

From Organizational Strategy to Product Implementation: A Sustainable Design Decision Support Method Based on Value Chain-Stakeholder Coupling

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I. INTRODUCTION

Abstract—Purpose: Addressing the prevalent "strategy-execution gap" in sustainable design practices within modern manufacturing industries like smart homes—whereby macro-level corporate sustainability strategies are difficult to effectively translate into concrete product design solutions—this study aims to develop and validate a systematic decision support method. **Methodology:** This research constructs an integrated decision support framework. First, through an innovative "Value Chain-Stakeholder Coupling" analysis, it systematically identifies the internal and external driving factors and diverse demands affecting sustainable design. Second, it establishes a three-level decision model encompassing strategic, tactical, and operational layers to facilitate the hierarchical translation of sustainability strategies into specific design solutions. Finally, it integrates simplified Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Social Impact Assessment, the Analytic Hierarchy Process (AHP), and Fuzzy Comprehensive Evaluation to form a multi-dimensional evaluation and selection mechanism capable of handling uncertainty. **Findings:** Applied to a smart home lighting product as an illustrative case, the proposed method was used to compare several feasible sustainable design alternatives. The results indicate that the method can effectively support the identification of a balanced solution with improved environmental and social performance while maintaining acceptable economic feasibility. This validates the method's effectiveness and practical feasibility in balancing multiple environmental, social, and economic objectives. **Conclusion:** The decision support method proposed in this study provides enterprises with an operational and replicable toolkit that can effectively bridge the decision-making chain from organizational strategy to product implementation. It highlights the critical role of systems thinking, a full life cycle perspective, and the dynamic coordination of diverse stakeholder needs in achieving sustainable design goals, offering powerful theoretical guidance and practical tools for manufacturing enterprises to formulate and execute sustainable design strategies in complex environments.

Keywords—Sustainable Design, Decision Support, Value Chain, Stakeholder Theory, Multi-Criteria Decision-Making (MCDM), Smart Home

With the rapid development of the Internet of Things (IoT), big data, and artificial intelligence, the smart home industry is experiencing unprecedented growth. According to the International Data Corporation (IDC), global shipments of smart home devices are expected to maintain strong growth, profoundly changing people's living environments and lifestyles [1]. At the same time, sustainable design and circular economy strategies have become increasingly important in guiding product innovation toward environmental and social responsibility [2]. Existing studies have also shown that ecodesign implementation remains challenging in practice, especially when companies attempt to embed sustainability considerations into product development processes in a systematic manner [3].

Although there is a broad consensus in academia and industry on the importance of sustainable design, in practice, companies commonly face difficulties in translating macro-level strategies into micro-level product solutions. Currently, sustainable design decisions for smart home products face three core challenges. First, there is a disconnect between organizational strategy and product design. Corporate sustainability strategies often remain at a macro level and are not effectively transmitted to the specific design and execution stages, leading to a misalignment between design solutions and strategic goals. Second, the needs of stakeholders across the value chain are diverse and conflicting. Different stakeholders, such as customers, suppliers, employees, and regulatory bodies, have varied and sometimes contradictory concerns regarding sustainability. Existing design methods lack a systematic mechanism for coordination and trade-offs. Third, the trade-off among environmental, economic, and social objectives is extremely complex. Sustainable design requires a balance between environmental friendliness, economic viability, and social equity, and traditional single-dimension evaluation methods cannot support such complex multi-objective comprehensive decision-making.

In response to these challenges, existing research has explored various perspectives. The first category of research focuses on eco-design tools and methods at the product level, such as Life Cycle Assessment (LCA), material selection matrices, and design for disassembly. These tools provide effective means for assessing and improving the

environmental performance of products, but their application is often detached from the company's organizational strategy and complex stakeholder network. The second category focuses on strategic-level sustainability frameworks, such as Corporate Social Responsibility (CSR), circular economy models, and the sustainable business model canvas. This line of research provides macro-level guidance for companies to build sustainability strategies but generally lacks an operational path to translate strategic goals into specific product design parameters. The third category is dedicated to applying Multi-Criteria Decision-Making (MCDM) methods to the evaluation and selection of sustainable design solutions. These methods can effectively handle multi-objective conflict problems, but in practice, they often simplify complex stakeholder needs into fixed weights or technical parameters, failing to fully capture the dynamics and context-dependency of the value chain.

A systematic review of the relevant literature reveals several remaining gaps in current research. First is the strategy-execution gap; existing research lacks an intermediate mechanism and a clear pathway to effectively connect an organization's macro-strategy with micro-level product design. Second is the partiality of stakeholder analysis; most studies focus only on customers or stakeholders in a single segment of the value chain, failing to place the analysis within the context of the complete value chain to systematically identify and coordinate diverse needs. Third are the limitations of evaluation methods; assessments of the environmental, economic, and social dimensions are often conducted independently, lacking a comprehensive framework that integrates all three, with quantitative assessment of the social dimension being particularly weak. Finally, the decision-making process is often static; most methods rely on evaluating and selecting from a predefined set of design alternatives, lacking a dynamic mechanism to systematically generate innovative design solutions derived from strategic objectives.

To bridge these research gaps, this study aims to construct a systematic decision support method that extends from organizational strategy to product solution implementation. The specific research objectives include: (1) to establish a value chain-stakeholder coupling analysis framework for systematically identifying the internal and external drivers and diverse stakeholder needs affecting sustainable design; (2) to build a three-level decision model (strategic, tactical, and operational) to enable the hierarchical translation and implementation of sustainability strategies into specific design solutions; (3) to develop a comprehensive evaluation system that integrates environmental, economic, and social dimensions to support complex multi-objective trade-off decisions; and (4) to demonstrate the applicability and practicality of the proposed method through an illustrative case in the smart home product context.

The remainder of this paper is structured as follows: Section 2 reviews the core literature on sustainable design, value chain analysis, stakeholder theory, and related decision-making methods to further clarify the theoretical positioning and contribution of this study. Section 3 elaborates on the proposed three-level decision support methodology, including its theoretical basis, model architecture, and analytical process. Section 4 introduces the case study design, data collection process, and sample

information. Section 5 presents the results obtained from applying the research method, including strategic scenario identification, design solution generation, and multi-dimensional evaluation. Section 6 provides an in-depth discussion of the research findings, analyzing their theoretical implications and practical value, and comparing them with existing research. Finally, Section 7 summarizes the entire paper and points out its limitations and directions for future research.

