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Design Practice and Effectiveness Research of Modular Concept in Sustainable Design of Consumer Electronic Products

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Abstract: Faced with the global electronic waste crisis and resource constraints, the sustainable transformation of the consumer electronics industry has become imperative. Modular design is recognized as a pivotal strategy for implementing the circular economy due to its inherent potential in extending product lifespans, facilitating repair and upgrades, and promoting component recycling. This study employs a case deconstruction and mixed-methods research approach to explore the practical implementation and comprehensive effectiveness of modular design. Taking the representative product Fairphone as a case study, the research deconstructs its "design-business-user" triad innovation, revealing specific strategies in modular architecture, standardized interfaces, emotional connection, and service models. By integrating user surveys (N=150, N=15 for interviews) with Life Cycle Assessment (LCA) data, the study assesses effectiveness across two dimensions: user behavior (repair intention, loyalty) and environmental benefits (carbon footprint, resource reduction). Results indicate that effective modular sustainable design is a systemic engineering approach that integrates forward-looking design, closed-loop business models, and deep user engagement. Finally, this study constructs an integrated design methodology framework and identifies core challenges—such as technical standardization and industrial ecology—to provide theoretical and practical guidance for sustainable innovation in consumer electronics.

Keywords: Modular Design; Sustainable Design; Consumer Electronics; Circular Economy; Product Life Cycle; User Behavior; Design Strategy.

1. Introduction

At present, the rapid iteration and obsolescence of consumer electronic products have become a global resource and environmental challenge. Dominated by the traditional linear economic model, highly integrated and non-disassemblable product design accelerates "planned obsolescence", resulting in a huge amount of electronic waste. Its improper disposal poses a serious threat to the ecological environment and public health. Therefore, promoting the industrial transformation to a circular model and seeking systematic solutions from the design source is an urgent task in the field of design science. The core demand of sustainable design is to comprehensively extend the effective life cycle of products, which requires design to take into account repairability, upgradability and material recyclability. The modular design concept provides a key structural basis for meeting this demand by deconstructing products into functionally independent subunits with standard interfaces. It not only technically supports the replacement and upgrade of components, but also can spawn new business models and promote the closed-loop flow of resources at the environmental level.

Academics at home and abroad have recognized the potential of modular design, and relevant studies are mostly carried out from the perspectives of engineering architecture, ecological design or environmental assessment. However, existing studies often separate the technical, commercial and user dimensions, and the discussion on how modular design is implemented through specific and systematic design practices and ultimately produces comprehensive effectiveness in user behavior and environmental aspects is not in-depth. Especially for the complex category of consumer electronics, there is a lack of in-depth case deconstruction and empirical evaluation that place design strategies, business models and user experience in the same analytical framework. In view of this, this study aims to systematically answer: How can the modular concept be transformed from concept to practice in consumer electronic products? What is the comprehensive effectiveness of its practice? What are the fundamental challenges? To this end, this study will comprehensively use theoretical combing, in-depth deconstruction of typical cases (represented by Fairphone), and mixed empirical methods combining user research and literature data, striving to present a complete picture from theory to practice and from design to effectiveness, so as to provide more integrated and operable insights for the sustainable design transformation of the consumer electronics industry.

2. Theoretical Basis

Modular design, specifically referred to in this study as a strategic method developed for consumer electronic products, focuses on decomposing complex systems into units with independent functions, standard interfaces, and flexible combination and replacement. This design paradigm is not a new technology, but its combination with the contemporary circular economy concept endows it with new sustainable connotations. The circular economy seeks to subvert the linear model of "take-make-dispose" and build a system for closed-loop regeneration of materials. Modular design is the key physical carrier to realize this closed loop: it makes repair, refurbishment and remanufacturing possible through design, thereby maximizing the value contained in materials, energy and labor during the product life cycle. This means that design thinking must shift from the optimization of a single product to considering the flow and iteration of modules in multiple life cycles and even different product platforms.

