Application of modular design strategy in the life cycle of household appliances under the goal of carbon neutrality

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Abstract: Modular design, a key strategy for achieving carbon neutrality in home appliances, provides a systematic solution for the industry's green transformation by restructuring carbon footprint management across all stages of the product lifecycle. This study systematically analyzes the application mechanisms of modular design in the design, production, use, and recycling stages of home appliances, revealing its carbon reduction benefits through three pathways: extending product lifespan, improving resource utilization efficiency, and promoting a circular economy. The study shows that home appliances employing modular design can reduce carbon emissions over their entire lifecycle by over 30%, with reductions of 15% in production, 10% in use, and 5% in recycling. The study further explores challenges facing modular design, including technical standards, market acceptance, and policy support, and proposes strategies such as establishing an open modular platform, innovating service models, and strengthening the standard system. Finally, the study explores the potential of modular design, enabled by digital technology, intelligent carbon management, business model innovation, and the construction of cross-industry circular systems, providing theoretical basis and practical guidance for the home appliance industry's path to carbon neutrality.

Keywords: Modular design; Carbon neutrality; Home appliances; Life cycle assessment; Circular economy; Carbon emission reduction

1 INTRODUCTION

In the context of global climate change response, carbon neutrality has become the core goal of national policies and industrial transformation. As an important area of energy consumption and carbon emissions, the home appliance industry faces the pressure of reducing emissions throughout its entire life cycle, from production to recycling. Traditional home appliance designs are often based on function priority or cost orientation, which makes the products difficult to repair, upgrade or recycle, not only increasing resource waste but also exacerbating carbon emissions [1]. Therefore, exploring sustainable design strategies has become an urgent need for industry, and modular design is regarded as one of the important paths to achieve low carbonization of home appliances due to its flexibility, scalability and environmental friendliness.

Modular design is not a new concept. It originated from standardization and division of labor in industrial manufacturing. However, with the rise of green manufacturing and circular economy, its connotation has gradually shifted from efficiency optimization to sustainable development. Modular design decomposes products into independent functional units, allowing each module to be developed, replaced or upgraded separately, thereby extending product life, reducing maintenance difficulty, and improving resource recycling [2]. This design concept is highly consistent with the goal of carbon neutrality, especially in reducing carbon emissions in the process of raw material mining, production energy consumption and waste disposal.

This study aims to systematically analyze how modular design strategies can help achieve carbon neutrality goals throughout the life cycle of home appliances. By combining through the theoretical basis of modular design and combining it with practical cases in the home appliance industry, this study explores its specific applications and emission reduction benefits in the design, production, use, and recycling stages [3]. The research methods include literature review, life cycle assessment (LCA), and comparative analysis of typical products to reveal the advantages and challenges of modular design and provide theoretical support and practical reference for the low-carbon transformation of the home appliance industry.

2 THEORETICAL BASIS OF MODULAR DESIGN STRATEGY

The core of modular design is to decompose complex systems into independent yet collaborative functional units. This concept originates from system engineering and product architecture theory. Its basic principles include functional independence, interface standardization, and module interchangeability, which enable products to flexibly adapt to changes in different needs [4]. In the field of home appliances, modular design can not only simplify the manufacturing process, but more importantly, it provides a structural basis for product maintenance, upgrading, and recycling. By defining clear module boundaries and universal interfaces, manufacturers can significantly reduce production complexity, while consumers can replace specific modules instead of the entire machine according to their needs, thereby reducing resource waste at the source. This design thinking breaks the limitations of the "production-use-disposal" model in the traditional linear economic model and provides a technical implementation path for the circular economy [5].

From the perspective of the product life cycle, modular design is deeply related to environmental performance at each stage. In the early stages of product development, modular architecture allows designers to optimize each module for different life cycle stages, such as using easily disassembled structures or environmentally friendly materials. After entering the production stage, standardized modules can achieve economies of scale and reduce energy and material consumption. During the use and maintenance phase, the replaceable module design significantly extends the product lifespan and prevents premature scrapping due to local failures [6]. When the product reaches the end of its life cycle, the modular feature enables valuable components and materials to be efficiently separated and re-entered into the production cycle. This full-chain optimization capability makes modularity a key link between product design innovation and sustainable development goals.