II. LITERATURE REVIEW

This section aims to systematically review the core theories, methods, and tools relevant to this study, laying a theoretical foundation for the decision support framework and further clarifying the positioning and contribution of this research.

A. Core Theoretical Foundations of Sustainable Design

As an interdisciplinary field, the development of sustainable design is rooted in several core theories, including sustainable development, value chain, and stakeholder theories..

1) The Fusion of Sustainable Development and Design

The concept of sustainable design originates from the idea of sustainable development proposed in the late 1980s, whose core idea is to meet the needs of the present without compromising the ability of future generations to meet their own needs [4]. This concept emphasizes the need to balance the three pillars of environment, economy, and society during development, the so-called "Triple Bottom Line" [5]. Design, as a bridge connecting technology, business, and society, plays a key role in promoting sustainable development. Sustainable design, or eco-design, therefore requires designers to systematically consider the environmental, economic, and social impacts of a product throughout its entire life cycle [6]. Early research on sustainable design primarily focused on the environmental dimension, giving rise to concepts such as green design and Design for Environment (DfE), with a focus on reducing resource consumption, lowering pollution emissions, and improving product recyclability [7]. As the theory deepened, its scope gradually expanded to include social equity and economic feasibility, leading to broader theoretical paradigms such as circular design, service design, and system innovation for sustainability [8][9].

2) Application of Value Chain Theory in Sustainable Design

Value chain theory, first proposed by Porter, decomposes a company's activities into a series of value-creating links, providing a powerful framework for analyzing competitive advantage [10]. In the context of sustainable design, the perspective of value chain analysis has expanded from single economic value creation to a more comprehensive consideration of environmental and social value. Researchers have used value chain and supply chain perspectives to identify environmental hotspots and social risks at different stages of the product life cycle, thereby providing targets for design improvements [11]. However, most existing research uses value chain analysis mainly as a descriptive or diagnostic tool, lacking a systematic method to deeply integrate it with specific design decision-making processes.

3) Stakeholder Theory and Design Decisions

Stakeholder theory posits that in the decision-making process, a company should not only be accountable to its shareholders but also consider the interests of all individuals or groups affected by its activities [12]. This theory provides an important ethical perspective and analytical framework for sustainable design. In sustainable design practice, identifying and integrating the needs of diverse stakeholders is crucial, as their understandings and demands regarding sustainability often differ and may even conflict. Existing research often uses stakeholder analysis to identify design requirements and assess the social acceptability of design solutions. However, challenges remain in how to systematically coordinate conflicts of interest among stakeholders and how to determine the priority of different stakeholders at different decision-making stages. The stakeholder salience perspective further suggests that stakeholder influence is dynamic and context-dependent, rather than static [13].

B. Methods and Tools for Sustainable Design

Under theoretical guidance, academia and industry have developed various methods and tools to support sustainable design practices.

1) Life Cycle Assessment (LCA) Method

Life Cycle Assessment (LCA) is an internationally recognized and standardized method for quantifying the environmental impact of a product or service throughout its entire life cycle [14]. It provides a “cradle-to-grave” systemic perspective, covering the entire process from raw material acquisition, production, transportation, use, to disposal. LCA can identify key environmental impact stages in a product’s life cycle, providing a scientific basis for design optimization. However, a full LCA analysis typically requires a large amount of precise data and is a complex and time-consuming process, which limits its application in the early stages of product design [15]. To address this issue, researchers have also discussed the broader integration of environmental, economic, and social dimensions within life cycle sustainability assessment frameworks [16].

2) Multi-Criteria Decision-Making (MCDM) Methods

Sustainable design is inherently a multi-objective decision problem that requires trade-offs among conflicting objectives such as environmental performance, cost, and functionality. Multi-Criteria Decision-Making (MCDM) methods provide effective analytical tools for this purpose [17]. Classic MCDM methods such as the Analytic Hierarchy Process (AHP), TOPSIS, and ELECTRE are widely used for ranking and selecting sustainable design alternatives. In recent years, fuzzy MCDM approaches have received increasing attention because they can better handle the uncertainty, ambiguity, and subjectivity involved in sustainability evaluation [18].

3) Strategic Analysis Tools

Classic strategic management tools such as SWOT analysis and PESTEL analysis have also been introduced into the field of sustainable design to analyze the internal and external environments affecting a company’s sustainable design strategy [19]. These tools help companies identify macro trends and assess their own capabilities, thereby formulating sustainable design directions that are consistent with their organizational strategy. However, the output of these strategic analysis tools is usually macroscopic and directional, and there is often a lack of clear conversion paths

and operational methods to link them with specific product design parameters and technical decisions.

C. Research on Decision Support from Strategy to Execution

To bridge the gap between macro-strategy and micro-execution, some research has begun to explore integrated decision support frameworks.

1) Integrated Frameworks for Strategy and Design

Some studies have attempted to build integrated frameworks connecting strategy and design. For example, Quality Function Deployment (QFD) has been used to translate customer needs into product design characteristics, key component characteristics, and production process parameters, providing a structured method for transmitting strategic objectives [20]. Similarly, the Balanced Scorecard (BSC) has been used to break down a company’s sustainability strategy into specific performance indicators, thereby guiding design activities [21]. These methods provide useful ideas for the integration of strategy and design, but in the specific context of sustainable design, their systematic consideration of environmental and social dimensions is still insufficient, and they have not fully integrated the perspectives of the value chain and diverse stakeholders.

2) Contextual Design Methods

Contextual design emphasizes that design decisions must be closely integrated with the specific context of the organization. International standards such as ISO 14006 provide guiding principles for companies to integrate eco-design into their environmental management systems, emphasizing the commitment of top management, analysis of the internal and external organizational context, and life cycle thinking [22]. Sansa et al. proposed a three-level decision framework that links the organizational context with sustainable design solutions through choices at the strategic, tactical, and operational levels [23]. These studies highlight the importance of customizing design strategies according to the specific circumstances of the company. However, existing research often remains at the level of principled guidance or framework construction for specific cases, lacking a methodology that is both universally applicable and operational, and capable of systematically generating and evaluating design solutions.

