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An Iterative Conceptual Design Process for Modular Product Based on Sustainable Analysis and Creative Template Method

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Abstract: The iterative design process of mechanical products has evolved towards a more sustainable direction driven by the concept of sustainable development. Modular design emphasizes the realization of user requirements under the condition of high efficiency and low cost, which is conducive to the diversification of product design. The sustainable innovative design methods are considered in modular design processes, which can improve the design capabilities of enterprises and enhance competitiveness. However, although the existing methods used in the iterative design of a product scheme contributes to satisfy the user requirements and generate the innovative scheme of the product, the sustainable design concepts such as the impact on the utilization of resources and environment during the iteration of the conceptual scheme and sustainability evaluation of product schemes have not been given sufficient attention. To resolve this, in this work, an iterative conceptual design process is proposed for modular products based on the sustainable analysis and creative template method. In this process, firstly, the KANO model is used to analyze the sustainable requirements of users. Secondly, a function behavior structure (FBS) model and creative template method are used to form sustainable innovative modular products conceptual design scheme. Finally, fuzzy analytic hierarchy process (FAHP) is used to evaluate the product scheme. The iterative conceptual design process proposed in this paper can be abbreviated as S-KFCF. The prototype conceptual scheme design of a novel low-temperature plasma deposition device is conducted. The results suggest that the proposed process could effectively reduce the total cost, shorten design cycles, increase product part recovery rates, and improve the environmental friendliness of the design schemes produced via sustainable analysis.

Keywords: modular design; sustainable analysis; innovative design; low-temperature plasma

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1. Introduction

Product innovation is an ancient and novelty topic, and it has existed since the beginning of the existence of commodities in human society. The development process of mechanical products innovative design can be divided into three stages [1]: first, the stage of the traditional innovative design based on explanation and description in the 1960s; second, the stage of the computer innovative design focused on the construction of mathematical models and computers from 1960s to 1990s; third, from the late 1990s to the beginning of the 21st century, the stage of knowledge-based information technology innovation and the network collaborative innovative design based on technologies such as virtual reality. The achievements of innovative theories and methods have been amply supplemented and developed in the development process of mechanical products' innovative design. The main achievements of innovative design theory and method research are as follows: Theory of Inventive Problem Solving (TRIZ) [2]; Quality Function Deployment (QFD) [3]; Value Engineering (VE) [4]; Creative Template Method, etc.

With the development of science and technology, the pace of product upgrading is getting faster. The dynamic market requires enterprises to continuously compress product development time and further expand the product diversity. Manufactures must pay more attention to the diversity and quickly launch new products that meet the individual requirements of users in order to increase market share and user satisfaction [5,6]. Therefore, the previous production mode of enterprises has been unable to adapt to the fierce market competition. Modular design emphasizes that different requirements from users can be realized under the condition of high efficiency and low cost. The products' variety can be achieved by adding, removing, replacing, or redesigning modules through using modular design techniques [7].

The change and innovation of the traditional development model is essentially to achieving sustainable development. The application of sustainable and innovative design methods can improve the modular design ability, enhance its competitiveness, and guide the direction of its development of the enterprises [8]. Meanwhile, the sustainable and innovative design methods can guide the consumption of social groups, change the consumption pattern, and promote the economy, resources, and environmentally sustainable development. Kim et al. demonstrated that both incremental and architectural innovation could have positive impact on sustainable market by example [9]. Garrette et al. outlined an approach to sustainable product improvement through the application of life cycle thinking elements and proposed that incremental innovation has the advantages of less risk and investment than radical innovation [10]. Bai et al. used the Bio TRIZ method to provide a satisfactory solution for green product design. At the same time, the application of the method can reduce the design process steps and improve the design efficiency [11].

At present, the common process of product iterative conceptual design is from user requirements analysis to the innovative design of product conceptual design scheme, and then to product scheme evaluation [12]. Guo et al. proposed a resilient design methodology and process for the conceptual design phase, using functional decomposition and conflict resolution to support resilient conceptual design [13]. Wang et al. proposed a demand-oriented innovation design model to meet the users' requirements and demonstrated the process of design based on this strategy [14]. In this kind of process, the impact of product function on resource recycling and environment is often ignored. At the same time, the product design will encounter a misunderstanding if sustainability is not taken as the evaluation index in the process of product scheme evaluation. The misunderstanding is that if all configurations are updated to the highest performance, this is not, in fact, the optimal design scheme. The product innovative design scheme that only serves the requirements of users but is not responsible for the environment does not have environmental friendliness and applicability in the product innovative design process. Guo et al. select the optimal solution by matrix deployment, candidate solution generation, and interactive genetic algorithm solution for the low carbon indicator in the conceptual design [15]. Zhang et al. proposed a smart knowledge application method based on design matrix in order to acquire and apply knowledge to implement green manufacturing [16].

