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LCD-AHP-TRIZ methodology enhances low-carbon principles in smart product design

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With the rapid development of the Internet of Things (IoT) and Artificial Intelligence (AI) technologies, their manufacturing processes have led to an increase in greenhouse gas (GHG) emissions and a significant increase in electronic waste, which adversely affects the global environment. Consequently, green and low-carbon transformation of smart products is imperative. To address the limitations of combining low-carbon principles with complex smart product design, this study proposes an innovative "LCD-AHP-TRIZ" methodology that integrates the full life cycle design (LCD), analytic hierarchy process (AHP), and theory of inventive problem solving (TRIZ) to systematically resolve low-carbon smart conflicts in product design and propose solutions. The method utilizes LCD to construct a low-carbon demand table for the life cycle of smart products, AHP to quantitatively assess the importance of indicators, and TRIZ theory to resolve conflicts, thereby successfully integrating low-carbon demand into smart product design. The applicability and effectiveness of this method were verified using a smart dehumidifier as a case study. The results demonstrate that the method can systematically identify low-carbon design requirements, solve innovation problems, and provide scientific strategies for sustainable development of smart products.

Keywords Low carbon design, Smart products, LCD-AHP-TRIZ integrated approach, Green low carbon transition

In response to climate warming, countries worldwide are implementing green and low-carbon transitions, and many have set their own carbon reduction targets[1–3].For example, the Chinese government announced a strategic plan for a "dual-carbon" goal, aiming to achieve carbon peaking by 2030[4] and carbon neutrality by 2060. With the rapid development and popularization of smart technology, an increasing number of smart products have entered people's lives, including smart home appliances[5,6], smart wearables[7,8], smart pet products[9], and smart fitness products[10]. These smart products not only have the advantages of traditional products but also traditional products. These smart products not only have the functions of traditional products, but also have more powerful computing, networking, and artificial intelligence technologies. In the digital economy era, user preferences for smart products are becoming increasingly dynamic, diversified, and personalized, and the lifecycle of smart products is constantly shortening. Although mass production and the rapid replacement of smart products bring considerable profits to enterprises, they also lead to large greenhouse gas emissions, which have a serious impact on the global climate. Therefore, it is particularly important to consider low-carbon smart product designs. The introduction of low-carbon design breaks the balance of traditional smart product design[11], leading to conflicts between conventional and low-carbon performance.

This study aimed to develop a systematic low-carbon integrated innovation approach using smart products as the research object. This study first developed a low-carbon planning framework that covers the entire life cycle of smart products, and constructed a low-carbon demand table for these products. Subsequently, the hierarchical analysis method (AHP) was used to determine the strategic prioritization of low-carbon design indicators. Finally, the theory of creative problem-solving (TRIZ) method was applied to resolve conflicts in low-carbon design and promote innovative design. The applicability of the method was demonstrated through an empirical application to the low-carbon design of smart dehumidifiers. This study addressed the following three research questions:

Q1: What are the low-carbon design indicators for smart products?

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Q2: Which metrics have a significant impact on the low-carbon design of smart products, and which do not?

Q3: Is this systematic approach applicable and compatible?

This study is significant in three dimensions: theoretical, practical, and social-environmental. In the theoretical dimension, the solutions and theoretical frameworks proposed in this study address research gaps in the application of low-carbon concepts to smart product design, thereby enriching and expanding the connotations and extensions of smart product design research. From a practical perspective, this study focuses on the optimization of smart product design methods and proposes targeted solutions and theoretical frameworks to assist enterprises in creating smart product design solutions that meet market and environmental needs, promote product upgrading, and contribute to the green and low-carbon transformation of smart products. Furthermore, the integration of smart product design and low-carbon concepts has given rise to novel business and service models such as the smart product leasing model based on the sharing economy, which enhances the efficiency of product utilization and reduces resource waste. Concurrently, smart product design encompasses multiple disciplines and technical fields, including artificial intelligence, the Internet of Things, materials science, and environmental science, which promote cross-field collaboration, facilitate technological upgrading and structural adjustment of relevant industries, and support their development in a green and sustainable direction. At the socio-environmental level, the significant reduction in the life cycle of smart products in the digital economy era has resulted in a substantial quantity of obsolete smart products being transformed into electronic waste, posing a considerable environmental burden and presenting an urgent problem requiring resolution. This study closely integrates low-carbon design with smart products, incorporating low-carbon concepts from design inception to provide robust support for environmental sustainability in the digital economy era and effectively addressing the environmental challenges arising from the shortened life cycle of smart products.

Literature review

Low carbon design study

Low-carbon design is a fusion of environmental concepts and design methodologies, emphasizing the reduction of environmental impacts and CO2 emissions throughout the product life cycle[12]. As an important branch of green design methodology, the core of low-carbon design lies in the product design stage because the performance of the product and its impact on the environment are already determined in the design and development stage, accounting for approximately 70–80%[13]. At this stage, designers must fully consider factors such as material selection, production process, usage, and end-of-life recycling to ensure that the product achieves low carbon emissions throughout its lifecycle. Low-carbon design has become an important strategy for industries to realize green transformation. In the fields of architecture, urban planning, and product design, researchers are actively exploring methods and applications of low-carbon design to reduce carbon emissions and promote environmental sustainability.

In the field of low-carbon research, Brooks et al.[14] conducted a comprehensive analysis of carbon emissions from buildings in the UK at various stages using Life Cycle Carbon Assessment methodology and proposed strategies for the implementation of low-carbon design and clean technologies, thereby providing an empirical foundation for the low-carbon transition of the building sector. Evangelos Panos et al.[15] conversely, assessed the pathway to net-zero CO2 emissions in Switzerland from the perspective of energy system transition, emphasizing the critical role of low-carbon technologies, efficiency, and flexibility in the energy transition. Attia et al.[16] examined the leadership role of EU member states in building carbon footprint regulations and analyzed the significant impact of regulations in driving the building sector towards low-carbon and circular development. Lin Chen et al.[17] provided an overview of the role of green buildings in low-carbon city construction, offering theoretical support and practical implications for low-carbon city development from multiple dimensions. These studies have primarily focused on architecture, urban planning, and spatial aspects. However, there is a relative paucity of research in the field of product design, particularly smart product design.

Research on low-carbon products has primarily focused on carbon footprint calculation and assessment. He, Pan, and Deng[18] proposed a product life cycle carbon footprint estimation method based on an undetermined numerical model. Wang et al.[19] proposed a product carbon footprint model based on macroscopic-microscopic design features and calculated the direct and indirect carbon emissions of the whole life cycle of gear hobbing machines. Shi J, Wang Y, Fan S, et al.[20] determined resource consumption, environmental emissions, and economic cost of mechanical product manufacturing from economic and geological dimensions, providing theoretical and data support for energy conservation and emission reduction in mechanical product manufacturing. Zhang et al.[21] utilized activity data and emission factors to establish calculation equations to quantify the carbon emissions in the raw material acquisition stage, the manufacturing stage, and the use stage of the hydraulic press. Guo et al.[22] employed the life cycle assessment (LCA) method to calculate the carbon emissions in the entire life cycle of a friction and wear testing machine. He et al.[23] also utilized the LCA method to calculate the carbon emissions at each life cycle stage of a cold-heading machine. Dong et al.[24] combined Life Cycle Assessment and Life Cycle Costing for eco-design of rubber products. Yi, Wu, C.-F[25] proposed a green extension design strategy to mitigate the environmental impact of existing consumer electronics products.

Intelligent product design research

Smart products were originally typical examples of software-based technologies that were used to track product performance and provide maintenance services. With the rapid development of technology, this concept has expanded to smart connected products. When building smart connected products, the core components should include physical components, intelligent modules, and interconnection functions, which together form the infrastructure of the product to ensure that it realizes true intelligence and interconnectivity. The intelligent components are connected to the physical product through interconnected components to maximize value. This not only emphasizes the intelligent elements within the product but also highlights the interconnectivity between products. Intelligent products are a class of products integrated with advanced technologies that not only have the functionality of traditional products but also enhance user experience, optimize resource utilization, reduce maintenance costs, and create new business models for enterprises through intelligent technologies.

In the field of smart product design, research has predominantly focused on smart interaction experience, smart function expansion, and smart product development. Wang K[26] applies human-computer interaction technology to smart automotive products to enhance the realism and immersion of users' human-computer interaction experience. Rijsdijk and Hultink[27] investigate consumer response to smart products, particularly the effects of various dimensions of smart products on consumer perception. Lee[28] concentrated on the development of user-oriented multi-functional fusion smart fashion products, with the objective of achieving deep integration of fashion and technology. Hou Y[29] examined the utilization of smart technologies to improve user experience and enhance the interactivity of museum visits. However, research on low-carbon smart products has been limited.