3) Research Gaps and Contributions of This Study

In summary, although existing research provides rich theoretical and methodological support for sustainable design, there are still significant gaps. First, there is a lack of a systematic transformation mechanism from organizational strategy to product solutions. Existing research either focuses on macro-strategy or micro-tools, with a huge gap between the two. Second, value chain analysis and stakeholder analysis have not been effectively integrated. These two theoretical perspectives are often applied independently, and their coupling mechanism and synergistic effect in design decision-making have not been fully explored. Third, the evaluation and integration of the environmental, economic, and social dimensions are still incomplete. Existing evaluation methods either focus on one dimension or face data and methodological challenges in the integration process. Fourth, the mechanism for generating design solutions is under-researched. Most methods rely on a pre-set of

alternatives, lacking an intrinsic mechanism to systematically generate innovative solutions from strategies and needs.

To address these gaps, the main contributions of this study are: (1) proposing a Value Chain-Stakeholder Coupling Analysis Framework that systematically identifies the internal and external factors affecting sustainable design by establishing a mapping relationship between value chain stages and stakeholders; (2) constructing a three-level (strategic-tactical-operational) decision model that provides a clear path for the hierarchical translation of sustainability strategies into specific product design solutions; (3) developing an integrated multi-dimensional evaluation and selection method that combines simplified LCA, LCC, social indicator assessment, and fuzzy MCDM to address the complexity and uncertainty in the decision-making process; and (4) demonstrating the practical applicability of the overall methodology through an illustrative smart home product case.

III. RELATED WORK

This section focuses on four key technology areas directly related to the decision support method proposed in this study: sustainable design scenario generation, value chain and stakeholder integration, multi-dimensional sustainability assessment, and computer-aided decision support tools. The aim is to further highlight the uniqueness and innovation of this research by comparing it with existing specific methods.

A. Sustainable Design Scenario Generation Methods

The generation of design scenarios is a critical front-end link in sustainable design, directly determining the scope and quality of subsequent evaluation and selection. Existing scenario generation methods in research can be broadly divided into two categories. The first category is heuristic methods based on expert knowledge, such as brainstorming, the Delphi method, and morphological analysis. These methods can fully utilize the tacit knowledge and creativity of experts to quickly generate a variety of design concepts. However, their process often lacks structure, and the comprehensiveness and systematicity of the results are difficult to guarantee. They are also highly dependent on the experience and knowledge background of the experts, easily overlooking the connection with the organization's macro-strategy. The second category is analytical methods driven by data and models. For example, some studies use Quality Function Deployment (QFD) to systematically translate customer needs into a combination of engineering parameters, thereby generating design solutions. Other studies use patent databases or historical project data to discover innovative design patterns through Case-Based Reasoning or data mining techniques. These methods improve the systematicity and objectivity of scenario generation, but their data sources are often limited to customer needs or historical projects, failing to fully integrate input from the broader value chain and stakeholders, and also failing to effectively connect with the organization's strategic intent.

Unlike the above methods, the scenario generation mechanism proposed in this study is strategy-driven and multi-participatory. It begins with strategic scenarios formed through an integrated SWOT-PESTEL-7S analysis, ensuring that the generated design solutions are consistent with the organization's strategic direction. On this basis, through the

value chain-stakeholder coupling analysis, diverse needs are systematically integrated into the definition of tactical criteria and operational alternatives, so that the generated scenarios are not only strategically relevant but also more context-adaptive and feasible.

B. Value Chain and Stakeholder Integration Methods

Value chain analysis and stakeholder analysis are widely used in sustainable design, but their integration remains a research challenge. There are three main integration paths in existing research. The first is sequential integration, where value chain analysis is first conducted to identify environmental or social hotspots, and then stakeholder analysis is carried out for the hotspot links to collect needs. This approach is logically clear but fails to reveal the deep coupling relationship between the two. The second is parallel integration, where value chain links and stakeholder groups are simultaneously considered as evaluation objects to analyze their impact on sustainability performance. This approach is more comprehensive but struggles to handle the cross-impacts between the two. The third is nested integration, where stakeholder analysis is embedded in each link of the value chain, treating stakeholders as endogenous variables of the link. This approach is closer to the thinking of this study, but existing research often remains at the theoretical framework level, lacking operational analysis tools and quantitative methods to handle the coupling relationship.

The Value Chain-Stakeholder Coupling Analysis Framework proposed in this study is a deepening and development of existing integration methods. We not only establish a mapping matrix of value chain stages and stakeholders but, more importantly, identify the dominant stakeholders and their core concerns at different stages through this matrix, and translate them into specific tactical design criteria. This method transforms the two analyses from simple information superposition to a deep fusion of decision logic, providing structured input for subsequent scenario generation and evaluation.

C. Multi-dimensional Sustainability Assessment Methods

Sustainability assessment in design requires trade-offs among the environmental, economic, and social dimensions. Existing research on multi-dimensional assessment integration mainly faces two major challenges: one is the heterogeneity of data and models, as the three major assessment methods — environmental (LCA), economic (LCC), and social (S-LCA)—have significant differences in data requirements, model assumptions, and quantification units, making direct integration difficult; the other is the subjectivity of weight determination, as the relative importance of different dimensions often depends on the subjective judgment of decision-makers, and how to scientifically and reasonably determine the weights is a key problem.

To address these challenges, researchers have proposed various integrated assessment methods. One category is monetization methods, which attempt to convert environmental and social impacts into monetary values, thereby unifying them into the economic dimension for cost-benefit analysis. This method is intuitive and easy to understand, but the process of monetizing environmental and social values is controversial and highly uncertain. Another category is Multi-Criteria Decision-Making (MCDM)

methods, which allow for comparison and trade-offs between indicators with different units and are currently the most widely used integrated assessment path. However, when applying MCDM methods, most studies use simplified linear weighting models and inadequately handle the uncertainty and ambiguity in the assessment data.