In this paper, a sustainable iterative conceptual design process is proposed, which is based on the sustainable analysis and the innovative design and takes structural iteration transformation as the starting point of the product modular design. In the early stage of equipment design and manufacturing improvement, the KANO model is used to analyze the sustainability satisfaction of users' requirements. Then, the function behavior structure (FBS) model is used to complete the mapping from function to structure and then accomplish the modular design of structures. The creativity template method is used to accomplish the sustainable design according to the working environment parameters and, in the meantime, finish the innovative design of product scheme incorporated with the product function structure tree. Finally, the product conceptual design scheme is evaluated by fuzzy analytical hierarchy process (FAHP), and the scheme of the best performance and most conducive to sustainable production is selected. Then, the users' opinions and feedback are collected by applying the product conceptual design scheme obtained from the FAHP evaluation to the market. The iterative design of the product is gradually completed by reusing the methods that are mentioned above. Therefore, a set of Sustainable-KANO, FBS, Creative template and FAHP (which can be abbreviated as S-KFCF) sustainable iterative conceptual design process is proposed for those modular products that have sustainable modular design requirements. Low-temperature plasma-enhanced chemical vapor deposition (PECVD) technology has the disadvantages of large gas consumption and high deposition cost compared with other types of chemical vapor deposition (CVD) technology. The design of low-temperature plasma deposition device is based on the shortcomings of PECVD technology, combined with the key points of energy saving in production and humanization to consumers under the concept of sustainable development. Therefore, the S-KFCF product iterative conceptual design process is applied to the sustainable innovation scheme design of low-temperature plasma deposition device. The deposition device, which is designed by the S-KFCF product iterative conceptual design process, has many advantages of low consumption of working gas, uniform deposition quality, little effect on environmental pollution and convenient maintenance, replacement and reuse of the parts and components.

The study is organized as follows: A process of iterative conceptual design is presented in Section 2. Section 3 introduces the process and describes its step and main application methods in solving iterative conceptual design problems of modular products. Section 4 describes the application of the proposed process and methodology in the design of the low-temperature plasma deposition device. The present study aims to demonstrate the effectiveness of an iterative conceptual design process in the design of sustainable innovation for modular products. The discussion and conclusion are presented in Sections 5 and 6, respectively.

2. S-KFCF Iterative Conceptual Design Process

The mechanical engineering devices with sustainable modular design requirements need to consider multiple constraints during the design process. The constraints mainly include a large number of engineering constraints and the sustainability constraints requirement in the entire life cycle of the device. The innovative design of a mechanical device is accomplished by meeting the sustainable modular requirements of users and ensuring the quality of product production. Hence, an S-KFCF iterative conceptual design process is proposed for a mechanical engineering device with sustainable modular design requirements.

This process is necessary to conduct sufficient user requirement analysis based on the KANO model. The FBS model is highly usable and has usage advantages in the user-centered design process [17]. Then, the FBS model and the creative template are used to achieve sustainable modular and innovative design for solving design problems. The FBS model makes the results of user requirement analysis more intuitive and accurate, and they reflect the actual requirement from multiple angles [18]. The creative template method has the advantage of generating competitiveness on the basis of minimal market information because this method considers that existing products inherently carry important codes in the process of development and evolution [19]. FAHP is used to evaluate the comprehensive scheme of mechanical products. FAHP is a combination of fuzzy logic and AHP. FAHP solves the problems of measuring the consistency of judgments and capturing the subjectivity of judgments while inheriting the advantages of both methods [20]. Finally, the product conceptual design scheme is obtained through the S-KFCF process, which form a device and apply it. At the same time, user requirements and opinions are collected during the application process of the device. The iterative conceptual design process is reused based on user feedback and opinions and gradually completes the iterative design of the product. The application of S-KFCF iterative conceptual design process can effectively solve the existing design problems while fulfilling the requirements of users and meeting the requirements of sustainable development. Figure 1 shows the S-KFCF iterative conceptual design process.