Further analysis shows that modular design adapts to sustainable goals from three dimensions: environmental, economic and social. In the environmental dimension, it directly supports resource reduction (through upgrading instead of replacement), reuse (reuse of functional modules) and efficient recycling (classification of pure materials). In the economic dimension, it may reduce users' long-term ownership costs and open up new revenue sources for manufacturers such as repair services, component sales, and trade-ins, changing the profit model of one-time sales. In the social dimension, it enhances the controllability and emotional attachment of products by empowering users with repair rights and personalized upgrade choices, thereby cultivating a more responsible and participatory consumption culture. However, it must be clearly recognized that the achievement of such multi-dimensional benefits is not a natural result of the modular structure, but depends on elaborate module division strategies, universal and durable interface standards, sustainable material selection, and business models and user support systems that are deeply coordinated with it.

3. Modular Design Case Analysis: Fairphone

3.1. Basis for Case Selection

To deeply explore how the modular concept is specifically transformed into design practice, this chapter selects Fairphone as a typical case for in-depth analysis. Its representativeness lies in that it is one of the few consumer electronics brands in the market that establishes modularity as a core sustainable strategy and successfully achieves commercialization and large-scale application, providing a complete observation sample from concept to market and from product to ecology. The following will systematically deconstruct its design practice from four interrelated levels.

3.2. Material Closed-Loop at the Material and Component Level

Firstly, at the material and component level, the core of Fairphone's practice is sustainable material selection and component-level closed-loop management. Its design is not limited to the detachability of modules, but goes deeper into the "birth" and "regeneration" of modules. For example, the back cover of Fairphone 5 uses 100% recycled plastic, the frame is made of 100% recycled aluminum, and the circuit board contains 100% recycled copper. This echoes the concept of "circular materials" in the circular economy, that is, preparing for recycling and recycling at the material level. At the same time, it practices "fair material" procurement, such as taking the lead in using fair trade certified gold in mobile phones, integrating social equity into design considerations. This transparent traceability of material sources and components essentially establishes a "material passport" for the product, laying a foundation for accurate disassembly and efficient recycling at the end of life.

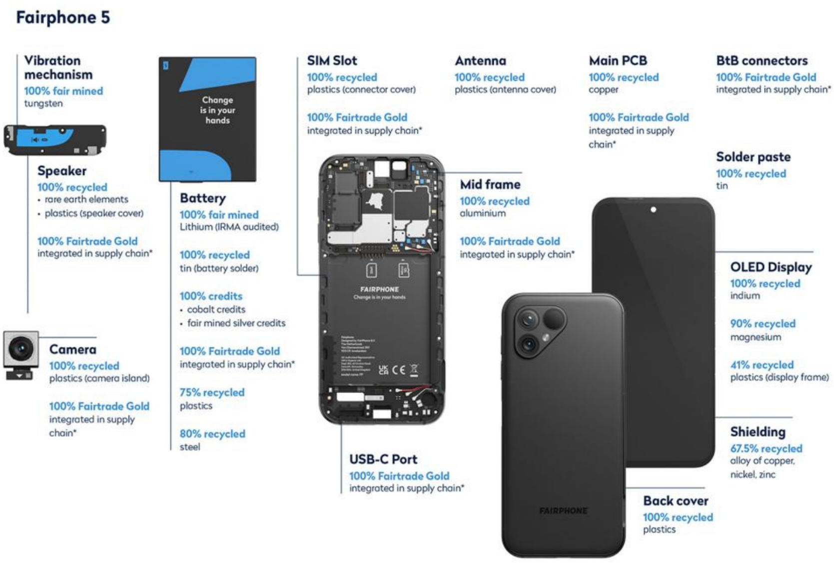

Figure 1. Disassembly structure of Fairphone 5

3.3. Design for Disassembly at the Structural and Interface Level

At the structural and interface level, its core strategy is design for disassembly and repair. This goes beyond the simple concept of "modularity" and enters the engineering implementation of "design for disassembly". Fairphone mobile phones extensively use standard screws and detachable connectors instead of gluing and welding commonly used in the industry, thus reducing operations that can only be completed by professional repairs to daily maintenance that users can safely complete with simple tools. This design choice directly reduces the technical threshold and cost of maintenance, and is the physical basis for empowering users with the "right to repair". Its structural design follows the principle of "reversible connection" emphasized in the field of demountable architecture, giving priority to non-destructive or low-loss separation methods.