The hybrid assessment method adopted in this study aims to overcome the above limitations. We first obtain quantitative results for the three dimensions separately through simplified LCA, LCC, and social indicator assessment. Then, we use the Analytic Hierarchy Process (AHP) to systematically obtain judgments from experts and stakeholders on the importance of the dimensions, determining the weights in a structured way to reduce the bias of single decision-maker's subjective judgment. Finally, considering the widespread ambiguity in assessment data and expert judgments, we introduce the Fuzzy Comprehensive Evaluation method to rank the solutions. This combined strategy of "independent quantification + systematic weighting + fuzzy ranking" can ensure the professionalism of each dimension's assessment while improving the scientificity and robustness of the final decision.

D. Computer-Aided Sustainable Design Tools

With the development of information technology, various computer-aided tools have been developed to support sustainable design. These tools can be divided into three categories. The first category is professional assessment software, such as SimaPro and GaBi for LCA, and dedicated modules for LCC. These tools are powerful and have detailed data, but they are often "black box" operations and have low integration with other design tools. The second category is integrated design platforms, such as embedding LCA modules in CAD software, allowing designers to quickly obtain environmental feedback in the early stages of design. These tools improve the convenience of assessment, but their assessment functions are usually simplified and do not integrate economic and social dimensions. The third category is Decision Support Systems (DSS), which are usually based on MCDM models and provide users with solution ranking and sensitivity analysis functions. These tools are very useful in the solution selection stage, but they usually do not have the functions of solution generation and preliminary strategic analysis.

In summary, existing computer-aided tools are mostly "point-like," targeting a specific link in the design process, and lack a full-process, end-to-end decision support system that covers from strategic analysis to solution generation, and then to multi-dimensional assessment and selection. The methodological framework proposed in this study, with its inherent logical structure (strategic-tactical-operational) and modular design (contextual analysis, solution generation, multi-dimensional assessment, solution selection), provides a clear blueprint and algorithmic basis for developing such an integrated decision support system, which is also an important direction for our future work.

IV. RESEARCH METHODOLOGY

To achieve systematic decision support from organizational strategy to product solutions, this study constructs an integrated methodology that includes a theoretical framework, a three-level decision model, multi-dimensional evaluation, and optimal solution selection. This

chapter will elaborate on the composition, process, and core tools of this methodology.

A. Research Strategy and Technical Roadmap

This study adopts a "theory construction - method development - case validation" research strategy. First, based on the theories of sustainable design, value chain, and stakeholders, a "Value Chain-Stakeholder Coupling" analysis framework is constructed as the theoretical cornerstone of the entire methodology. Second, based on this framework, a three-level decision support model encompassing strategic, tactical, and operational layers is developed, with corresponding analysis and evaluation tools integrated. Finally, an illustrative smart home product case is used to apply the proposed method and to examine its applicability, operability, and practical relevance.

The specific technical roadmap is shown in Figure 1, divided into five interconnected stages:

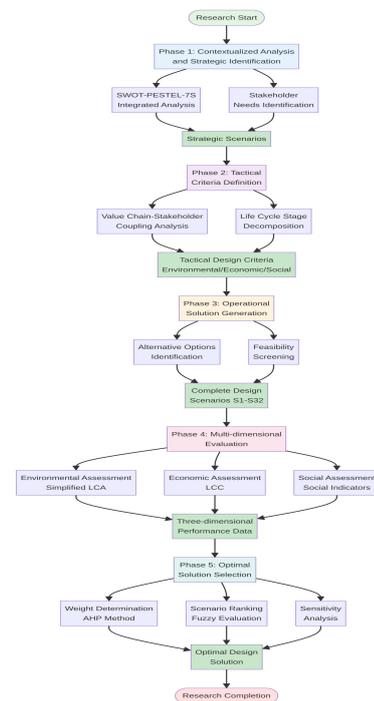


Fig. 1. Research Technical Roadmap

Phase 1: Contextualized Analysis and Strategic Identification: The goal of this phase is to "clarify the direction." Through an integrated SWOT, PESTEL, and 7S model for a comprehensive internal and external environmental analysis, combined with a systematic identification of key stakeholder needs, several macro-level sustainable design strategic scenarios that match the company's development stage and external environment are ultimately formed.

Phase 2: Tactical Criteria Definition: The goal of this phase is to "decompose the objectives." The macro-level strategic scenarios are broken down into specific, measurable tactical design criteria for each stage of the product life cycle (raw materials, manufacturing, distribution, use, disposal), covering the environmental, economic, and social dimensions.

Phase 3: Operational Solution Generation: The goal of this phase is to "formulate solutions." For each tactical criterion, multiple specific and feasible operational

alternative solutions are identified through literature research, industry best practice analysis, and expert interviews. By combining these alternatives, a series of complete, evaluable systematic design scenarios are generated.

Phase 4: Multi-dimensional Evaluation: The goal of this phase is to "quantify performance." Simplified Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and social impact indicator assessment are used to quantify the environmental, economic, and social performance of all generated design scenarios, providing data support for subsequent decisions.

Phase 5: Optimal Solution Selection: The goal of this phase is to "make scientific decisions." The Analytic Hierarchy Process (AHP) is used to determine the weights of each evaluation indicator, and the Fuzzy Comprehensive Evaluation method is used to comprehensively rank all alternative solutions, ultimately selecting the design solution with the best sustainability performance, and conducting sensitivity analysis to test the robustness of the results.

B. Value Chain-Stakeholder Coupling Analysis Framework

This framework is the theoretical core of this study, aiming to break the limitation of independent value chain analysis and stakeholder analysis, establish an organic connection between the two, and thus more systematically identify the key factors affecting sustainable design.

Value Chain Analysis: This study adopts Porter's classic value chain model and extends it to the entire product life cycle, divided into five core stages: raw material extraction, manufacturing, distribution, use, and end-of-life. The analysis focuses not only on the economic activities at each stage but also on identifying the accompanying environmental impacts (e.g., resource consumption, pollution emissions) and social impacts (e.g., labor conditions, community relations).

Stakeholder Analysis: First, based on literature and industry characteristics, nine key stakeholder categories related to the smart home product value chain are identified: suppliers, manufacturers (the company itself), distributors, customers, employees, regulators, community, investors, and non-governmental organizations (NGOs). Then, the classic "influence-interest" matrix is used to prioritize these stakeholders to determine the key objects of concern in decision-making. Finally, through semi-structured interviews, questionnaires, and other methods, the core needs and expectations of different stakeholders in terms of sustainability are deeply understood.