Under the framework of sustainable development, the role of modular design has gone beyond simple technical optimization and evolved into a systematic solution. Through innovation in physical architecture, it effectively addresses multiple challenges such as resource efficiency, carbon emission reduction, and circular economy. From an environmental perspective, modularity reduces carbon emissions in the process of material mining and processing; from an economic perspective, it creates new business models such as module leasing and upgrading services; from a social perspective, it improves product accessibility and fairness. Especially driven by the goal of carbon neutrality, modular design is transforming from an optional strategy to a necessary choice. Its value is not only reflected in the improvement of individual products, but also in its leverage role in promoting the transformation of the entire home appliance industry to a green and low-carbon paradigm [7]. This transformation requires collaborative innovation in design methods, manufacturing processes, and consumption patterns, and modularity provides a feasible technical foundation for this collaboration.

3 LIFE CYCLE ANALYSIS OF HOUSEHOLD APPLIANCES UNDER THE GOAL OF CARBON NEUTRALITY

The environmental impact of home appliances runs through the entire life cycle chain from raw material acquisition to final disposal, and each stage generates a unique carbon footprint. In the design stage, product architecture and material selection often lock in more than 80% of the product's life cycle environmental impact, but traditional design methods rarely systematically consider the carbon emission reduction needs of subsequent stages. The production stage concentrates high-energy manufacturing processes and complex supply chain networks, especially metal processing, injection molding and other processes that are directly related to a large amount of greenhouse gas emissions. Although the use stage reduces single-use emissions due to improved energy efficiency, the frequent replacement caused by the shortened product life has increased the overall carbon burden [8]. The recycling stage faces technical bottlenecks in the treatment of electronic waste. Currently, only a small number of materials can be effectively recycled, and many valuable resources are eventually landfilled or incinerated, causing secondary pollution and carbon emissions. This carbon accumulation effect throughout the entire life cycle makes the home appliance industry one of the areas that need to be broken through to achieve the goal of carbon neutrality.

An in-depth analysis of the carbon emission hotspots in the life cycle of home appliances reveals several key contradictions. The mining and refining of raw materials consumes a lot of energy, but the proportion of recycled materials used is still relatively low; although the production process is constantly being optimized, the application of flexible manufacturing and clean energy has not yet been popularized; there is a significant gap between consumer usage habits and product energy efficiency, and the potential of intelligent and energy-saving design has not been fully released; the imperfection of the recycling system leads to high disassembly costs, and insufficient economic efficiency restricts the realization of closed-loop circulation [9]. These challenges are intertwined, forming structural barriers, making the emission reduction efforts of a single link often ineffective. Especially in the context of global division of labor, the transfer and leakage of carbon emissions are more complicated, requiring a solution that is coordinated across the entire value chain.

The current mainstream design strategies in the home appliance industry have shown obvious limitations in responding to the challenge of carbon neutrality. Although integrated design reduces manufacturing costs, it sacrifices maintainability and upgradeability; the business strategy of planned obsolescence stimulates consumption but runs counter to the principles of sustainable development; material selection focuses on performance and cost, ignoring carbon footprint and circular compatibility; and product end-of-life design is generally missing, resulting in low recycling efficiency [10]. These traditional practices are rooted in the linear economic model and are difficult to adapt to the new requirements under the carbon neutrality goal. Crucially, existing design methods lack systematic tools for assessing the carbon impact of a product's entire life cycle, making it difficult to strike a balance between environmental and economic benefits when making decisions. This limitation is becoming increasingly prominent as the pace of carbon neutrality accelerates, necessitating design innovation to overcome development bottlenecks.

4 APPLICATIONS OF MODULAR DESIGN IN THE LIFE CYCLE OF HOME APPLIANCES

Embedding modular concepts at the source of product design can fundamentally reshape the environmental performance of home appliances. By breaking down the entire appliance into independent modules with clear functions, designers can select the most appropriate low-carbon materials and manufacturing processes based on the characteristics of each module. Such as the shell module can be made of recycled plastics or bio-based materials, while the core electronic module optimizes the circuit design to reduce the use of rare metals. This modular material strategy not only reduces the overall carbon footprint but also lays the foundation for subsequent recycling. More importantly, modular architecture allows high-carbon modules to be gradually replaced as technological advances without changing the overall design, enabling products to dynamically adapt to evolving environmental standards [11]. This forward-looking design thinking breaks the dilemma in traditional product development where environmental goals often give way to functional requirements and provides new possibilities for innovation under the goal of carbon neutrality.

The carbon emission reduction potential of the manufacturing process is fully released through modular design. The mass production of standardized modules can significantly improve equipment utilization and energy efficiency and reduce energy waste caused by production changes and commissioning. At the factory level, the modular production system facilitates the introduction of renewable energy power supply and waste heat recovery systems, allowing the manufacturing process to gradually decarbonize. At the same time, the standardization of interfaces between modules simplifies supply chain management and reduces carbon emissions from parts transportation. Some leading companies have begun to establish module sharing platforms, where different models of products share the same basic modules. This not only reduces inventory requirements, but also significantly reduces resource consumption in the initial investment of mold development. This shift in production mode allows economies of scale to be balanced with personalized needs, providing a feasible path for green manufacturing.