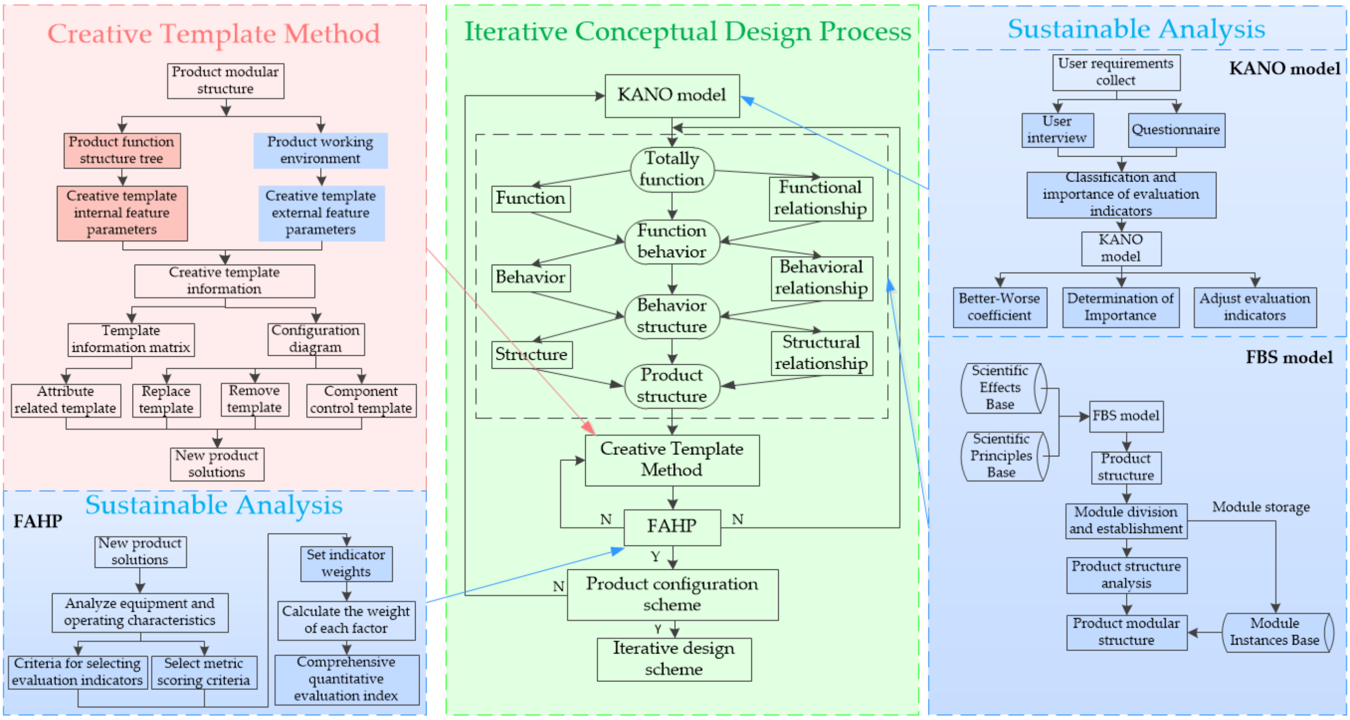


Figure 1. S-KFCF Iterative Conceptual Design Process.

3. Methodology

Design for sustainable (DFS) originated from the concept of sustainable development and is an effective solution to explore and solve existing problems and seek a way out for future development [21]. The approach of sustainable analysis will improve the innovation capability and the market competitiveness of the enterprises, while promoting the sustainable development of economy, resources, and environment [22]. In this paper, the S-KFCF iterative conceptual design process is proposed by giving sustainability features in the whole process in the conceptual design. Sustainable analysis and the creative template method can be used to provide a design basis for the development of iterative conceptual design solutions aimed at the modular innovative design of mechanical engineering devices with sustainable modular design requirements. Initially, the sustainable design requirements of users are collected by means of questionnaires or other methods, for which the degree of satisfaction are analyzed by using the KANO model. Then, the initial design elements are determined by the degree of satisfaction of user requirements. Afterwards, the FBS model is used to complete the mapping from function to behavior and behavior to structure because of the complexity of design elements [23]. Among them, the modular design of the product is also completed by the FBS model, then the structural design information of the product is obtained [24]. After that, the creative template analysis method is used to complete the sustainable design of the product structure according to the working environment parameters of the product. At the same time, the innovative design of the product structure is completed by using four modules and the product structure information obtained by FBS. Eventually, a new product conceptual design scheme is obtained by sustainable design and innovative design. However, the product conceptual design scheme needs to be analyzed and evaluated by FAHP, and the optimal product design scheme that is most conducive to sustainable development is output ultimately [25]. The product design scheme obtained through the S-KFCF iterative conceptual design process not only can meet the production requirements, but also balance the development of the natural environment.