Coupling Mechanism: Coupling is the key innovation of this framework. We systematically analyze the interaction between the two by establishing a two-dimensional matrix of "Value Chain Stage \times Stakeholder," as shown in Figure 2.

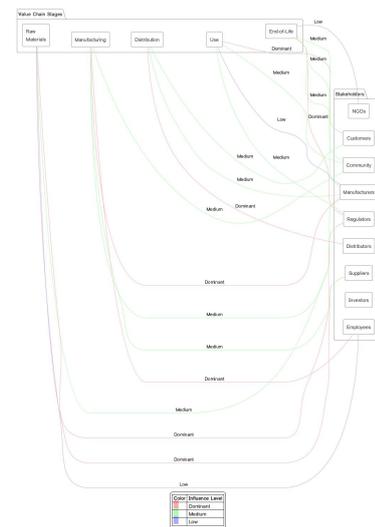


Fig. 2. Value Chain-Stakeholder Coupling Matrix

This matrix clarifies which stakeholders play a dominant role at each stage of the value chain and what their core concerns are. For example, in the raw material extraction stage, suppliers and regulators are the dominant stakeholders, and their core concerns are cost control and environmental compliance, respectively; while in the use stage, customers and the community become the dominant parties, and their core concerns shift to product energy efficiency, user experience, and the convenience of waste disposal. Through this coupling analysis, broad stakeholder needs can be accurately mapped to specific life cycle stages, thereby forming contextualized design constraints and optimization objectives.

C. Strategic-Tactical-Operational Three-Level Decision Model

This model is the core tool for transforming macro-strategies into micro-solutions, and its three-level structure ensures the logical consistency and operability of decisions, as shown in Figure 3.

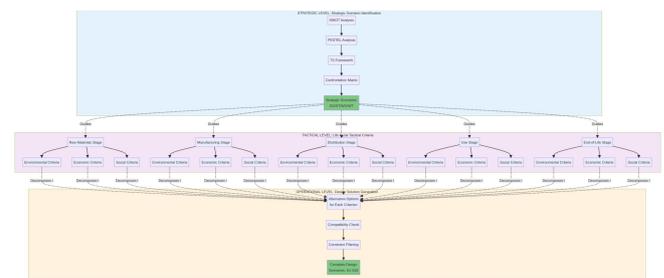


Fig. 3. Three-Level Decision Model

1) Strategic Level: Contextualized Analysis and Strategic Scenario Identification

The goal of the strategic level is to form high-level sustainable design directions based on a deep understanding of the company's internal and external environment. To this end, this study integrates three classic strategic analysis tools:

- **PESTEL Analysis:** Used to systematically scan the external macro-environment and identify opportunities and threats in the political, economic, social, technological, environmental, and legal aspects.

- 7S Analysis: Used to deeply analyze the company's internal capabilities and assess its strengths and weaknesses in the seven aspects of strategy, structure, systems, shared values, skills, style, and staff.
- SWOT Analysis: Integrates the above internal and external factors to form a comprehensive SWOT matrix.

On this basis, this study introduces the Confrontation Matrix, which systematically generates four types of scenarios with clear strategic intent by combining the four elements of SWOT, as shown in Figure 4:

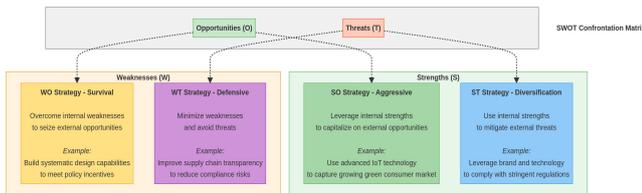


Fig. 4. SWOT Confrontation Matrix

- Aggressive Strategy (SO): Use internal strengths to seize external opportunities.
- Diversification Strategy (ST): Use internal strengths to avoid external threats.
- Defensive Strategy (WT): Overcome internal weaknesses to deal with external threats.
- Survival Strategy (WO): Overcome internal weaknesses to seize external opportunities.

Through expert evaluation, the company can select one or a combination of these four strategies that best fits its current development stage and market environment as the macro-guideline for subsequent design activities.

2) Tactical Level: Life Cycle Tactical Criteria Definition

The goal of the tactical level is to translate the macro-strategic scenarios into executable and measurable design criteria at each stage of the product life cycle. For the selected strategic scenario, combined with the results of the value chain-stakeholder coupling analysis, tactical criteria for the five life cycle stages are defined for the environmental, economic, and social dimensions. For example, if the company chooses a "Diversification Strategy" to cope with strict international environmental regulations, the tactical criteria for the "raw material extraction" stage might include "the proportion of renewable materials used is not less than 30%," "the supply chain carbon footprint must be lower than the industry average," etc.

3) Operational Level: Design Solution Generation and Combination

The goal of the operational level is to find specific technical and managerial implementation paths for the tactical criteria and combine them into complete design solutions. This process is divided into two steps:

Identification of Operational Alternatives: For each tactical criterion, 2-4 specific operational alternative solutions are identified through literature research, patent analysis, industry best practice studies, etc. For example, for the criterion "reduce energy consumption in the use phase," alternatives could include "using higher energy efficiency

grade LED chips," "optimizing circuit design to reduce standby power consumption," "adding smart light-sensing adjustment function," etc.

Design Scenario Combination and Screening: In theory, combining the alternatives for all life cycle stages will produce a huge number of design scenarios (combinatorial explosion). To solve this problem, this study introduces constraints and compatibility checks for screening. Constraints mainly come from limitations in cost, technical feasibility, etc. (e.g., the total cost increase should not exceed 15%); compatibility checks are used to exclude technically or logically incompatible solution combinations (e.g., a certain environmentally friendly material is not compatible with the existing production process). Through preliminary screening, a limited number of representative feasible design scenarios are retained for subsequent evaluation.

D. Multi-dimensional Sustainability Assessment Method

For the screened design scenarios, this study conducts a comprehensive quantitative assessment from the environmental, economic, and social dimensions.

