems
Green Design	Resource efficiency, pollution reduction, sustainable material sourcing [30, 31]	Often targets specific lifecycle stages, not always full lifecycle
Socially Responsible Design	Prioritizes social and ethical impacts, equity, and inclusivity [32, 33]	Focus on social impact, underserved communities, and ethical concerns

3. Methods

This study employs a systematic literature review to investigate existing methods for low-carbon product design and identify remaining opportunities to support the development of low-carbon products. The systematic review process followed established guidelines to ensure rigour and transparency [34]. The literature search was conducted using the Scopus database, selected for its extensive coverage of peer-reviewed journals and publications in engineering, environmental science, and related disciplines [35]. To ensure comprehensive coverage of relevant literature, we defined keywords that captured both the concept of low-carbon design and its application within product development processes. Specifically, the search terms used were "low carbon product", "low carbon" AND "product design" OR "product development". The initial search yielded 455 articles, which formed the foundational pool for further screening. The initial set of articles was screened by reading the titles, abstracts, and keywords. Studies were included if they directly addressed low-carbon product design methods, product development strategies targeting carbon reduction, or lifecycle approaches to low-carbon product development. Studies not explicitly focused on low-carbon objectives or lacking a direct connection to product design or development stages were excluded. After the final selection of relevant studies (76 studies), a data extraction process was conducted, capturing key information on the design methods proposed, the product development stages addressed, and the extent to which a lifecycle perspective was incorporated. This allowed us to map existing design methods to stages and to analyse whether studies incorporated a lifecycle approach, a critical perspective for low-carbon design given its emphasis on end-to-end carbon impact reduction. The extracted data was then synthesised according to the stages of product development. Based on the synthesis of findings, propositions were developed, each associated with a specific stage of the product development process. These propositions were formulated to offer actionable changes or enhancements to current design approaches to better align with low-carbon objectives and form the basis for the further development of a Design for Low-Carbon Lifecycle (DfLCL) approach.

4. Results

The results were structured according to the phases of product development as proposed by Ulrich and Eppinger (2012) [36], which cover: i) concept development, ii) system-level design, iii) detail design, iv) testing and refinement, and v) production ramp-up. Overall, the proposed approaches covered more than one stage of the product development process, and most of the literature on the topic is quite recent.

4.1. Concept development

Studies emphasise the importance of setting low-carbon objectives at the outset to guide design decisions throughout the product's lifecycle. Examples of recent studies include Zhang et al. (2024) [37], who emphasise carbon footprint allocation as a critical factor in conceptualisation, suggesting an optimisation model that integrates carbon impact assessments early in the design process. Another study by Wu (2024) [38] addresses the importance of postponement strategies in green product family design. This approach introduces a bilevel optimisation model to manage low-carbon product configuration while minimising carbon emissions based on shifting consumer demands. Zou et al. (2023) [39] introduce a bi-objective product configuration model that integrates product cost and carbon-neutral expenditure, providing a structure for balancing economic performance with environmental impact early in the design process. Li et al. (2024) [40] examine policy interactions and the effect of carbon quota allocation on product strategy selection. By aligning concept development with government-imposed carbon quotas, the authors posit that companies can optimise their design approach to meet emissions regulations while meeting market demand for low-carbon products. This integration of regulatory frameworks into concept design ensures that the entire product lifecycle aligns with low-carbon objectives. Gao et al. (2023) [41] propose establishing carbon emission factors as critical parameters in product ideation. One key limitation in this phase is the challenge of balancing carbon efficiency with other design constraints. The literature reveals that current conceptual design tools often lack the capability to incorporate emerging technologies, such as bio-based materials or advanced recycling processes, that could significantly alter the carbon footprint of a product. This restricts the ability of designers to explore innovative low-carbon solutions.

Proposition 1: To address these challenges, the concept development phase should adopt integrated predictive modelling that simulates lifecycle carbon impacts and financial trade-offs of various design options. These tools should allow for the integration of emerging materials, advanced recycling technologies, and regulatory considerations. By enabling dynamic scenario modelling, designers can explore multiple design pathways and assess their carbon implications over the entire product lifecycle.

4.2. System-level design

System-level design involves defining the product architecture and selecting materials and components that will determine the carbon efficiency of the final product. Zhang et al. (2024) [37] propose a structural topology optimisation that incorporates carbon footprint considerations in material selection and component structure. Another study by Li, Lan, and Jin (2024) [42] delves into low-carbon supply chain strategy, where system-level decisions such as channel selection and carbon trading impact the entire production ecosystem. This approach underscores the importance of designing product systems that are inherently low carbon by facilitating decisions on supplier selection and material usage that align with carbon reduction goals. Furthermore, the study by Bai et al. (2024) [43] suggests decarbonising product portfolios through the strategic elimination of high-emission products, thereby optimising the entire system-level design to prioritise low-carbon items in the product lineup. Xiang et al. (2023) [44] propose a novel product-service system (PSS) configuration model that incorporates a greenhouse gas structure tree, enabling designers to visualise the carbon footprint across product and service modules.

A limitation in current system-level design approaches is the lack of integrated assessment tools that can evaluate the cumulative carbon impacts of decisions made across different subsystems. Therefore:
Proposition 2: System-level design should incorporate holistic lifecycle assessment frameworks that evaluate carbon impacts across all subsystems and support trade-off analysis between different design strategies. These frameworks should facilitate the quantification of lifecycle benefits associated with modular designs, such as reduced emissions through enhanced repairability and recyclability, considering products' multiple lifecycles.