Regarding research methods for smart products, Wang et al.[30] proposed an innovative smart system design for household food waste management by integrating the Analytic Hierarchy Process (AHP) and theory of preventive problem solving (TRIZ) methods, focusing on analyzing user needs and exploring intelligent solutions. Lee et al.[31]proposed a novel system approach integrating the advantages of text mining, Quality Function Deployment (QFD), and creative problem solving, which can e establish a foundation for the future development of smart glasses. Dai et al.[32] also designed a foldable isolation device based on the INPD/AHP/TRIZ methodology, which enhances the utility and innovativeness of the device by resolving conflicting design problems. Neira-Rodado D et al.[33] proposed a novel integrated approach that combines Fuzzy Carnot, Analytic Hierarchy Process (AHP), Decision Making Test and Evaluation Laboratory and Quality Function Deployment (QFD) as a key process for smart medical product design. Li X et al.[34] proposed integrating the AHP and QFD methods to construct a hierarchy of user requirements and align them with design specifications to identify specific product function and service design elements.

These studies elucidate the interdisciplinary nature of smart product design, encompassing diverse fields, such as artificial intelligence, anthropology, the Internet of Things, design, and environmental science. Presently, the research methodology of smart product design emphasizes the integration and innovative application of multiple methods. Frequently employed methods include the AHP, QFD, and TRIZ. However, these methods primarily focus on addressing user needs, product functional requirements, and market demands and exhibit notable limitations in addressing the environmental factors of products, particularly in the comprehensiveness and depth of research methods for the low-carbon design of smart products. To achieve this low-carbon objective, there is an urgent need to introduce novel smart-product design methods. Life Cycle Design (LCD) encompasses the entire life cycle of a product, from raw material acquisition to production, use, and disposal, and can assess the environmental impact of a product more comprehensively. Currently, there is a dearth of research that combines the LCD, AHP, and TRIZ methods for the low-carbon design of smart products. Therefore, this study proposes a comprehensive methodology for low-carbon design of smart products that integrates full life cycle design (LCD), hierarchical analysis method (AHP), and theory of creative problem solving (TRIZ). In this approach, the LCD initially identifies comprehensive low-carbon life-cycle design requirements to ensure that low-carbon factors and decarbonization potential are fully considered at all stages of product design. Subsequently, AHP screens the identified low-carbon requirements, quantitatively analyzes the low-carbon design indicators, and prioritizes them. Finally, TRIZ addresses screened and sequenced low-carbon design requirements to resolve unavoidable conflicts and contradictions and provides innovative solutions to optimize resource efficiency and environmental impact. The integrated application of the LCD-AHP-TRIZ methodology is expected to address the challenges of multidimensional demand analysis, low-carbon design solutions, scientific decision-making, and environmental performance optimization in the design of low-carbon smart products[22] and provide robust support for the sustainable development of smart products.

Research limitations

Although the aforementioned research has made significant progress in promoting the decarbonization of traditional products, the existing literature still exhibits notable deficiencies in addressing the emergence and rapid iteration of intelligent products. First, the research scope of low-carbon products is limited, with existing studies on low-carbon product design focusing primarily on traditional mechanical products, whereas research in the domain of intelligent product design remains comparatively scarce. Intelligent products, an emerging and rapidly evolving field, have not yet received adequate attention or comprehensive research regarding their unique design requirements and environmental impacts. Second, research on life-cycle stages is unbalanced. While current research on the full life cycle design of products is expanding and deepening, the majority of studies have concentrated on green design methods and technologies for the back-end stage of the product life cycle or for specific objectives such as green material selection, lightweight design, recycling-oriented design, energy-saving design, and modular design. However, the initial development stage of a product determines more than 70% of its life cycle cost[13] and has extensive implications for low-carbon performance. Consequently, overcoming the barriers between the various stages of a product's full lifecycle and establishing a comprehensive lifecycle design that incorporates low-carbon considerations have become critical research issues. Finally, the integration of smart technology and low-carbon design is insufficient. Although the application of smart technology in product design is becoming increasingly prevalent, research on the combination of smart technology and low-carbon designs remains relatively limited. The novel technology of smart products can facilitate the efficient use of energy and minimize the environmental impact; however, existing research fails to fully explore and utilize the potential of smart technology in promoting low-carbon design and lacks systematic methodologies and case studies to guide the practice of low-carbon design for smart products.

Methodology
Research framework
This study proposes a "LCD-AHP-TRIZ" research framework that integrates the life cycle design (LCD), analytic hierarchy process (AHP), and TRIZ theory for low-carbon design, with the objective of constructing an integrated methodology for the low-carbon design of systematic intelligent products. The framework initially conducts a comprehensive analysis of the entire life cycle of a product using life cycle design methodology and identifies key low-carbon design indicators. Subsequently, it quantitatively evaluates these low-carbon design indicators using an analytic hierarchy process to determine their priorities. Finally, TRIZ theory is applied to address conflicts and contradictions in the design process to propose innovative design solutions. This framework not only effectively facilitates the precise transformation of low-carbon design concepts but also assists smart product designers and manufacturers in seeking the optimal balance between product performance and low-carbon requirements, thereby providing a practical approach to promote socioeconomic progress towards the goal of sustainable development, as shown in Fig. 1.

Phase 1: constructing a low carbon design requirements table based on LCD
In the initial phase, this study developed a life-cycle requirement table for low-carbon smart products by incorporating low-carbon design requirements based on the life-cycle analysis of smart products. This analysis was conducted through a comprehensive literature review of three major databases. The full life cycle requirement table effectively elucidates the low-carbon design requirements of smart products at various stages. Using this methodological approach, 56 low-carbon design requirements were established for smart products, thereby providing a foundation for evaluating the low-carbon levels of smart products and their associated processes.

Phase2: AHP-based screening and weighting analysis of low-carbon demand
The objective of the second stage was to screen and analyze the weights of the 56 low-carbon requirements for smart products. Initially, through a combination of expert interviews and observations of the research participants, 56 low-carbon requirements for smart products were screened for expert consensus, resulting in 25 low-carbon indicators. Subsequently, the Analytic Hierarchy Process (AHP) was utilized to construct a three-tiered structural model comprising the goal, criterion, and indicator layers. Finally, expert evaluation was conducted.

Phase 3: low-carbon conflict resolution and innovative design based on TRIZ
In the domain of smart product design, the incorporation of low-carbon indicators frequently disrupts established design equilibrium and engenders conflicts across various aspects. These conflicts extend beyond the mere adjustment of product functions and performance, potentially affecting the manufacturing processes, cost-effectiveness, and other critical areas. By implementing conflict resolution strategies for the low-carbon design of smart products based on the TRIZ, it is possible to identify specific innovative design strategies and methodologies for each low-carbon indicator. These innovative design approaches are generalizable and can serve as valuable references for low-carbon design of smart products.

Phase 4: design verification
In this phase, we selected a smart dehumidifier as a representative smart product for low-carbon design[35] verification. Utilizing the fuzzy evaluation method, the research results from the initial three phases were applied for the design verification. User representatives were invited to evaluate the low-carbon design solution of the smart dehumidifier in order to determine the validity of the conclusions or strategies derived from the first three stages.

Research methodology
Full life cycle design (LCD)
Product Life Cycle Design is understood as the "development" of a holistic concept of the entire life cycle of a product, a concept discussed in detail in the 2009 book Design of Sustainable Product Life Cycles[36]. The book states that product life cycle design involves planning at the product conceptualization stage to determine the path of the product through the entire life cycle[36]. These include service planning, material recovery methods, component reuse, recycling logistics organization, and subsequent use of the product. The U.S. The Environmental Protection Agency (US EPA) proposes that Product Life Cycle Design is the application of a full life cycle framework to the actual product development process to minimize the total aggregate risks and environmental impacts throughout the product's life cycle[37]. This approach emphasizes the balancing of environmental, product performance, cost, social impact, and legal and regulatory requirements during the design process. KATO and other scholars[38] have defined full life cycle design as a design process from macro to micro and from whole to detail, including the business strategy of the product, product life cycle strategy, product, and life cycle process. Hauschild, Herrmann, Kara, and others point out[39]that the core of product lifecycle design is to establish a link between engineering design activities and sustainability requirements. This method integrates multidisciplinary knowledge, such as material science, environmental science, and economics, breaks down disciplinary barriers, and promotes the innovative integration of knowledge. The application of product lifecycle design allows for a comprehensive review of the low-carbon design needs of smart products and the incorporation of low-carbon design into the conceptual pre-design of product lifecycle[40].