3.4. Upgradability at the System Level and Business Model

At the functional and system level, the goal is to ensure the long-term performance and upgradability of products. Modularity here is not only convenient for maintenance, but also a path for functional iteration. By providing up to 8 years of software support (since release), Fairphone ensures long-term usability and security at the system level. In terms of hardware, its modular architecture allows users to independently upgrade core functional modules such as cameras and speakers without replacing the main body of the mobile phone. This design extends the service life of the core product platform (such as motherboards and screens), and is the key to combating rapid technological obsolescence of electronic products. At the level of business model and ecosystem, its innovation is reflected in building closed-loop services and industrial collaboration supporting modular cycles. Modular design will be difficult to sustain without the support of a business model. Fairphone has built an integrated system of "sales (complete machines and modules) + services (repair guides and tools) + recycling (trade-ins and responsible disposal)". It implements the "electronic waste neutrality" program: for every mobile phone sold, it recycles and disposes of electronic waste of the same weight through partners. This marks a shift in its business model from selling products to managing the value stream of the entire product life cycle. It actively cooperates with suppliers, recyclers and even industry organizations to jointly explore paths for module reuse, which reflects the systematic industrial ecological transformation required to realize the circular economy.

4. Modular Design Strategy Analysis

4.1. Refinement of Core Design Strategies

Combined with the in-depth analysis of typical cases of modular design above and its theoretical correlation with sustainable goals and circular economy, this chapter refines three core strategies of modular design. These strategies do not act independently in a certain design practice, but link the three dimensions of "design-business-user", run through the entire life cycle of products, and aim to fundamentally solve the pain points of "difficult to repair, difficult to upgrade, difficult to recycle" in the current consumer electronics field.

Table 1. Correlation matrix between modular design strategies and sustainable effectiveness

Strategy Dimension	Specific Design Actions	Environmental Benefits (LCA Dimension)	Economic and Commercial Effectiveness	User Behavior Impact
Material Closed-Loop	Application of recycled metals, material passports, targeted recycling	Reduce energy consumption and resource exploitation	Reduce the risk of raw material price fluctuations	Enhance recognition of environmental protection brands
Interaction Standard	Standardized interfaces, non-destructive disassembly architecture	Extend product lifespan and reduce electronic waste	Reduce after-sales repair labor costs	Improve repair intention and autonomy
System Collaboration	PSS business model, trade-in	Realize "electronic waste neutrality"	Create sustainable revenue	Establish in-depth brand loyalty

4.1.1. Component Full Life Cycle Closed-Loop Strategy

Firstly, the component full life cycle closed-loop strategy provides an important guarantee for the efficient recycling of resources. Its core content includes sustainable material selection at the source and a closed-loop recycling system at the end. Sustainable material selection at the source ensures that the environmental benefits of each component are determined at the beginning of production. For example, Fairphone 5 mostly uses 100% recycled metals as raw materials to reduce the demand for primary resource exploitation from the source. The closed-loop recycling system at the end establishes a special recycling channel for old modules, refurbishes the recovered functional modules and puts them back into the market, and conducts targeted material recycling for modules that cannot be reused, forming a closed loop of "use-recycle-regenerate-reuse", effectively reducing the disorderly discarding of electronic waste and the environmental pollution of toxic and harmful substances, and further improving the recycling efficiency of products. According to the quantitative calculation of relevant LCA literature, the energy consumption and material consumption of remanufactured components are reduced by 60% and 70% respectively compared with new products, and their life cycle Global Warming Potential (GWP) and Primary Energy Demand (PED) are significantly reduced [1], which also confirms the synergistic effect of recycled material selection at the source and closed-loop recycling at the end.