Carbon emission control during the product use phase is the most innovative contribution area of modular design. Traditional home appliances are often eliminated due to local failures or poor performance, while modular design gives products the ability to continuously evolve. Users can improve energy efficiency or add new functions by replacing specific modules without having to purchase a new device [12]. Such as a modular refrigerator can improve energy efficiency by upgrading the refrigeration module or adapting to the needs of the Internet of Things by adding an intelligent control module. This "incremental innovation" model significantly extends the actual service life of the product and fundamentally reduces the waste of resources and carbon emissions caused by frequent replacement. At the same time, the modular structure lowers the maintenance threshold, making third-party maintenance services easier to carry out, and further enhancing the sustainability of the product. This userparticipated product evolution is redefining the relationship between consumers and home appliances.

When a product reaches the end of its life cycle, modular design demonstrates unique environmental value. The carefully designed module interface eliminates the need for specialized tools or complex processes during disassembly, greatly improving recycling efficiency. Modules of different materials can be quickly sorted, allowing metals, plastics, and other materials to maintain a high degree of purity, greatly enhancing the value of recycling [13]. Some manufacturers have begun to establish a module recycling system, directly using tested functional modules for new product assembly, achieving a true closed-loop cycle. More forward-looking companies are developing a "module passport" system that uses digital technology to record the material composition and carbon footprint of each module, providing data support for subsequent precise recycling. This circular economy model, which considers the source of design, is changing the passive situation of traditional waste disposal, moving resource flow from linear to circular, and providing a practical solution for the goal of carbon neutrality.

5 MODULAR DESIGN CONTRIBUTES TO CARBON NEUTRALITY GOALS

Quantitative research shows that modular design strategies can significantly reduce carbon emissions for home appliances. Such as washing machines using a modular design can reduce carbon emissions by approximately 30% over their entire lifecycle. This includes a 15% reduction during the production phase due to material savings and process optimization, a further 10% reduction during the use phase through energy-efficient module upgrades, and a further 5% reduction during the recycling phase due to improved disassembly efficiency. This reduction primarily stems from three factors: streamlined material usage avoids carbon emissions from upstream mining and processing; standardized production processes reduce manufacturing energy consumption; and a module replacement mechanism delays the end of life of the appliance. Life Cycle Assessment (LCA) data shows that extending the product lifespan from the traditional five years to ten years can reduce the carbon footprint of each appliance by 40-50%. If this scale of emission reduction is applied to the entire industry, it will have a substantial impact on achieving carbon neutrality goals.

Extended product lifespan is the most direct environmental benefit of modular design. While the average service life of traditional home appliances is limited by the failure time of their weakest components, modular architecture overcomes this limitation by enabling localized upgrades. Market research has found that TVs that support modular upgrades can last 3-5 years longer than traditional models, adapting to new video standards by simply replacing the display driver module. This "gradual upgrade" model not only reduces waste but also shifts consumer usage habits from "use it and throw it away" to "update it on demand." More notably, modular design has spawned new service models, such as module leasing and performance upgrade services. These business model innovations further enhance resource efficiency. Data shows that under modular service models, the actual utilization rate of home appliances has increased by 2-3 times, and resource consumption per unit of service time has significantly decreased.

Industry practice has provided strong evidence for the carbon-neutral value of modular design. A modular air conditioning system launched by an international brand features a standardized core compressor module, allowing users to select different power modules based on room size. The refrigerant circuit utilizes quick-connect connectors for easy maintenance. This design reduces the product's carbon footprint by 28% and cuts repair time by 70%. Another example is a modular kitchen appliance system. By sharing a power supply and control module, users can simply replace the function head to achieve different functions such as juicing and grinding, reducing material usage by 45% compared to purchasing multiple separate appliances. These successful practices show that modularity is not only an innovation in technical solutions, but also an innovation in product concepts. By systematically optimizing the relationship between products, users and the environment, it explores a sustainable development path for the home appliance industry that balances commercial value and environmental responsibility.

6 CHALLENGES AND COUNTERMEASURES

The promotion and application of modular design in the home appliance industry faces multiple technical bottlenecks, with the standardization of module interfaces and long-term compatibility being the most prominent challenges. Module interoperability across product generations requires sophisticated mechanical and electrical interface design, placing higher demands on companies' R&D capabilities. Maintaining the cost advantage of modular product lines is also challenging. High initial R&D investment and a long payback period inhibit the willingness of small and medium-sized enterprises to participate. To address these technical and economic barriers, the industry is exploring the establishment of open modular platforms, sharing core module technologies through alliances and reducing the development burden on individual companies. Some leading companies are beginning to adopt digital twin technology to verify the compatibility of different module combinations in a virtual environment, significantly shortening physical testing cycles. Regarding cost control, through large-scale module production and cross-category sharing, a cost structure comparable to traditional products can be gradually achieved, eliminating the need for high prices to achieve environmentally friendly attributes.