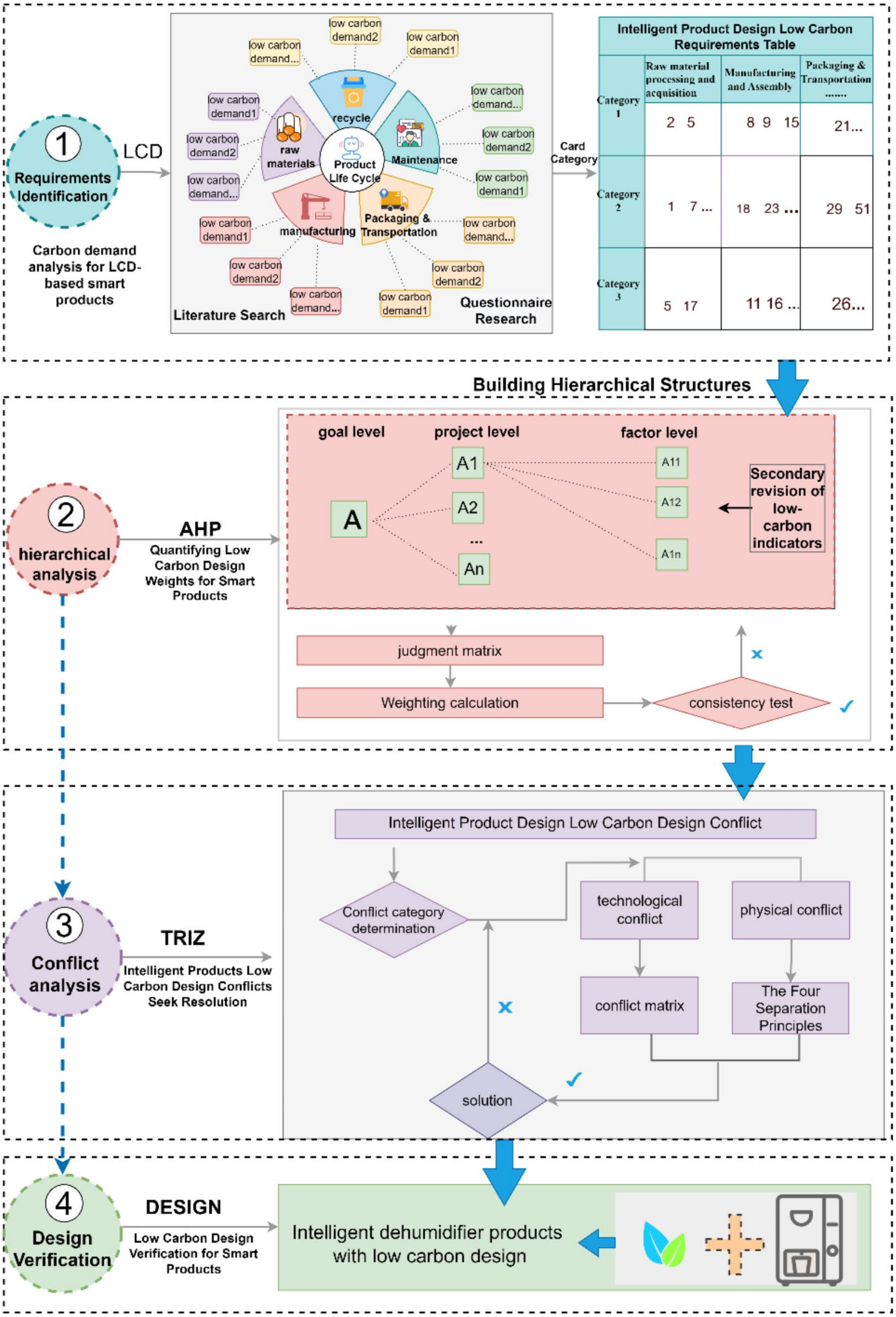

Fig. 1. "LCD-AHP-TRIZ" research framework from a low carbon perspective.

Card taxonomy

Card Sorting is an approach that combines qualitative and quantitative methods to elucidate a user's cognitive model and information organization pattern by asking the user to sort through a series of labeled cards[41]. The procedure consists of the following steps:

(1) Prepare the cards: Label each card with a concept or information item, and ensure randomization of the card order to minimize categorization bias. Select the appropriate type of card categorization: open, closed, or hybrid.
(2) Implement card sorting: Explain the purpose of the activity and content of the cards to participants to ensure that they understand the meaning of each card. Without disturbing the participants, we observed and recorded their categorization behavior and reasoning. After completing the categorization, participants' final results were recorded, including the names of the categories they generated and the cards assigned to each category.
(3) Analysis of results: We synthesized the categorization results from all participants and analyzed common categorization patterns and category nomenclature.

AHP hierarchical analysis

The hierarchical analysis method (AHP)[42] is a systematic hierarchical analysis method combining qualitative and quantitative analysis proposed by the American operations researcher L. Saaty, was initially proposed in the 1970. This method mathematizes the thinking process of complex systems, transforms qualitative analysis, which mainly relies on subjective judgment, into quantitative analysis, quantifies the differences between the evaluation factors, and determines the weights of each evaluation factor. AHP can solve problems that traditional optimization methods cannot solve, and is especially suitable for fuzzy comprehensive evaluation systems[43]. As an effective multi-criteria decision analysis tool, AHP is characterized by simplicity and efficiency, and plays a key role in multi-criteria decision problems[44]. The application of AHP is particularly widespread in complex systems such as the entire life cycle design of intelligent products. Because of the complexity of the factors involved, AHP can be used to systematically determine the importance and priority of each index and provide a basis for design decisions. The steps for solving the weights using AHP are as follows.

(1) Classification of the progressive hierarchy of the requirements system: The collected user requirements were categorized to establish a hierarchy of user requirements. The hierarchy of the model includes the total target requirements at Level 1, the sub-requirements at Level 2, which are refined from Level 1, and the sub-requirements at Level 3, which are refined from Level 2. The number of levels in the requirement hierarchy is closely related to the degree of refinement of the requirements, and the degree of refinement of the requirements will change accordingly for different products and different stages of their development iterations.
(2) Constructing the judgment matrix of relative importance of each demand level: After constructing the user demand hierarchy, domain experts are invited to compare the relative importance of each demand in the matrix and score it, and the numbers 1–9 and their reciprocals are used as the scales of the judgment matrix A, i.e., $A = (a_{ij})_{n\times n}$, in which a_{ij} denotes the quantitative value of the degree of importance of i indicators in relation to the indicators of j, and n is the number of indicators of a certain level. Scale of judgment matrix and its definition. Subsequently, the judgment matrix of user requirements[42] of $A_1 - A_m$ sub-demand relative to the total goal of demand is constructed sequentially $A_{11} - A_{1n}$ The judgment matrix of user requirements of tertiary demand relative to sub-demand until $A_{m1} - A_{mn}$ The judgment matrix of user requirements of tertiary demand relative to sub-demand (see Table 1).
(3) Calculate the relative weight of the demand: then calculate the geometric mean of each layer of factors separately according to the judgment matrix: $\bar{w_i} = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}$, normalize the w_i to determine the proportion of each factor in the single sort:

$$w_i = \frac{\bar{w_i}}{\sum_{i=1}^{n} wi}$$

Test the consistency of the judgment matrix[43]: In order to determine the extent to which the judgment matrix deviates from the consistency, the consistency indicator CI is introduced to calculate the judgment matrix, calculated as shown,

9-level scale	Interpretation (comparing the importance of evaluation indicators with r_i vs. r_j)
1	Evaluation indicator r_i is as important as r_j
3	Evaluation indicator r_i is slightly more important than r_j
5	Evaluating Indicators r_i and r_j is significantly important
7	Evaluation metrics r_i and r_j are strongly important
9	Evaluation metrics r_i and r_j are extremely important
2,4,6,8	Median value of upper neighboring scales
reciprocal	When the evaluation indicator r_i is compared with r_j, its judgment value is $C_{JI} = 1/C_{IJ}$, $C_{JI} = 1$

Table 1. Judgment matrix scaling and its interpretation.

$$CI = \frac{\lambda_{max} - n}{n-1}, CR = C1/R1 .$$

When $CR < 0.1$ passes the test, the final composite weight is calculated.