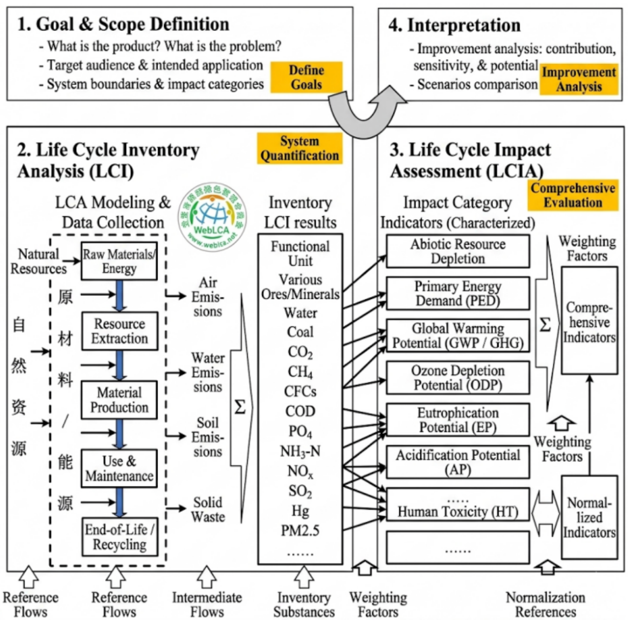

Figure 2. Main stages and framework of Life Cycle Assessment (LCA)

4.1.2. Module Simplification and Interface Standardization Strategy

The module simplification and interface standardization strategy focuses on optimizing user experience. According to Hick's Law [2], too few choices limit function expansion, and too many modules increase user decision-making costs. Therefore, module simplification should follow the principles of "core function integration" and "necessary function splitting", reducing user operation complexity while meeting personalized needs, thereby improving product user stickiness. In addition, adopting unified interface standards in modular design can reduce the technical threshold and operation cost of repair and upgrade, empower users with independent maintenance rights, extend the service life of the core product platform, and fundamentally combat premature product obsolescence caused by "planned obsolescence". Moreover, the unification of interface standards can provide expansion space for users' personalized needs. For example, Framework Laptop adopts physical modular slots by "hollowing out" the interfaces on the side of the laptop, uses USB-C as the interface, and provides adapter slots such as USB-A and HDMI to meet the needs of different users.

Figure 3. Modular interface design of Framework Laptop

4.1.3. Business Model and Industrial Ecological Collaboration Strategy

The business model and industrial ecological collaboration strategy is the core support for the sustainable implementation of modular design. The long-term value of modularity cannot be achieved only by product design itself, and long-term guarantee needs to be built through business model innovation and industrial ecological linkage. It shifts the source of commercial value from one-time hardware sales to a diversified combination of "hardware + services + circular value", and at the same time links suppliers, recyclers, users and other stakeholders to build a co-construction and sharing circular ecosystem, ensuring the economic feasibility and industry replicability of modular design. Diversified business models improve the brand's risk resistance and profitability. Fairphone mentioned above is one of the most typical cases. The proportion of Fairphone's module sales and service revenue has reached 25% of its total revenue [3], which verifies the economic feasibility of this model. It can be seen that the collaborative linkage of the industrial ecosystem reduces the large-scale cost of modular design, and at the same time promotes the formation of industry circular standards, laying a foundation for the popularization of modular design in the industry.

4.2. Mixed Research Methods and Data Sources

To achieve a systematic evaluation of the comprehensive effectiveness of modular design, this study specifically adopts the following research methods and implementation steps. In terms of in-depth case disassembly analysis, this study selects Fairphone 5 as the core analysis object, and systematically sorts out its module division mode, interface type, fastener specification and material identification by consulting official disassembly guides, technical white papers and detailed disassembly reports of the third-party maintenance platform iFixit. At the same time, Framework Laptop is introduced as a control case to focus on analyzing its differentiated path in interface modular design, so as to enhance the universality and comparative value of the research conclusions.