- Environmental Dimension Assessment: A Simplified Life Cycle Assessment (Simplified LCA) method is used. Considering the difficulty of obtaining precise data at the design stage, this study focuses on the key indicators and links that contribute most to the final environmental impact. To improve applicability under limited data conditions, the environmental assessment focuses on a small number of key indicators, with carbon emissions used as the primary reference indicator. The analysis is based on public literature, industry-average data, and reasonable engineering assumptions. The calculation method follows the ISO 14040/14044 standards.
- Economic Dimension Assessment: A Life Cycle Costing (LCC) method is used. The economic assessment mainly considers the major cost components related to materials, manufacturing, and use-stage energy consumption. A simplified life-cycle cost comparison is adopted to support relative evaluation among alternatives.
- Social Dimension Assessment: A Social Impact Indicator Assessment method is used. Based on the United Nations Sustainable Development Goals (SDGs) and S-LCA guidelines, this study constructs an indicator system containing six categories, including labor rights, consumer health and safety, and community impact. The social dimension is assessed using a small set of qualitative indicators, such as user safety, basic compliance, and stakeholder acceptability. These indicators are evaluated through expert judgment and literature-informed scoring.

E. Optimal Solution Selection Method

After obtaining the three-dimensional assessment data for all design scenarios, a hybrid MCDM method is used for the selection of the optimal solution.

Weight Determination: The Analytic Hierarchy Process (AHP) is used to determine the weights of the evaluation indicator system. A small group of domain-informed evaluators is invited to construct the judgment matrix through pairwise comparisons. This method can transform

qualitative preference judgments into quantitative weights and ensure the logical consistency of the judgments through a consistency check ($CR < 0.1$).

9Solution Ranking: Considering the widespread uncertainty and ambiguity in the assessment data and expert judgments, this study uses the Fuzzy Comprehensive Evaluation method for the final ranking. This method uses the membership degree theory of fuzzy mathematics to handle fuzzy information, which can more realistically reflect the "this and that" nature of the evaluation objects. First, the fuzzy membership function of each indicator is constructed; then, combined with the weights determined by AHP, a fuzzy matrix operation is performed to obtain the comprehensive evaluation value of each solution; finally, a clear ranking result is obtained through defuzzification (e.g., the centroid method).

In addition, a basic sensitivity check is carried out by adjusting several key parameters to examine whether the ranking results remain broadly stable.

F. Innovativeness of the Research Methodology

The innovativeness of this research methodology lies mainly in its integration and systematicity. First, it innovatively proposes the Value Chain-Stakeholder Coupling Analysis Framework, which organically combines two important analytical perspectives, providing a more comprehensive and contextualized starting point for sustainable design. Second, the constructed strategic-tactical-operational three-level decision model bridges the decision-making chain from macro-strategy to micro-execution, effectively solving the problem of strategy-design disconnect. Third, its hybrid evaluation and selection method systematically integrates the three dimensions of environment, economy, and society, and comprehensively uses AHP and fuzzy mathematics to handle the complexity and uncertainty in decision-making, improving the scientificity and robustness of the decision. Finally, the entire methodology forms a closed-loop decision-making process from problem identification, solution generation to evaluation and selection, providing companies with an operational and replicable systematic tool.

V. CASE STUDY AND DATA

To validate the effectiveness and feasibility of the decision support method proposed in this study, we selected a leading and representative company in the Chinese smart home industry (referred to as "SmartHome Company" for confidentiality) as the case study subject. This chapter will detail the background of the case company, the data collection process, basic data information, and preprocessing methods.

A. Case Company Background

To illustrate the application of the proposed method, this study considers a representative smart LED bulb as the focal product. The product was selected because it has a relatively clear life-cycle structure, involves typical sustainability issues in materials, manufacturing, use, and end-of-life stages, and is suitable for demonstrating how strategic sustainability considerations can be translated into product-level design decisions.

B. Data Collection Methods

The data used in this study were collected from three main sources. First, public literature and industry reports were reviewed to identify the main sustainability issues and common improvement strategies for smart lighting products. Second, product-related information such as material composition, manufacturing characteristics, use-stage energy features, and end-of-life considerations was compiled from product documentation, comparable market information, and engineering estimates. Third, a small-scale expert consultation was conducted to support indicator weighting and alternative evaluation. Informed consent was obtained from all subjects involved in the study.

C. Basic Data Information

"For the baseline product, the environmental, economic, and social characteristics were described using a set of simplified indicators. The environmental profile mainly focused on carbon-related impacts and energy use; the economic profile focused on major cost components across the life cycle; and the social profile considered several qualitative aspects, including user safety, compliance, and stakeholder acceptability. These baseline descriptions were used as reference points for comparing alternative design scenarios rather than as exact measurements

D. Data Preprocessing Methods

To improve the consistency of the analysis, the collected information was reviewed for completeness and logical consistency. When some values were unavailable, they were estimated using comparable references from published studies or industry-average assumptions. To facilitate comparison across indicators with different scales, the indicator values were normalized before the comprehensive evaluation.

VI. RESULTS

This chapter will systematically present the results obtained from applying the decision support method proposed in this study to the SmartHome Company case. The content will follow the logical sequence from the strategic, tactical, to operational levels, and finally provide the results of the multi-dimensional evaluation, sensitivity analysis, and optimal solution selection.

A. Strategic Level Analysis Results

1) SWOT-PESTEL-7S Integrated Analysis

Through a systematic scan and diagnosis of SmartHome Company's internal and external environment, we identified the following key elements:

- **Strengths:** The company has a strong brand influence and leading R&D capabilities in IoT technology; it has established an efficient and agile supply chain system; senior management has a clear strategic intent and commitment to sustainable development.
- **Weaknesses:** There are significant shortcomings in systematic methods and tools for sustainable design, with design decisions often relying on experience; there is a lack of complete life cycle data collection and analysis capabilities; the transparency and traceability of the supply chain need to be improved.
- **Opportunities:** The global green consumption market continues to expand, with a significant increase in

consumers' willingness to pay for environmentally friendly and healthy smart products; the Chinese government has introduced a series of incentive policies to support green manufacturing and the circular economy; advances in related technologies such as new materials and low-power chips provide possibilities for sustainable design innovation.