TRIZ conflict resolution
TRIZ is an innovative method that provides a framework and tools for solving complex engineering problems through problem-conflict analysis[45]. The core idea is to find innovative solutions by analyzing conflicts and potential conflicts in existing systems. TRIZ conflicts are divided into two main categories: physical and technological conflicts. TRIZ includes eight laws of evolution for technological systems[45](the law of increasing ideality, law of unbalanced subsystems, law of dynamics and controllability, etc.), scientific methods of problem analysis (functional analysis, object-field model analysis, etc.), problem-solving tools (76 standard solutions, knowledge base of scientific principles, principle of separation, 40 principles of innovation, invented problem-solving algorithms, conflict matrix method, material field analysis, 39 engineering and technical characteristics), and many others. These theories and methods have become core forces that drive product innovation and design. In the low-carbon design of smart products, designers can apply the principles and steps of TRIZ to find innovative solutions by changing materials, improving the design structure, or introducing new technologies while pursuing the goals of increasing resource efficiency, reducing energy efficiency, and lowering environmental impacts[46–48].

Fuzzy integrated evaluation method
The fuzzy comprehensive evaluation method[49]is a type of evaluation methodology based on fuzzy mathematics, which quantitatively and comprehensively evaluates the evaluation object and its multiple factors through the theory and methods of fuzzy mathematics. This approach enables the transformation of qualitative evaluation into quantitative assessment[49], rendering the evaluation results more precise and systematic. It effectively addresses fuzzy and difficult-to-quantify problems[50], and is applicable to various uncertainty issues. The specific procedural steps are as follows.

The first step establishes the set of evaluation factors U: It is the set of factors that are taken into account when evaluating the object of evaluation, and the formula is expressed as $U = \{1, 2, 3, \ldots, \mathrm{n}\}$.

The second step to determine the evaluation set V: refers to the evaluation of the evaluation object set the collection of the various levels, the formula expressed as $\mathrm{V} = \{1, 2, 3, \ldots, \mathrm{n}\}$.

The third step determines the weighting set A: it refers to the quantification of the importance of each evaluation factor, and the formula is expressed as $A = \backslash$ left$\backslash$ $\{1{,}2, 3 \ldots \backslash$ left. n$\backslash$ right$\backslash$ $\}\backslash$ right.1,2, 3…n, $A = \{a1, a2, \ldots, an\}$,and the elements in the weight set need to satisfy: each element is greater than or equal to zero, this step applies the expert scoring method.

In the fourth step, the fuzzy matrix R is calculated: it refers to the matrix of corresponding values formed between each rating factor and each rubric, and the formula is expressed as $\begin{bmatrix} r_{11} & r_{12} & \ldots & r_{1n} \\ r_{21} & r_{22} & \ldots & r_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ r_{n1} & r_{n2} & \ldots & r_{nm} \end{bmatrix}$

,and finally the comprehensive evaluation results are determined as B: the fuzzy comprehensive evaluation is carried out through the fuzzy relationship matrix R and the weight vector A, and the formula is expressed as $B = A \times R$.

Data sources

Stage 1: screening of low-carbon demand indicators for smart products
Utilizing "low-carbon smart product design" as the key search term, this study identified 208 relevant publications in the Knowledge Network and Web of Science databases through a systematic literature review. This study integrates five key stages of the smart product life cycle: material processing and acquisition, manufacturing and assembly, packaging and transportation, use and maintenance, and recycling and disposal. It compiles 223 low-carbon keywords from a comprehensive multidimensional perspective, as shown in Fig. 2. This compilation constitutes the initial step in keyword screening facilitated by the literature review method. During the keyword screening process, the word cloud function of the professional statistical analysis software SPSSAU was employed during the first round of screening. To identify more representative and meaningful keywords, a questionnaire was administered during the second screening round. This study carefully selected 30 experts in the field of product design, comprising 10 university faculty members, 10 corporate designers, five corporate engineers, and five retail salespeople, to evaluate low-carbon demand keywords for smart products.

Stage 2: classification of low-carbon demand indicators for smart products
To further distill the representative categories of low-carbon needs, this study employed a cardinality taxonomy for categorization. Given the significance of the level of understanding of low-carbon design terminology and smart products, 15 postgraduate students who had completed their studies on smart product design were invited to participate. They were allocated 2 h to categorize the 56 keywords using an open-ended card-sorting method.

However, upon assessment of these low-carbon needs, it was determined that there is insufficient correlation between certain needs and smart products. To address this issue, a refined screening process was conducted.

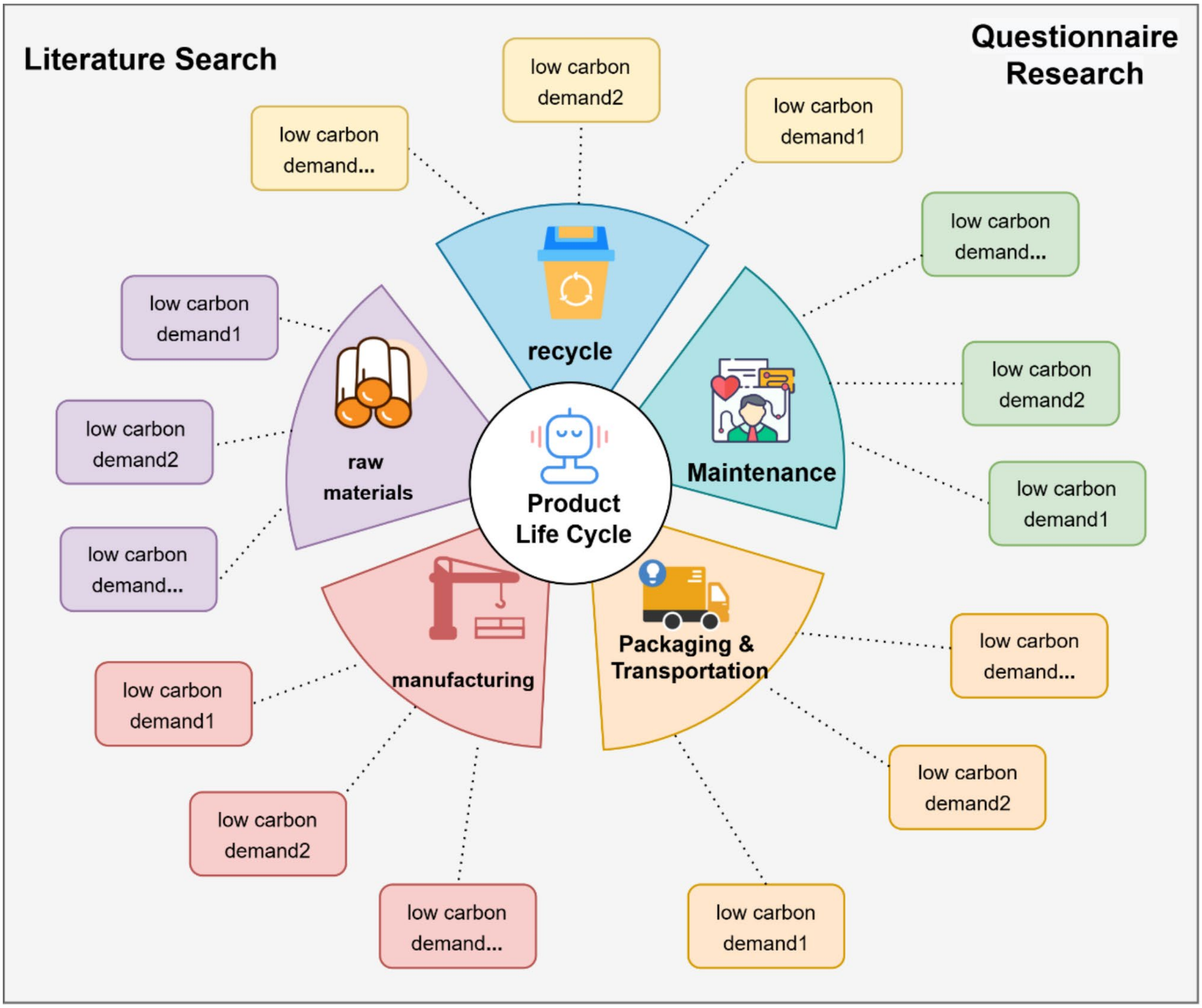

Fig. 2. Product Life Cycle Diagram.

Keywords with similar content were examined, and through this process, the 25 low-carbon requirements with the highest correlation with the low-carbon requirements of smart products were selected to form the final indicator system of this study.

Stage 3: weighting analysis of low-carbon indicators for smart products
In accordance with the low-carbon demand system for smart products, this study employed the Analytic Hierarchy Process (AHP) to develop a research questionnaire. The study successfully recruited 32 participants, including product designers (eight), user representatives (16), and industry salespeople (eight), to complete the survey. The 32 questionnaires were distributed to experts via electronic mail and WeChat, resulting in 32 valid responses with a final response rate of 100%.