In terms of semi-structured user interviews, this study recruited and completed interviews with 15 respondents from October to November 2025 through a combination of online meetings and offline face-to-face interviews. The respondents included actual users of modular mobile phones (N=8), traditional smartphone users (N=5) and electronic product maintenance enthusiasts (N=2), aged between 22 and 38 years old. The interview content focused on four themes: users' subjective experience of the current difficulty of electronic product maintenance, cognition and attitude towards modular design, key factors affecting maintenance behavior decisions, and willingness and reasons to pay a premium for sustainable products. Each interview lasted about 30 to 45 minutes, was recorded and transcribed into a manuscript after obtaining the informed consent of the respondents, and then the interview data were coded and summarized by thematic analysis method.

Based on the key variables extracted from the interviews, this study designed a structured questionnaire, which was distributed and collected through online channels (including Reddit modular mobile phone community, environmental protection design forum, university campus community). A total of 150 valid questionnaires were recovered, including 32 from actual modular mobile phone users and 118 from potential interested users. The questionnaire covered user basic information, maintenance experience and frequency, purchase intention of modular design, brand loyalty, environmental attitude scale and other dimensions. The data were processed by descriptive statistics and cross-analysis to reveal the attitude and behavior differences between different user groups.

In terms of cross-validation of LCA literature data, this study systematically retrieved Chinese and English literature on modular products, remanufacturing and life cycle assessment in Web of Science, CNKI and Google Scholar databases, screened empirical studies similar to the product types and material categories involved in this study, and focused on extracting key environmental indicators such as global warming potential, primary energy demand, material recovery rate and waste reduction. Through analog calculation and cross-validation, the quantitative results in the literature were applied to the environmental benefit evaluation of Fairphone and similar modular products, and the rationality of the differences between different data sources was discussed.

In terms of user behavior dimension, the results of questionnaire survey (N=150) and interviews (N=15) show that: 82% of respondents are willing to replace batteries or screens by themselves, much higher than the usual level of less than 30% for traditional mobile phone users; the brand loyalty of modular mobile phone users is significantly higher, and 78% are willing to choose the same brand when replacing the next mobile phone; 55% of respondents are willing to pay a premium of 10% to 20% for repairable and upgradable modular products. Meanwhile, the analog calculation based on LCA literature data shows that modular design combined with the use of remanufactured modules can reduce the life cycle global warming potential of products by about 30% to 40%, and primary energy demand by 50% to 70%. Each use of a remanufactured module is equivalent to saving about 30 kilograms of ore mining. If modular design reaches 10% market penetration, it is expected to reduce more than

600,000 tons of electronic waste per year.

Overall, modular design shows significant positive effectiveness in both user behavior and environmental benefit dimensions, and there is a mutually reinforcing positive cycle between the two.

5. Design Methodology and Practical Challenges

Based on the foregoing theoretical and case studies, a modular sustainable design methodology framework for consumer electronic products can be constructed. The framework emphasizes systematic innovation and includes three core levels: at the product design level, it is necessary to implement the principles of design for disassembly, design for upgrade and design for recycling, focusing on reasonable module division, long-lasting standardized interfaces and environmentally friendly material selection. At the interaction and service level, it is necessary to develop a friendly interface supporting users' independent maintenance, including clear identification, simple tools and intuitive guides, and build a closed-loop service system covering module supply, professional maintenance support and old part recycling. At the business and ecosystem level, it is necessary to innovate business models, shift the source of value from one-time hardware sales to a combination of hardware, services and circular value, and actively cooperate with suppliers, recyclers and even competitors to promote the co-construction of interface standards and circular ecosystems.