4.3. Detail design

The detail design stage is where more precise specifications for materials, manufacturing processes, and components are defined, making it a critical phase for achieving low-carbon outcomes. Fracchia and Mus (2024) [45] demonstrate, for example, the use of secondary aluminium alloys in producing low-carbon e-mobility components, showcasing how recycled materials can significantly lower the carbon footprint of high-volume production. In addition, He et al. (2024) [46] analyse product line design in low-carbon supply chains, emphasising configuring product lines to cater to environmentally aware consumers. Lin et al. (2023) [47] present an evaluation framework combining the analytic hierarchy process (AHP) and deep learning aimed at evaluating and refining product designs for sustainability. He et al. (2023) [41] contribute to the detailed design phase by introducing multibody dynamics analysis to optimise the structural performance and carbon footprint. Their model integrates dynamic load simulations with carbon impact metrics, providing insights into structural modifications that minimise carbon emissions while maintaining functionality. While sustainable materials, such as recycled metals and bio-based polymers, offer potential for carbon reduction, their adoption is often hampered by inconsistent supply chains and a lack of standardised evaluation criteria. Many studies, including Lin et al. (2023) [47], emphasise the need for multi-criteria decision-making frameworks that can evaluate materials based on carbon footprint, cost, and performance attributes. These multi-criteria approaches should also consider other aspects related to component decisions beyond material choices to integrate emissions into the value chain.

Proposition 3: Multi-criteria evaluation frameworks for material, process selection, and component specification should be considered in detail design, prioritising carbon footprint reduction alongside technical and economic factors.

4.4. Testing and refinement

The testing and refinement phase allows for validation of design choices and optimisation for improved carbon efficiency. He et al. (2023) [41], for example, demonstrate the use of kinematic analysis to optimise structural designs of offshore platforms, showing how simulation tools can reduce the carbon footprint by refining designs based on operational conditions. This phase is crucial for ensuring that low-carbon goals are met under real-world conditions and for making adjustments that enhance both performance and sustainability. Luo et al. (2023) [48] address this stage by using quantum evolutionary algorithms in production line optimisation, refining product family configurations in response to test results and emissions data. This iterative approach allows companies to dynamically adjust configurations based on testing outcomes, enhancing carbon efficiency while accommodating evolving market demands and production variables. A notable gap in this phase is that carbon reduction efforts are often reactive rather than proactive, focusing on optimising existing designs rather than exploring alternative configurations that might achieve greater carbon savings. Moreover, there is also a limited integration of consumer-driven data into the testing process. Therefore: Proposition 4: Iterative lifecycle simulation and assessment processes during testing and refinement should be considered, allowing for continuous evaluation of how design adjustments impact emissions throughout the lifecycle. This should include the integration of consumer feedback into refinement processes.

4.5. Production ramp-up

In the production ramp-up phase, emphasis is placed on integrating low-carbon practices across the supply chain to support scalable production. Li, Cui, and Song (2024) [49] focus on channel selection for low-carbon products within competitive markets. They employ game models to evaluate the trade-offs of different distribution channels under carbon constraints, providing guidance for companies aiming to minimise emissions in logistics and distribution. Ke et al. (2023) [6] introduce an integrated remanufacturing design model aimed at optimising carbon emissions in the reuse of product materials. By employing a multi-constrained objective model and an improved bald eagle search algorithm, they successfully minimise emissions in remanufacturing scenarios. This method supports sustainable ramp-up by extending the lifecycle of materials through low-carbon remanufacturing. He et al. (2023) [41] also present a digital twin-driven framework that integrates real-time data for continuous carbon monitoring and optimisation during production. By connecting physical and virtual entities, the digital twin framework enables adaptive production processes that respond to real-time carbon data, enhancing the scalability of low-carbon manufacturing.

A major limitation during production ramp-up is the variability in carbon performance across different production sites, which can lead to inconsistencies in achieving low-carbon objectives. Additionally, the complexity of coordinating low-carbon supply chains poses challenges in aligning the carbon reduction goals of different suppliers. Therefore:

Proposition 5: Companies should develop collaborative carbon management frameworks that integrate carbon reduction practices across the entire supply chain and production network. These frameworks should include real-time carbon monitoring tools, standardised protocols for low-carbon supplier engagement, and adaptive production line configurations that facilitate the adoption of low-carbon processes. Emphasising cross-industry collaboration and technology sharing can help companies overcome the challenges of scaling low-carbon practices while maintaining consistent emissions reductions.

5. Conclusions

This study conducted a systematic literature review to explore low-carbon product design methods and identify adaptations across product development stages. Its main contribution is mapping low-carbon design strategies to each development phase, offering a roadmap for design teams and manufacturers to prioritise carbon reduction throughout the product lifecycle. This approach highlights the importance of addressing carbon reduction comprehensively, from conceptualisation to production ramp-up. Collaborative frameworks are emphasised, particularly in the production ramp-up phase, advocating for coordinated low-carbon practices across supply chains as production scales.

The findings provide practical guidance for industries transitioning to low-carbon economies, recommending lifecycle-oriented strategies that address direct emissions, material choices, supply chain configurations, and consumer usage. This holistic approach can help create environmentally responsible and economically viable products. Limitations include reliance on the Scopus database, which may not capture all relevant literature, and the rapid evolution of low-carbon design, which may outdate some studies. Future research could expand by using multiple databases and incorporating insights from industry practitioners to enhance understanding of real-world low-carbon design applications.

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