Results

LCD-based low carbon design requirements identification results for smart products

In this study, the collected keywords were statistically analyzed for word frequency using the professional statistical analysis software SPSSAU and its word cloud function. After rigorous screening, keywords with a word frequency of less than three were eliminated, and 121 high-frequency keywords were ultimately identified to construct a pool of indicators for the low-carbon design requirements of smart products. On this basis, this study employed a questionnaire research method to present 121 keywords of low-carbon design needs for smart products on white paper to ensure legible handwriting and a logical layout for expert review. Experts were invited to evaluate the keywords independently and objectively based on their professional knowledge and practical experience in the field of smart product design and low carbon, fully respecting their subjective judgment and minimizing external interference. Through statistical analysis of the experts' selection results, 56 keywords with a frequency of more than five words were identified, thus forming the initial draft of keywords for the life cycle of smart products.

Subsequently, 56 keywords were categorized using an open-card classification method. The experimental procedure is as follows:

Experiment Preparation: 56 keywords were numbered and printed on blank cards with uniform specifications.

Execution of the experiment: A sufficiently large table was prepared, and participants were informed that the 56 keywords represented the low-carbon needs of the smart products. They were instructed to divide words with similar meanings into groups, according to their perceptions. The number of groups was not restricted, and minimizing the number of groups was encouraged.

Grouping information collection: The number of groups formed by each participant and the number of keywords in each group were recorded, as shown in Fig. 3.

Category identification was conducted based on the multiple low-carbon requirements within each category. Following the statistical analysis, five distinct categories of low-carbon requirements for smart products were established: energy efficiency, design, technology, environment, and cost.

Utilizing these five categories, five life-cycle stages, and 56 low-carbon demand indicators, a low-carbon smart product life-cycle demand table was constructed to form the initial indicator pool for this study. A 5 × 5 low carbon demand table was developed for this investigation. The model incorporates the product life cycle on the horizontal axis and five major categories of low-carbon requirements on the vertical axis, thereby effectively illustrating the low-carbon design requirements of smart products at different stages. The five categories are energy efficiency, design, environment, technology, and cost, as shown in Fig. 4.

In terms of energy efficiency, it mainly includes low-carbon needs such as using clean energy (1), improving equipment operation efficiency (21), low energy efficiency usage patterns (38), and low energy efficiency recycling and processing (34); in terms of design, it mainly includes designing for the use of recyclable and biodegradable materials (36), designing for the digital simulation of products (36), designing for separable packaging of products (13), and designing for multi-functional use (50), component modularization design (29) and other low-carbon needs; in the environmental aspect, it mainly includes biodegradable materials (10), environmentally friendly production processes to reduce pollutant emissions (22), to strengthen the management of e-waste (39), to achieve product recycling (40) and other low-carbon needs; in the technical aspect, it mainly includes the tracing of the source of the material (43), intelligent low-carbon production processes (49), low-carbon packaging based on intelligent technology (41), intelligent safety and protection (41), and low-carbon packaging based on intelligent technology (42). packaging (41), intelligent safety and protection technology (45), intelligent product recycling monitoring (23), and other low carbon requirements. Cost mainly includes reducing the cost of material recycling (20), reducing the cost of manufacturing (11), reducing the cost of technological inputs (8), reducing the cost of the user (4), and other low-carbon needs.

AHP-based evaluation system for low-carbon design of smart products and weighting analysis of low-carbon indicators

Determination of AHP-based evaluation system for low-carbon design of smart products

The indicators of low-carbon design of intelligent products are multilevel and multifactorial problems. In order to systematically analyze and determine these indicators, through card taxonomy and secondary modification, we determined a three-level evaluation system for low-carbon design of smart products, and the evaluation system item level includes energy efficiency A_1, design A_2, environment A_3, technology A_4, and cost A_5, energy efficiency level A_1 focuses on applying clean energy A_{11}, improving the efficiency of equipment operation A_{12}, optimizing

Low Carbon Requirement Card Classification for Intelligent Products	
Category 1:	1、9、16、21、38、34、42、46、48...
Category 2:	2、5、13、14、18、25、28、29、31、35...
Category 3:	3、7、10、22、24、27、32、39、40、47...
Category 4:	6、12、15、19、23、26、30、37、41、43...
Category 5:	4、、8、11、17、20、33...

Fig. 3. Categorization of low carbon demand cards for smart products.

Intelligent Product Design Low Carbon Requirements Table					
	Raw materials selection & processing	Manufacturing & Assembly	Packaging & Transportation	Use & Maintenance	recycling process
Energy efficiency	56、1、51	9、21、16	42	38、48、46	34、54、55
Design	36	5、35、53、2、18	14、31	25、50、28	25、29
Environment	32、10、27	52、24、22	47	39	3、7、40
Technology	15、43、44	49、26、30、6	41	12、45、19	23、37
Costs	20	11、8	33	4	17

Fig. 4. Low-carbon design requirements identification for the whole life cycle of smart products.

the production process A_{13}, energy recycling A_{14}, and adjusting of fuel ratios A_{15} five indicators; design layer A_2 focuses on five indicators: digital simulation design of products A_{21}, lightweight design of components A_{22}, standardized design of components A_{23}, modular design of components A_{24}, and integrated design of products A_{25}; environmental layer A_3 focuses on the five indicators of carbon dioxide recovery A_{31}, clean production A_{32}, noise-reducing structures and material applications A_{33}, strengthening e-waste management A_{34}, and use of biodegradable recycled materials A_{35}; and the technology layer A_4 focuses on the five indicators of intelligent security protection technology A_{41}, intelligent repair and diagnostic technology A_{42}, and intelligent operation and interaction technologiesA_{43}, carbon capture, carbon capture, separation and storage technologies A_{44}, and smart traceability and recycling guide A_{45} five indicators; and the cost layer A_5 involves reduce material recycling costs A_{51}, reducing manufacturing costs A_{52}, reducing user costs A_{53}, reducing technological input costs A_{54}, and reduce recycling costs A_{55} five indicators, as shown in Fig. 5.

AHP-based weighting analysis of low-carbon design indicators for smart products

Following the clarification of the low-carbon indicator system, the geometric mean of the 32 scale values was calculated to aggregate the data through expert evaluation and obtain a new aggregated judgment matrix, A'. Using the five indicators in the Level 1 guideline layer as an example, weight values for each indicator were derived according to the Analytic Hierarchy Process (AHP) calculation procedures (see Table 2).

The above table yields W = (0.2025,0.1630,0.2668,0.2244,0.1432), which allows the maximum eigenvalue $\lambda\, max$ = 5.0157 to be found, and the consistency index test can be performed. By calculating $c_1 = \frac{\lambda\, max - n}{n-1} =$ 0.0039, CR $= \frac{C1}{R1} = 0.0035$. The consistency ratios of the groups for the second-level criterion, presented in Table 3, show that all CR values remained below 0.1, which is regarded as a verification of the transferability of the aggregated judgment matrix. Therefore, the consistency is acceptable. Consequently, the results of the assessment of the importance of each indicator are considered reasonable.

Ultimately, by multiplying the item-by-item multiplication of the weight values of the first-level item level and the factor level, the combined weight value of each second-level requirement in the overall target requirement architecture is calculated and ranked in order of magnitude. The detailed results are presented in Table 4.

From the combined weights of the indicators in Table 4, it is evident that the Level 1 guideline tier emphasizes the environmental and energy efficiency aspects more than the other tiers. Examining the Level 2 indicator layer, the top 12 indicators with higher weights were selected as key requirements and categorized into three tiers to identify essential low-carbon design indicators for smart products.

As shown in Table 5, among the low-carbon design indicators for smart products, the notable Level 1 indicators are the use of biodegradable recycled materials A_{35}, use of clean energy A_{11}, carbon dioxide recovery A_{31}, intelligent operation and interaction technology A_{43}. The notable Level 2 indicators are energy recycling A_{14}, intelligent security protection technology A_{41}, trengthening e-waste management A_{34} and reduce recycling costs A_{55}. Level 3 significant indicators are carbon capture, separation, and storage technologies A_{44}, clean production A_{32}, modular design of components A_{24}, smart traceability, and recycling Guide A_{45}. These tertiary indicators are important for low-carbon design of smart products.

Fig. 5. Low-carbon evaluation system for smart products.

	A1	A2	A3	A4	A5	Wi
A1	1.0000	1.3862	0.6686	0.8639	1.5037	0.2025
A2	0.7214	1.0000	0.6323	0.7161	1.2475	0.1630
A3	1.4957	1.5817	1.0000	1.2784	1.5713	0.2668
A4	1.1576	1.3965	0.7822	1.0000	1.6110	0.2244
A5	0.6650	0.8016	0.6364	0.6207	1.0000	0.1432

Table 2. Aggregation judgment matrix A.