- Threats: International regulations such as the EU's Ecodesign Directive and the Carbon Border Adjustment Mechanism (CBAM) are becoming increasingly stringent, posing potential barriers to product exports; intensified homogeneous competition in the industry and price wars are squeezing the profit margins for companies to invest in sustainability; the price volatility and supply uncertainty of key raw materials are increasing.

2) Stakeholder Needs Analysis

Through questionnaires and interviews, we identified the core sustainability needs of nine key stakeholder groups. Among them, customers are most concerned about product energy efficiency, durability, and data privacy protection; the core requirement of regulators is that products must comply with various domestic and international environmental and safety regulations; investors value the company's ESG (Environmental, Social, and Governance) rating and long-term risk management capabilities. According to the "influence-interest" matrix analysis, customers, regulators, and investors were identified as the highest priority stakeholders, and their needs should be given key consideration in subsequent decisions.

3) Strategic Scenario Identification

Based on the SWOT analysis and the confrontation matrix, we generated four types of strategic scenarios. Based on the contextual analysis, a combined strategic orientation emphasizing both risk response and capability improvement was identified as the most suitable direction for the case. This means that the company's sustainable design activities should focus on two core objectives: first, to leverage its technological and brand advantages to actively respond to increasingly stringent international regulations and market competition, and to consolidate and expand its market share by improving the sustainability performance of its products; second, to make efforts to address the shortcomings in systematic design methods and supply chain management to mitigate potential compliance risks and cost pressures.

B. Tactical Level Analysis Results

According to the selected combined strategy, we defined tactical criteria for the five life cycle stages of the smart LED bulb, covering the environmental, economic, and social dimensions. For example, in the raw material extraction stage, the environmental criterion was set to "the proportion of renewable or recyclable materials used is not less than 30%," the economic criterion was "the increase in raw material costs should not exceed 10% while meeting the environmental criteria," and the social criterion was "core suppliers must be certified by the SA8000 social responsibility standard." In the use stage, the environmental criterion was "the product's energy efficiency level reaches the national first-class standard," the economic criterion was "the life cycle cost (LCC) is reduced by at least 5% compared to the baseline product," and the social criterion

was "ensure 100% encrypted transmission and storage of user data."

C. Operational Level Analysis Results

For the above tactical criteria, we identified a series of operational alternative solutions. For example, to achieve the criterion of "the proportion of renewable materials is not less than 30%," the alternatives included: (A1) using bio-based plastics for the lamp body; (A2) using recycled aluminum for the heat sink; (A3) a combination of both. By combining the alternatives for all life cycle stages and screening them using preset cost and technical feasibility constraints, a number of representative feasible design scenarios were generated for subsequent evaluation.

D. Multi-dimensional Evaluation Results

We conducted a comprehensive sustainability performance evaluation of the 32 design scenarios and compared them with the baseline product (S0).

- Environmental Dimension Assessment: The results showed that the environmental performance of different scenarios varied significantly. Taking Global Warming Potential (GWP) as an example, the carbon emissions of the 32 scenarios ranged from 6.2 to 10.5 kg CO₂ equivalent. Among the evaluated alternatives, one representative scenario showed the best overall environmental performance, with a clear reduction in carbon-related impacts compared with the baseline design. The excellent performance of this scenario was mainly due to its use of a high proportion of recycled aluminum in the raw material stage, the use of more than 50% renewable energy in the manufacturing stage, and the design of an efficient closed-loop recycling system at the end-of-life stage.
- Economic Dimension Assessment: In terms of economy, the life cycle cost (LCC) of each scenario ranged from 148 to 198 RMB. Interestingly, some scenarios with excellent environmental performance did not lead to a significant increase in costs. For example, scenario S12, through optimized circuit design and extended product life, had an LCC of 148 RMB, a 5.1% reduction compared to the baseline product (156 RMB), achieving a win-win situation for both environmental and economic benefits. The best-performing environmental scenario involved a modest increase in initial cost, but this increase remained within an acceptable range from a life-cycle perspective.
- Social Dimension Assessment: In the social dimension, the comprehensive score of each scenario ranged from 3.2 to 4.3 (out of 5). The same scenario also showed better social performance than the baseline alternative, especially in terms of user safety, supply-chain responsibility, and end-of-life management considerations. This was mainly due to its strict requirements for supply chain labor rights and enhanced protection measures for consumer data privacy.

E. Optimal Solution Selection and Sensitivity Analysis

Using the AHP method, the weighting results indicated that environmental and economic considerations were slightly prioritized, while the social dimension also played an important supporting role in the final decision. Based on

these weights, the Fuzzy Comprehensive Evaluation method was used to calculate the comprehensive sustainability score of all scenarios. The comprehensive evaluation results showed that one scenario achieved the best overall balance among the environmental, economic, and social dimensions, while several other alternatives also demonstrated competitive performance.

To test the robustness of the results, we conducted a sensitivity analysis. In the weight sensitivity analysis, we varied the weights of the three dimensions within a range of $\pm 20\%$. A basic sensitivity check suggested that the ranking results were relatively stable under moderate changes in key assumptions, indicating that the selected solution had acceptable robustness. This indicates that the superiority of the S18 solution is systematic and not dependent on specific parameter assumptions.

F. Characteristics of the Optimal Solution

The preferred design scenario can be characterized by several improvement directions: increasing the use of recyclable or bio-based materials where feasible, improving manufacturing energy efficiency, adopting lighter and more sustainable packaging, reducing use-stage energy consumption through component optimization, and enhancing disassembly and recovery considerations at the end-of-life stage. These measures together provide a practical illustration of how strategic sustainability goals can be translated into product-level design actions.

VII. DISCUSSION

This section will provide an in-depth analysis of the research results, expound on their theoretical implications and practical value, and compare them with existing research to further clarify the contributions and limitations of this study.

A. Theoretical Implications of the Results

The core theoretical contribution of this study lies in constructing and validating a systematic decision support method that can effectively connect organizational strategy with product design.