3.1. Sustainable Analysis in Conceptual Design

3.1.1. User Requirements and Satisfaction Analysis

Product design based on market requirements are often repeatedly changed, and the functions and properties of the products are constantly updated and iterated. Therefore, the product design method based on market requirements leads to wasted time in the design process and manufacturing cycle. However, product design based on user requirements satisfaction can better mine user requirement information and effectively reduce the waste of time, resources, and costs caused by repeated modification of requirements compared with the product design based on the market requirements.

The product design issues are solved by analyzing the design elements that affect the product quality and enumerating the design elements that affect the environment. Afterward, users' sustainable design requirements and their satisfaction are collected by means of questionnaires and user interviews. Then, the KANO model is used to analyze user requirements after classifying the collected questionnaire data and evaluating its importance. The results obtained by the KANO model are classified and summarized to establish a quality prototype. Finally, the quality prototypes are analyzed, and the sensitivity of specific measurement metrics are identified. The consumption pattern of users will be changed through the analysis of requirements sustainability, which can better promote sustainable development.

3.1.2. FBS Model

A complex system can be modularly and hierarchically dissected by the FBS model. The complex system is decomposed into multiple interconnected and functionally independent modules. Many solutions are obtained by diverging each function module in a layer-by-layer approach and the best solution of the functional module is obtained by evaluate. The complex systems are modularly in line with sustainable design concepts. Each module can be recombined and used according to design requirements due to different functions. The modules that are not scrapped can be reused after the product is scrapped in line with the green design concept in the design scheme.

The total function of the product needs to be analyzed to better complete the modular design. However, it is difficult to directly analyze due to the complexity of the total function in complex product system design. The total function can be decomposed into multi-level sub-functions to form a functional structure diagram in order to simplify the problem. In the FBS model, structure is the carrier of the function, and behavior is the design information bridge between function and structure. Functions are mapped to behaviors to generate behavioral solutions under the premise of satisfying various constraints, and to achieve the proposed design goals in principle. Behaviors are mapped to functions to realize the product structure design. In general, function of the product is realized through the structure. The FBS model adopts the analogy reasoning method based on the design knowledge base, which can find the structure to realize the function according to the design requirements. In other words, the behavior mapped by the current function is compared and matched with the behavior that can be achieved by the structural solution in the design knowledge base. If the behaviors of the current function and the known function are similar, the structures mapped to the two behavior sets also have similar components and relationships. Then, the new structures that meet the requirements are found by adding constraints to structures with similar components and relationships [26].

The modular design from the function to the structure of the product is completed step by step by using the FBS model. The application of the FBS model is not only conducive to transforming complex product function information into design structural information, but also conducive to the sustainable design of product structural modules [27].

3.1.3. Fuzzy Analytic Hierarchy Process

Fuzzy Analytic Hierarchy Process (FAHP) is the combination of the Analytic Hierarchy Process (AHP) and the Fuzzy Comprehensive Evaluation (FCE) method. AHP is a method of calculating weights, and FCE is a method of comprehensively evaluating problems. In fact, FAHP has a greater consistency of thinking than AHP because of the establishment of the matrix and the different calculation methods of each factor weight. Usually, FAHP is used to quantify the evaluation indicators of the product conceptual design scheme [28]. Then, the weight of each indicator is set according to the importance and sustainability of the evaluation indicator. A fuzzy consistent judgment matrix is constructed by pairwise comparison of factors and calculates the relative importance of each element. Afterward, all schemes are prioritized by calculating the comprehensive importance, ultimately, providing a scientific basis for selecting the optimal option for decision making [29].