Conflict problem solving results for TRIZ-based low carbon design of smart products

Through a comparative analysis of the key issues presented in Table 5, TRIZ conflict-resolution theory was implemented for innovative design. Two categories of physical conflict and three categories of technical conflict were transformed through conflict analysis and table examination, as presented in Table 6.

	A1	A2	A3	A4	A5
CR	0.0125	0.0006	0.0071	0.0030	0.0077

Table 3. Consistency ratios for level 2 indicator tiers.

Level 1 Criterion Layer A (weights)	Level 2 Indicator Layer	Combined weights	arrange in order
Energy efficiency A1 (0.2025)	Use clean energy A_{11}	0.0705	2
	Improvement equipment operating efficiencyA_{12}	0.0192	24
	Optimization of production process A_{13}	0.0350	13
	Energy recycling A_{14}	0.0525	5
	Adjustment of fuel ratios A_{15}	0.0252	22
Design A2 (0.1649)	Digital simulation design of products A_{21}	0.0348	14
	Lightweight design of components A_{22}	0.0280	20
	Standardized design of parts A_{23}	0.0296	19
	Modular design of components A_{24}	0.0378	11
	Integrated product design A_{25}	0.0327	17
Environment A3 (0.3081)	Carbon Dioxide Recovery A_{31}	0.0613	3
	Clean production A_{32}	0.0408	10
	Noise-reducing structures and material applications A_{33}	0.0324	18
	Strengthening e-waste management A_{34}	0.0502	7
	Use of biodegradable recycled materials A_{35}	0.0821	1
Technology A4 (0.2022)	Intelligent Security Protection Technology A_{41}	0.0511	6
	Intelligent Repair and Diagnostic Technology A_{42}	0.0332	16
	Intelligent Operation and Interaction Technology A_{43}	0.0583	4
	Carbon capture, separation and storage technologies A_{44}	0.0443	9
	Smart Traceability and Recycling Guide A_{45}	0.0375	12
Cost A5 (0.1383)	Reduce material recycling costs A_{51}	0.0333	15
	Reduce manufacturing costs A_{52}	0.0275	21
	Reduced user costs A_{53}	0.0171	25
	Reduce technology input costs A_{54}	0.0208	23
	Reduce recycling costs A_{55}	0.0445	8

Table 4. Combined weighting results.

Onflict number	Low Carbon Design Indicators for Smart Products			
Level 1	Use of biodegradable recycled materials A_{35}	Use clean energy A_{11}	Carbon Dioxide Recovery A_{31}	Intelligent Operation and Interaction Technology A_{43}
Level 2	Energy recycling A_{14}	Intelligent Security Protection Technology A_{41}	Strengthening e-waste management A_{34}	Reduce recycling costs A_{55}
Level 3	Carbon capture, separation and storage technologies A_{44}	Clean production A_{32}	Modular design of components A_{24}	Smart Traceability and Recycling Guide A_{45}

Table 5. Key indicators for low-carbon design of smart products.

Conflict number	Design requirements	Type of conflict	contradiction parameter	Inventive principle serial number
1	Use of biodegradable and recycled materials	Technological conflict	Intensity 14 Harmful factors arising from VS objects31	35 40 27 39
2	Use clean energy	Physical conflict	Time separation	9, 10, 11, 15, 16, 18, 19, 20, 21, 29, 34, 37
3	Carbon Dioxide Recovery	Physical conflict	Condition-based separation	1, 7, 22, 25, 23, 8, 14, 25, 13
4	Intelligent Operation and Interaction Technology	Technological conflict	Degree of Automation38 VS Complexity of Control and Testing37	34 27 25
5	Energy recycling	Technological conflict	Operability 33 vs. time loss 25	4, 28, 10, 34

Table 6. Transformation of TRIZ problems for conflicting issues.

For each of the above five conflict issues, one technical conflict and one physical conflict were selected for specific analysis.

(1) Utilization of biodegradable and recyclable materials can enhance environmental compatibility and contribute to low-carbon objectives. However, such materials often exhibit inferior mechanical strength compared with traditional materials, which presents challenges in meeting the requisite stability and reliability of smart products. Consequently, the structural integrity of smart products and mitigation of environmentally detrimental factors constitute a pair of technical conflicts. Based on technical conflict analysis, key principles such as 35, 40, 27, and 39 were identified to resolve the conflict by examining the 39 × 39 conflict matrix.
(2) The implementation of clean energy technologies aims to reduce environmental management costs and energy-related risk. However, the associated high technology and equipment costs present a significant contrast, particularly in the input, production, and utilization phases, and constitute a physical contradiction to the low costs of environmental management. This physical contradiction can be addressed by applying the time separation principle, which is one of four separation principles. By examining the 39 × 39 matrix of contradictions, several inventive principles were identified to address this issue, including 9, 10, 11, and 15 principles.

Practical validation results

The increasing demand for improved air quality and enhanced living comfort has led dehumidifiers to become essential appliances in numerous households. Dehumidifiers effectively reduce the proliferation of bacteria and molds in high-humidity environments, thereby protecting human health and preserving furniture and electrical equipment, thereby extending operational lifespans. However, traditional dehumidifier products exhibit limitations, such as substantial power usage and poor choice of materials throughout their life cycle. With the continuous advancement of intelligent technology, dehumidifier products are undergoing upgrades, and have become representative examples of the transformation from traditional to intelligent products. Consequently, the aim of this design is to create an intelligent dehumidifier that complies with low-carbon design principles, aiming to achieve both environmental sustainability and an enhanced user experience.

Low carbon demand identification for LCD-based smart dehumidifier

To enhance the low-carbon performance of dehumidifiers more effectively, it is imperative to conduct a comprehensive analysis of their equipment lifecycle. Based on the low-carbon design demand identification table for the product's full life cycle presented in Table 1 and in conjunction with the specific characteristics of the dehumidifier products, the low-carbon requirements for intelligent dehumidifiers are identified.

(1) Raw material stage.

Refrigerants utilized in dehumidifier products, such as chlorofluorocarbons (CFCs), have a considerable adverse impact on the environment as they possess the capacity to deplete ozone shields and thus exacerbate global warming trends, corresponding to the low-carbon requirements of No. 32 (replacement of low-toxicity materials) under the environmental category.
Dehumidifier products employ non-renewable or difficult-to-recycle materials such as plastics and metal alloys containing hazardous substances, which consume substantial amounts of energy during the production process and are extremely challenging to degrade or recycle after use, thereby imposing long-term environmental pressure. This corresponds to the low-carbon needs of the Technology and Environment Categories No. 27 (use of environmentally friendly materials) and No. 36 (design of recyclable and biodegradable materials).

(2) Processing and manufacturing.

Compression refrigeration technology has been widely implemented for dehumidifiers. However, its substantial energy usage and poor energy efficiency characteristics contradict the core concepts of contemporary energy conservation and emission reduction. This corresponds to the life-cycle stage of energy efficiency under Category No. 21 (improving the operational efficiency of equipment) for low-carbon needs.
For dehumidifiers, such as industrial and household products, the susceptibility of their key components to failure necessitates their frequent replacement. However, limited product disassembly options impede the component replacement process, resulting in increased product utilization costs. This corresponds to the low-carbon needs of design category 5 (design for the easy replacement of damaged components) and low-carbon needs of cost category 8 (reduction in technical input costs).

(3) Utilization of the maintenance phase: Traditional dehumidifier products are undergoing intelligent transformation and upgrading, necessitating the implementation of intelligent technologies to achieve advanced control of dehumidifiers, remote monitoring, energy-efficiency optimization, and low-carbon environmental protection. This corresponds to technology categories 12 (intelligent operation and interaction technology), 45 (intelligent safety and protection technology), and 19 (intelligent maintenance and diagnostic technology) for low carbon demand.
(4) Packaging and transportation stage: The emergence of new intelligent technologies enables intelligent packaging to achieve comprehensive product tracking, optimize transport routes, reduce logistics costs,

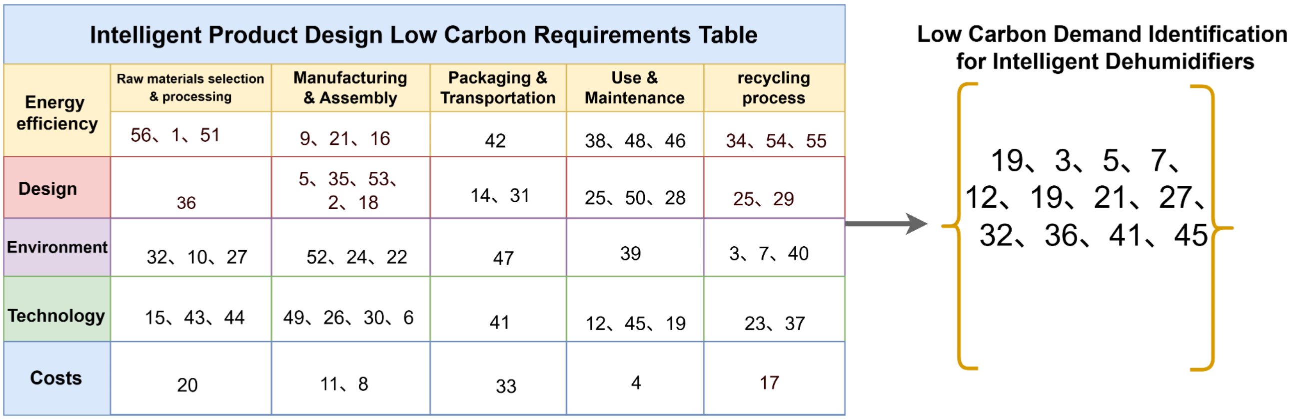

Fig. 6. Low carbon demand identification for smart dehumidifiers.