First, this study deepens the integrated application of value chain and stakeholder theories in the field of sustainable design. Traditional research often treats the two as separate or performs simple linear superposition. The "Value Chain-Stakeholder Coupling" analysis framework proposed in this study, by establishing a two-dimensional matrix, identifies the dominant stakeholders and their core concerns at different life cycle stages, advancing the integration of the two theories from the descriptive level of "what" to the operational level of "how." This provides a new analytical perspective for understanding the complex context-dependency of sustainable design decisions and offers structured input for subsequent tactical criteria definition and solution generation, which is a deepening and concretization of the contextual design ideas proposed by Sansa et al. (2019) [4].

Second, this study provides an operational path to solve the "strategy-execution gap" problem. By constructing a "strategic-tactical-operational" three-level decision model, this study decomposes the macro, vague corporate sustainability strategy into specific, measurable product design parameters and action plans layer by layer. This

model not only ensures a high degree of consistency between the final design solution and the organizational strategy but also makes the strategy execution process more transparent, traceable, and manageable. Compared with traditional strategy transformation tools such as QFD and BSC, this model is more closely integrated with the particularity of sustainable design, systematically incorporating full life cycle thinking and considerations of the environmental, economic, and social dimensions, thus having stronger domain specificity.

Finally, this study makes a useful exploration of the multi-dimensional evaluation and selection methods for sustainable design. Facing the high complexity and uncertainty in the evaluation process, the hybrid method of "simplified LCA/LCC/social indicators + AHP + Fuzzy Comprehensive Evaluation" adopted in this study balances the scientificity of the evaluation with practical operability. Compared with studies that rely solely on LCA or MCDM methods, this method can more comprehensively integrate quantitative and qualitative information and effectively handle the subjectivity of expert judgments and the imprecision of data through fuzzy mathematics theory, thereby improving the robustness and credibility of the final decision.

B. Practical Value of the Results

For smart home and even broader manufacturing enterprises, this study provides a set of understandable, learnable, and usable decision support tools with significant practical value.

First, it improves the scientificity and efficiency of sustainable design decisions. This method decomposes the complex decision-making process into a series of structured steps, providing a clear roadmap for the design team. Through systematic analysis and quantitative evaluation, it can help companies break away from the previous decision-making model that relied on intuition and experience, reduce trial-and-error costs, and quickly identify the optimal solution that balances environmental, social, and economic benefits among many alternatives. The case analysis suggests that the proposed method can help decision makers move from general sustainability intentions to more structured product-level choices.

Second, it enhances the company's ability to cope with external challenges and seize market opportunities. Through systematic internal and external environmental analysis and stakeholder needs identification, this method can help companies anticipate potential regulatory risks (such as the EU's carbon tariff) and market trends (such as green consumption) in advance and integrate them into product design, turning passivity into proactivity. The optimal solution S18 selected in the case, with its excellent performance in carbon emissions and recyclability, will provide strong support for SmartHome Company to cope with future international environmental regulations and become a "stepping stone" for it to explore the high-end green market.

Third, it promotes cross-departmental collaboration and the formation of internal consensus within the organization. Sustainable design is a systematic project involving R&D, procurement, production, marketing, and other departments. The decision support method proposed in this study, with its clear process and data-based results, provides a common

working language for cross-departmental communication. In the process of applying this method, different departments must work together to complete data collection, solution evaluation, and weight determination, which in itself is a process of building consensus and aligning goals.

C. Limitations and Future Research Directions

Although this study has achieved some innovative results, there are still some limitations that need to be further explored in future research.

First, the generalizability of the case study results needs to be further verified. This study conducted an in-depth case study on a single company, and the results obtained have good internal validity. However, due to the specificity of the industry and the company, whether the method and results can be directly applied to other industries (such as automotive, textiles) or companies of different scales (such as small and medium-sized enterprises) needs to be verified by more case studies.

Second, the data collection and evaluation process can be further optimized. Although this study adopted a simplified LCA method, the data collection workload is still considerable, which may pose a challenge for companies with weak data foundations. Future research can explore how to further simplify the data collection process, such as by developing industry-specific parameter databases or using big data and machine learning techniques to predict life cycle performance.

Third, the development of supporting computer-aided tools is an important direction for future work. The method proposed in this study involves a large amount of data processing and model calculation, and manual operation is inefficient and prone to errors. Developing an integrated decision support software system that integrates the entire process from strategic analysis, solution generation, to multi-dimensional evaluation and selection will greatly improve the usability and application value of this method.

Finally, the dynamic evolution of the decision-making process deserves further attention. This study provides a static decision-making process. However, in reality, the external environment and stakeholder needs are constantly changing. How to establish a dynamic feedback and adjustment mechanism to update the design strategy and solutions in real-time in response to these changes is a topic worthy of in-depth research.

VIII. CONCLUSION

In the context of increasingly severe global sustainability challenges, how to effectively translate macro-level corporate sustainability strategies into micro-level product design solutions has become a key issue that manufacturing enterprises urgently need to solve. This study, aiming at the "strategy-execution gap" in sustainable design, constructs and validates a systematic decision support method from organizational strategy to product implementation.

This study makes three main contributions. First, it proposes an innovative "Value Chain-Stakeholder Coupling" analysis framework, which provides a new perspective for systematically identifying the complex factors affecting sustainable design. Second, it constructs a "strategic-tactical-operational" three-level decision model, which provides a clear and operational path for bridging the gap between

strategy and execution. Third, it develops a hybrid multi-dimensional evaluation and selection method, which effectively handles the complexity and uncertainty in the decision-making process, improving the scientificity and robustness of the decision.

The case study at a leading Chinese smart home company shows that this method can effectively help companies identify the optimal sustainable design solution that balances environmental, social, and economic benefits, providing a powerful tool for the implementation of their sustainability strategies. The illustrative case indicates that the proposed method can support the identification of a design solution with improved environmental and social performance while maintaining reasonable economic feasibility.

In summary, the decision support method proposed in this study provides a systematic solution for manufacturing enterprises to practice sustainable design. It not only has important theoretical significance but also has broad application prospects. We believe that with the continuous deepening of research and the development of supporting tools, this method will play a greater role in promoting the green and sustainable transformation of the global manufacturing industry.

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AUTHOR CONTRIBUTIONS

Muhammad Haziq bin Zainal: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Visualization.

Nur Aina binti Azmi: Supervision, Validation, Resources, Writing – review & editing, Project administration.

COMPETING INTERESTS

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