3.2. Creative Template Method

The creative template method is an innovative design and problem-solving method based on product information proposed by Israeli scholars Goldenberg Jacob and David Mazursky [19]. The application object of this method is the existing products, and its focus is on the development and improvement of the main and auxiliary functions of the products. The creative template method has the characteristics of highly targeted, easy to operate, simple, and efficient, compared with other innovative methods such as TRIZ [30] and brainstorming method [31].

The creative template method is a method to implement product-oriented innovation strategies. The product information is described in layers according to the complex functional structure of mechanical products. Then, an information model based on internal and external parameters is established by the demands of the creative template method. Among them, the external parameter information model is determined by the working environment of the product. The role of market users is changed from passive recipients to active design participants by the establishing of external feature information. Ultimately, the personalized design for user participation is realized. In other words, the product design scheme is more in line with the sustainable design concept of humanization for consumers by the introduction of external parameter information. The internal parameter information model is determined by the product function structure tree. Then, the specific features of the product are functionally decomposed by the internal feature information. Finally, the innovative product design scheme is generated by the internal feature information combined with four creative templates. The product information model based on internal and external parameters integrates cognitive psychology, Kansei engineering, and ergonomics to analyze and support the product design process from multidisciplinary and perspectives. Thereby, the innovative design of the product is better supported by extracting the abstract features of the product from the product information model and expressing the product information in its entirety [32].

4. Results

Compared with the traditional manufacturing process technology of thin film, low-temperature Plasma-Enhanced Chemical Vapor Deposition (PECVD) process is a new type of green manufacturing technology. Therefore, the plasma deposition device is needed to design improvement for further ensure that no toxic and harmful gases are generated during the production process when PECVD technology is used to deposit polymer films. Low-temperature plasma deposition devices have their respective priorities and problems to be improved when the devices are built according to the processing requirements of different enterprises, such as the design improvement of the plasma device [33], plasma sprinkler heads [34], and Radio Frequency discharge unit [35]. Hence, the S-KFCF iterative conceptual design process is used to carry out modular innovative design of the low-temperature plasma deposition device, which have the difficulties and sustainable modular design requirements.

4.1. User Requirements and Satisfaction Analysis

Low-temperature plasma deposition devices exhibit some problems, including uneven film quality, poor thickness uniformity, and significant color differences in the films deposited. Hence, the deposition device is required to design innovative improvements for making the deposition process greener and more sustainable. The function of the various components of the low-temperature plasma deposition device is analyzed and the factors affecting the environment during the operation of the deposition device are studied in order to fully understand and identify user requirements. Then, user requirement satisfaction is collected by means of user interviews and questionnaires [36,37].

The satisfaction questionnaire for the existence or absence of each function of the low-temperature plasma deposition device is shown in Table A1 (which is in the Appendix A). The function point in the questionnaire needs to contain two questions, positive and negative, and the questions' differences should be emphasized.

The data of the questionnaire is analyzed and recorded from 25 possible results per user. Then, the percentage of each possibility is counted and filled in the classification comparison table of KANO evaluation results in Figure 2. The quantified data is calculated by the Better-Worse coefficient method to show the degree of influence of achieving this factor attribute on increasing satisfaction or eliminating dissatisfaction. The value of better coefficient is usually positive, and the user satisfaction will be increased if the product provides a certain function and service. Therefore, the positive coefficient value becomes larger to represent that the effect of improving user satisfaction is better and the increase in satisfaction is faster and vice versa [38]. Hence, the function with higher absolute scores of the coefficient should be implemented first according to the Better-Worse coefficient calculation. Eventually, the design priorities of the initial design elements of the low-temperature plasma device are obtained by the KANO model. The design priorities of functions of the low-temperature plasma deposition device are as follows: (1) Low-temperature plasma generating stably is a mandatory attribute. (2) Uniform low-temperature plasma gas distribution is an attractive attribute. Excellent vacuum degree, exhaust gas pollution control device, and gas mixing system are desired attributes. (3) Low-temperature plasma parameter visualization design is an undifferentiated attribute.

Product Service Requirements	Negative (if the product do not have some kind of function, the review is :)					
Positive (if the product have some kind of function, the review is :)	scale	Enjoyed it	As it should be	No matter	Reluctantly accepted	Disgusted
	Enjoyed it	Q	A	A	A	O
	As it should be	R	I	I	I	M
	No matter	R	I	I	I	M
	Reluctantly accepted	R	I	I	I	M
	Disgusted	R	R	R	R	Q

Figure 2. KANO evaluation results classification comparison. A: Attractive attribute; R: Reverse attribute; M: Mandatory attribute; I: Indifference attribute; O: Desired attribute; Q: Questionable attribute.