Serial number	Low carbon design requirements	Low-carbon design indicators	Indicator weights
1	Compressor refrigeration energy efficiency 21	Improvement equipment operating efficiencyA_{12}	Sort 24
2	Difficulty in replacing parts5	Modular design of components A_{24}	Sort 11 (√)
3	non-recyclable material applications2, 27	Use of biodegradable recycled materials A_{35} Carbon Dioxide Recovery A_{31}	Sort 1 (√) Sort 3 (√)
4	Refrigerant impact on the environment	Use clean energy A_{11}	Sort 2 (√)
5	Ineffective utilization of water resources1,3,7	Energy recycling A_{14}	Sort 5 (√)
6	Intelligent technology use 12, 45, 19, 41	Intelligent Security Protection Technology A_{41} Intelligent Repair and Diagnostic Technology A_{42} Intelligent Operation and Interaction Technology A_{43}	Sort 6 (√) Sort 4 (√) Sort 16
7	Reducing the cost of smart upgrades8	Reduce technology input costs A_{54}	Sort 23

Table 7. Low-carbon design index weights for intelligent dehumidifiers.

and facilitate packaging reuse. This corresponds to technology category 41 (low-carbon packaging based on intelligent technology) and the other low-carbon requirements.

(5) Recycling treatment stage: The primary function of the dehumidifiers is to extract moisture from the air; however, the collected water, as a resource, currently does not achieve closed-loop utilization of water resources. This corresponds to the environmental category under the low-carbon requirements of recycling treatment stages 1 (use of clean energy), 3 (carbon dioxide recycling application), and 7 (waste materials into energy).

The low-carbon demand for smart dehumidifiers is derived from the aforementioned analysis, as shown in Fig. 6.

AHP-based low-carbon design index analysis of dehumidifiers

The low-carbon design of an intelligent pot plant dehumidifier was systematically examined. Initially, the low-carbon requirements of the dehumidifier products (1, 3, 5, 7, 11, 12, 19, 21, 27, 32, 33, 36, 41, 45) were considered in relation to the corresponding low-carbon indicators (A_{11}, A_{12}, A_{14}, A_{24}, A_{31}, A_{35}, A_{41}, A_{42}, A_{43}, and A_{54}), as shown in Fig. 2. Subsequently, Table 4 was used to establish the weighting hierarchy of indicators. This analysis culminated in the identification of seven critical indicators for intelligent dehumidifiers: clean energy utilization (A_{11}), energy recovery and recycling (A_{14}), component modular design (A_{24}), biodegradable material implementation (A_{35}), CO_2 recycling and reuse (A_{31}), intelligent safety mechanisms (A_{41}), and the incorporation of intelligent operational and interactive technologies (A_{43}). The results are summarized in Table 7.

TRIZ-based low-carbon innovation design of intelligent potting dehumidifier

In the low-carbon design process of the intelligent pot plant dehumidifier, for the weight analysis of the low-carbon design indices of intelligent products throughout the entire life cycle, in conjunction with the core elements of the low-carbon design of intelligent products, utilizing the contradiction matrix table in TRIZ theory, we identified inventive principles such as No. 40 (application of composite materials), No. 34 (principle of abandonment and restoration), No. 22 (turning harm into benefit), No. 25 (self-service), No. 1 (division principle), and No. 17 (dimensional change), as shown in Table 8.

In this study, based on the TRIZ theoretical solutions presented in Table 8, a practical exploration of low-carbon design concepts was conducted for a smart-potting dehumidifier. The design scheme is illustrated in Fig. 7. In the material selection process, the dehumidifier incorporates an ecological innovation strategy by

Serial number	Low-carbon design indicators	Indicator weights	TRIZ Theory Solutions
1	Use of biodegradable recycled materials A_{35}	Sort 1	40 (**Composite Material)**
2	Use clean energy A_{11}	Sort 2	34(Principles of Abandonment and Restoration)
3	Carbon Dioxide Recovery A_{31} Energy recycling A_{14}	Sort 3 Sort 5	22 (Turning Harm into Benefit)
4	Intelligent Security Protection Technology A_{41} Intelligent Operation and Interaction Technology A_{43}	Sort 6 Sort 4	25 (Self-Service)
5	Modular design of components A_{24}	Sort 11	1(Partition) 17(Dimensional change)

Table 8. Specific solutions to the TRIZ problem of low-carbon conflicts in smart dehumidifiers.

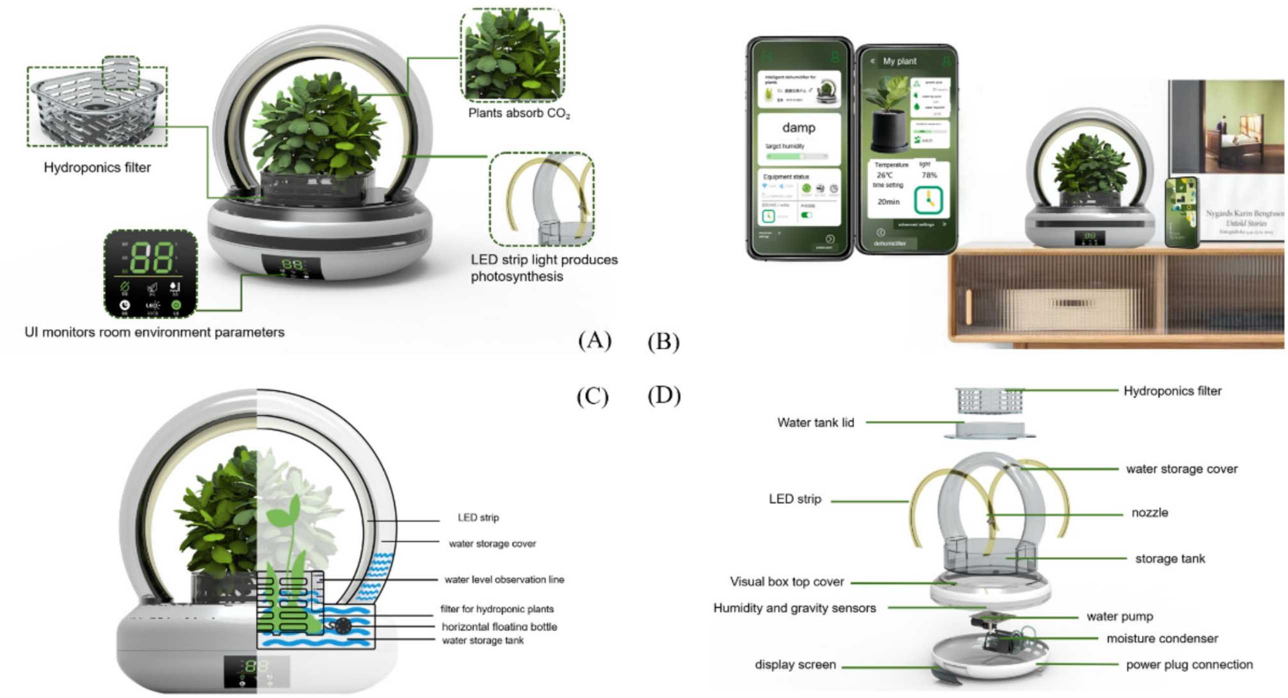

Fig. 7. (**A**) Product design plan; (**B**) Smart interactive interface; (**C**) Principle of interlligent potting dehumidifier; (**D**) Modular design function. All images were designed and drawn by the author in collaboration with Min Zhang using 3D Modeling Software Rhino 7.0 (Version 7.0, URL: https://www.rhino3d.com)).

utilizing naturally degradable and environmentally friendly materials to ensure that the environmental effects of the product are minimized at the disposal stage, thereby significantly reducing the environmental burden. Furthermore, the design innovatively integrates the photosynthesis mechanism of potted plants to establish a highly efficient carbon cycle system that facilitates effective recycling and reuse of waste carbon dioxide. Through the integration of intelligent sensing and regulation technology, the smart potted plant dehumidifier achieves automated regulation and optimization of the dehumidification function, thereby significantly enhancing energy utilization efficiency. Regarding the product structure design, a modularized layout concept is employed, which enhances the expandability and maintainability of a product and effectively extends its service life. These design innovation strategies collectively constitute the low-carbon design scheme of a smart potted plant dehumidifier, aiming to achieve the dual objectives of environmental sustainability and user experience optimization.