Cognitive biases and consumer resistance in the market are also not to be ignored. Most consumers are accustomed to the traditional model of purchasing complete products and have limited understanding of the value proposition of modular products' "upgrade on demand." Market research shows that approximately 60% of consumers are concerned about the quality and reliability of detachable modules, which has slowed market acceptance. To overcome this dilemma, companies need to restructure their marketing strategies, using intuitive user demonstrations and transparent cost comparisons to ensure consumers truly experience the economic benefits and convenience of modular design. Establishing a comprehensive module replacement and recycling service system is also crucial, making upgrades and maintenance as easy as buying a new device. Some leading brands have launched "trade-in" upgrade programs, allowing consumers to use their old modules to offset the cost of new ones. This model effectively lowers the barrier to entry for users and gradually fosters a sustainable consumer mindset.

Improved policy environments and standards systems are institutional barriers hindering the promotion of modular design. Current energy efficiency standards in various countries primarily target complete products and lack specific considerations for modular architecture, making it difficult for innovative designs to reap the benefits of policy. Recycling regulations are also mostly based on traditional product forms and fail to fully reflect the advantages of modular design in terms of ease of disassembly. To address this situation, governments, industry organizations, and businesses need to work together to build an institutional framework that supports modular innovation. At the policy level, the degree of modularity can be incorporated into green product evaluation systems, leading to tax incentives or procurement priorities. Regarding standards development, unified module interface standards and performance testing methods are urgently needed to facilitate cross-brand compatibility. The EU's "Product Environmental Passport" system, currently being implemented, is worth learning from. This system requires detailed documentation of the material composition and carbon footprint of product modules, providing official certification of the environmental value of modular design. Only when technological innovation, market education, and policy support form a virtuous interaction can modular design truly become a mainstream path towards carbon neutrality in the home appliance industry.

7 CONCLUSION AND OUTLOOK

This study systematically explores the unique value of modular design strategies in achieving carbon neutrality throughout the entire life cycle of home appliances. By analyzing practical applications across the design, production, use, and recycling stages, it confirms that modular architecture not only significantly reduces carbon emissions but also reshapes the sustainable development model of the home appliance industry. The study finds that modular design offers a systematic solution for carbon reduction in the home appliance industry through three key pathways: extending product lifespan, improving resource efficiency, and promoting a circular economy. This shift in philosophy represents a paradigm shift from a "product-oriented" to a "service-oriented" approach, enabling the synergy between environmental and economic benefits. Especially in the current context of global supply chain restructuring and the rise of green consumption, modular design demonstrates strategic significance beyond simple technological improvements, becoming a key lever for driving the green transformation of industry.

Looking ahead, modular design holds significant potential for achieving carbon neutrality. With the advancement of technologies such as digital twins and the Internet of Things, modular home appliances are poised to achieve smarter carbon footprint management. Sensors embedded in each module monitor energy consumption and wear in real time, enabling cloud-based algorithms to optimize usage and maintenance strategies, further reducing lifecycle environmental impact. In terms of business model innovation, modular subscription services may become mainstream. Instead of purchasing complete products, consumers can rent functional modules on demand. This shift will fundamentally reduce idle resources and waste. Even more promising, modular design could foster a cross-industry material recycling ecosystem, with different categories of home appliance modules sharing standard interfaces and material specifications. This will allow resource flows to transcend the boundaries of individual products and achieve a closed-loop system on a larger scale.

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To further unlock the carbon neutrality potential of modular design, subsequent research needs to focus on several areas. First, developing more accurate carbon accounting methods for modular products and establishing dynamic assessment models covering the entire value chain to provide data support for design decisions. Second, exploring the application of artificial intelligence in modular design optimization, using machine learning algorithms to automatically generate optimal module division schemes and material combinations. At the societal level, in-depth research is needed on consumer acceptance mechanisms for modular products and the development of more effective behavioral guidance strategies. Furthermore, integrating modular design with renewable energy systems is a promising area, such as developing smart home appliance modules that can flexibly adapt to different power supply modes. These studies will jointly promote modular design from current product innovation to a fundamental methodology to support the carbon neutrality transformation of the entire home appliance industry and contribute industry solutions to global climate change response.

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