However, there are still severe challenges to promote this methodology to large-scale industrial practice. The primary challenge is the technical standardization problem. At present, the internal architecture and interfaces of various brands are seriously privatized, and there is a lack of industry-general module interface standards, which hinders the development of the third-party maintenance market and the recycling of cross-brand components. Secondly, the economy of large-scale production constitutes a constraint. Modular design may bring higher R&D and parts costs in the initial stage. In the market competition pursuing extreme thinness and short-term profits, its long-term environmental and social benefits are difficult to be fully reflected in the traditional pricing model, which needs to be supported by consumers' willingness to pay a premium for sustainability. Finally, the inertia of the industrial ecosystem cannot be ignored. Transformation means reconstructing the existing supply chain, production process and profit distribution model, which is bound to touch the vested interests, so it needs the joint promotion of strong policy guidance, consumer awareness awakening and leading enterprises in the industry. Specifically, the policy level should strengthen the legislation of the right to repair and implement the extended producer responsibility system; the market level needs the transformation of consumers' values; the industrial level depends on the demonstration and driving of pioneering enterprises.

6. Conclusion and Prospects

Through the systematic combing of modular design theory, in-depth analysis of the typical case of Fairphone, and two-dimensional effectiveness evaluation, this study reveals the internal mechanism of modular design enabling sustainable development in the field of consumer electronics. The research holds that the sustainable value of modular design does not only come from the detachable physical structure, but from the construction of a collaborative innovation system. The real sustainable modular design is a unity of technical rationality, business wisdom and humanistic care, which not only responds to the systematic challenges of resource crisis, but also recalibrates the ethical relationship between people and products. This study expands the problem domain of sustainable design research. In practice, the case of Fairphone shows that to realize industrial migration, modular design needs to seek a balance between standardization and openness, product life cycle and business model sustainability. At the same time, this study has certain limitations: the universality of a single case needs to be verified by multi-industry comparative research; the sample size of user research can be further expanded; the environmental benefit evaluation is based on literature deduction, and needs to be accurately quantified combined with full life cycle data in the future.

Looking forward, the research direction can be expanded from the following dimensions: firstly, explore the differentiated application paths of modular strategies in a wider range of product categories such as laptops and home appliances; secondly, study the enabling mechanism of technologies such as digital twin and Internet of Things in module tracking and circular management; thirdly, discuss the design-driven mechanism and policy tools to promote the formation of industrial standards. Ultimately, the transition of modular design from pioneer experiment to mainstream practice requires continuous dialogue and collaborative action by design researchers, industry, policy makers and consumers.

References

[1] Zheng Handong, Chen Yi, Li Enzhong, et al. Life Cycle Assessment Modeling and Application of Remanufactured Product Service Systems[J]. China Mechanical Engineering, 2018, 29(18): 2197-2203.

[2] Tang Shisi, Qin Zheng, Ou Lu. Menu Usability Research Based on Hick's Law and Fitts' Law[J]. Computer Engineering and Applications, 2016, 52(10): 254-258.

[3] Fairphone. (2025, April 17). Fairphone-Impact-Report-2024 [R/OL]. Fairphone website. https://www.fairphone.com/wp-content/uploads/2025/04/ Fairphone-Impact-Report-2024.pdf.

[4] Liu Yuxi, Xie Jiaping. Research on Saving-Sharing Contract for Leasing Product-Service System Under Remanufacturing [J]. Chinese Journal of Management Science, 2016, 24(03): 99-108.

[5] Spreafico, C. An analysis of design strategies for circular economy through life cycle assessment. Environ Monit Assess 194, 180 (2022).

[6] Agrawal, V.V., Atasu, A. and Ülkü, S. (2016), Modular Upgradability in Consumer Electronics: Economic and Environmental Implications. Journal of Industrial Ecology, 20: 1018-1024.

[7] Schischke, K., Proske, M., Nissen, N.F. et al. Impact of modularity as a circular design strategy on materials use for smart mobile devices. MRS Energy & Sustainability 6, 16 (2019).

[8] van den Berge, R., Magnier, L., and Mugge, R. (2022) Enhancing consumers' willingness to repair electronic products: How design can nudge sustainable behaviour, in Lockton, D., Lenzi, S., Hekkert, P., Oak, A., Sádaba, J., Lloyd, P. (eds.), DRS2022: Bilbao, 25 June - 3 July, Bilbao, Spain.