Low carbon design evaluation of intelligent potting dehumidifier

In order to verify the feasibility of the low-carbon design scheme of the intelligent potting dehumidifier, according to the hierarchical analysis weights[51], the evaluation factor set $U = \{U1, U2, U3, U4, U5, U6, U7\}$ is established by selecting the indicators A_{11}, A_{14}, A_{24}, A_{31}, A_{35}, A_{41}, and A_{43}. The rubric set is a collection of indicator evaluation levels, and the rubric set $V = \{V1, V2, V3, V4, V5\}$ is established to represent good, better, average, poor, and very poor, respectively, and is also assigned the value of V= [5, 4, 3, 2, 1]. Weight vector W was derived from the AHP-normalized weights as W= {0.1705, 0.1269, 0.0914, 0.1482, 0.1985, 0.1235, 0.1410}. To ensure the objectivity and scientificity of the survey and research, this study adopted an expert questionnaire for the evaluation. The degree of affiliation of the indicators refers to the ratio of the number of people whose evaluation result was a comment to the total number of people who conducted the evaluation. The

norm	Weights	(Of an unmarried couple) be close	Rather or relatively good	General	Differ from	Poorly
A_{11}	0.1705	0.26	0.42	0.16	0.08	0.02
A_{14}	0.1269	0.28	0.50	0.08	0.04	0.04
A_{24}	0.0914	0.30	0.40	0.12	0.08	0.04
A_{31}	0.1482	0.28	0.48	0.12	0.06	0.00
A_{35}	0.1985	0.32	0.50	0.08	0.04	0.00
A_{41}	0.1235	0.30	0.40	0.16	0.06	0.02
A_{43}	0.1410	0.30	0.48	0.10	0.04	0.02

Table 9. Valuation of indicator affiliation.

key to the fuzzy comprehensive evaluation method lies in determining the degree of affiliation for each indicator. Fifty survey respondents were invited to evaluate the indicators and to calculate an affiliation matrix. A total of 50 questionnaires were distributed and 47 valid questionnaires were recovered, which was 94% effective. The affiliation matrices are listed in Table 9.

(1) The score for each indicator is calculated as follows:

$Q1 = R1*V = * [0.26\ 0.42\ 0.16\ 0.08\ 0.02]\ [5\ 4\ 3\ 2\ 1]^T = 3.64.$
$Q2 = R2*V = * [0.28\ 0.50\ 0.08\ 0.04\ 0.04]\ [5\ 4\ 3\ 2\ 1]^T = 3.76.$
$Q3 = R3*V = * [0.30\ 0.40\ 0.12\ 0.08\ 0.04]\ [5\ 4\ 3\ 2\ 1]^T = 3.66.$
$Q4 = R4*V = * [0.28\ 0.48\ 0.14\ 0.06\ 0.00]\ [5\ 4\ 3\ 2\ 1]^T = 3.80.$
$Q5 = R5*V = * [0.32\ 0.50\ 0.08\ 0.04\ 0.00]\ [5\ 4\ 3\ 2\ 1]^T = 3.92.$
$Q6 = R6*V = * [0.30\ 0.40\ 0.16\ 0.06\ 0.02]\ [5\ 4\ 3\ 2\ 1]^T = 3.72.$
$Q7 = R7*V = * [0.30\ 0.48\ 0.10\ 0.04\ 0.02]\ [5\ 4\ 3\ 2\ 1]^T = 3.82.$

(2) The total affiliation vector and scores were calculated.

$$R = \begin{bmatrix} 0.26\ 0.42\ 0.16\ 0.08\ 0.02 \\ 0.28\ 0.50\ 0.08\ 0.04\ 0.04 \\ 0.30\ 0.40\ 0.12\ 0.08\ 0.04 \\ 0.28\ 0.48\ 0.14\ 0.06\ 0.00 \\ 0.32\ 0.50\ 0.08\ 0.04\ 0.00 \\ 0.30\ 0.40\ 0.16\ 0.06\ 0.02 \\ 0.30\ 0.48\ 0.10\ 0.04\ 0.02 \end{bmatrix}$$

$$B = W*R = [0.1705\ 0.1269\ 0.0914\ 0.1482\ 0.1985\ 0.1235\ 0.1410] * \begin{bmatrix} 0.26\ 0.42\ 0.16\ 0.08\ 0.02 \\ 0.28\ 0.50\ 0.08\ 0.04\ 0.04 \\ 0.30\ 0.40\ 0.12\ 0.08\ 0.04 \\ 0.28\ 0.48\ 0.14\ 0.06\ 0.00 \\ 0.32\ 0.50\ 0.08\ 0.04\ 0.00 \\ 0.30\ 0.40\ 0.16\ 0.06\ 0.02 \\ 0.30\ 0.48\ 0.10\ 0.04\ 0.02 \end{bmatrix} = [0.29\ 0.46\ 0.12\ 0.06\ 0.02]$$

$Q = B*V = [0.29\ 0.46\ 0.12\ 0.06\ 0.02] * [5\ 4\ 3\ 2\ 1]^T = 3.77.$

The calculation shows that the evaluation results of each index of the low-carbon design scheme of the smart potting dehumidifier are greater than 3.77 points, and the low-carbon design of the smart potting dehumidifier verifies the universal adaptation of the integrated methodology.

Conclusion

The concept of carbon neutrality has become significant in the product design for low-carbon development. With the rapid advancement of the digital economy and smart products, the environmental impacts of their design and production have become substantial, eliciting widespread concern. However, existing design frameworks exhibit deficiencies in addressing the complexity of smart products, making it challenging to satisfy sustainable development requirements. This study constructs an integrated "LCD-AHP-TRIZ" methodology by combining low-carbon design and smart products, thereby providing a novel perspective and systematic solution for the sustainable development of smart products. Through a system model, it identifies and prioritizes key low-carbon design indicators and resolves design conflicts to achieve more sustainable product design. The conclusions of this study are as follows.

(1) The proposed LCD-AHP-TRIZ integration method demonstrated efficacy for the low-carbon design of smart products. This methodology effectively addresses the complexity and dynamics of smart product design and significantly enhances the systematic and scientific nature of low-carbon designs.
(2) This study establishes a comprehensive set of low-carbon design requirement tables for smart products, systematically categorizing low-carbon design requirements into five core categories: energy efficiency, design, environment, technology, and cost. Based on a whole-process analysis of the product life cycle,

this study developed a 5 × 5 low-carbon requirement table encompassing 56 low-carbon design indicators. These indicators provide a comprehensive and quantitative analytical foundation for the low-carbon design of smart products, offering scientific and systematic support for the subsequent design decision-making process, thereby ensuring that the design process responds precisely to the low-carbon objectives.

(3) The strategic prioritization of low-carbon design indicators for smart products was identified, with the environmental category emerging as the most significant among the low-carbon demand categories, followed by the energy efficiency and technology categories. Among the low-carbon design metrics, the most significant tier 1 metrics included the use of biodegradable materials (A_{35}), utilization of clean energy (A_{11}), recycling of CO_2 (A_{31}), and smart operation and interaction technologies (A_{43}). Conversely, reducing user costs (A_{54}) is identified as the least significant low-carbon demand indicator.

(4) A low-carbon innovation design scheme for smart products is proposed. For the most significant low-carbon design indicators, this study proposes various low-carbon design strategies through TRIZ contradiction and conflict analysis, including the composite material principle (40), performance conversion principle (35), substitution principle (27), and pressure method (39). These methods exhibit wide applicability and can provide specific implementation pathways for low-carbon design of smart products.

In future research, as market demand evolves and intelligent technology progresses, this study will further refine and enhance the LCD-AHP-TRIZ strategic model. Continuous optimization of the model will facilitate the advancement of low-carbon and intelligent products and contribute to the sustainable development of the intelligent product industry.

Data availability

The Te datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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