4.2. FBS Map of Low-Temperature Plasma Deposition Device

The maps from function-to-behavior and behavior-to-structure with the assistance of the scientific principles base and the scientific effects base are completed according to the initial design elements of the low-temperature plasma deposition, which are provided by the KANO model. Then, the modular design of the low-temperature plasma deposition device is realized by using the FBS model and supporting with the module instances base. The FBS map of the low-temperature plasma deposition device as shown in Figure 3.

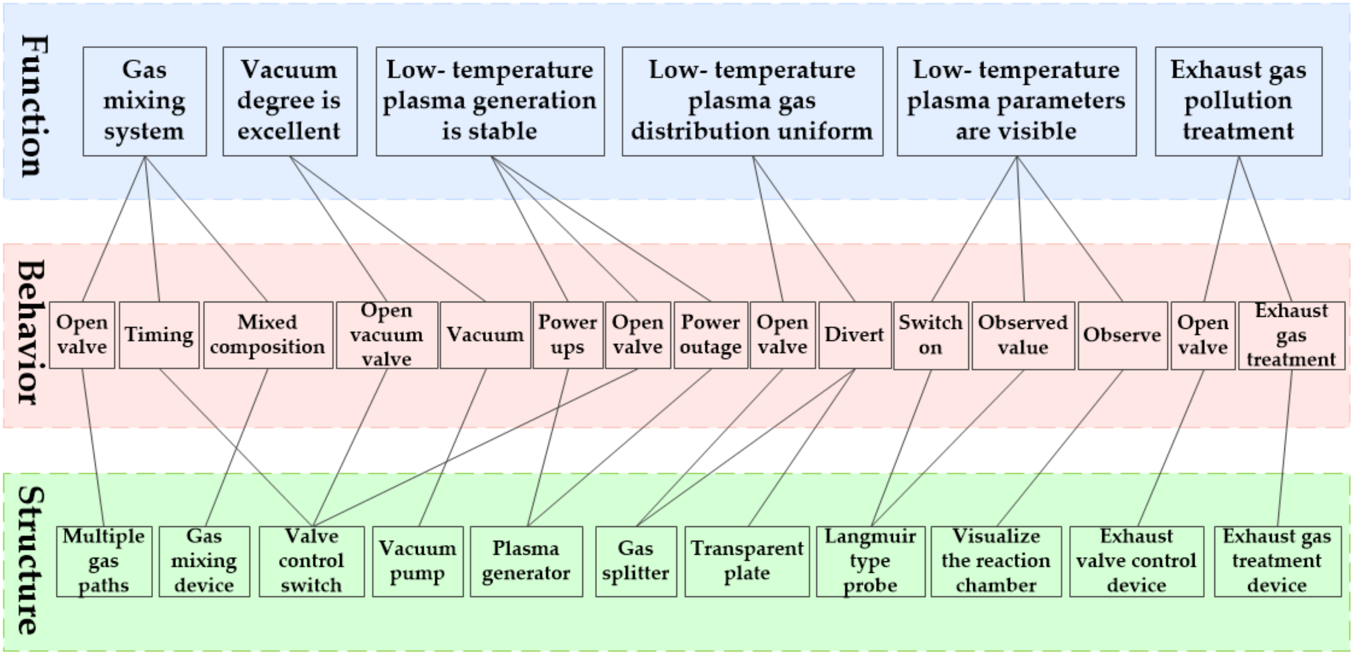


Figure 3. The FBS map of the low-temperature plasma deposition device.

4.3. Iterative Conceptual Design of Low-Temperature Plasma Deposition Device

The design priority of the product structure information is further determined through FBS mapping according to the priority of the initial design elements that are obtained by the KANO model. Afterward, the product structure information is combined with the creative template method to complete the sustainable innovative design of the product by using the four creative templates and extracting the internal and external parameters. Ultimately, the design of the low-temperature plasma equipment in the part with high user satisfaction and the basic structural design on the premise of ensuring the product function in the part with low user satisfaction are completed. The product conceptual design scheme of the low-temperature plasma deposition device produced by the creative template method is user-oriented, in line with the consumption trend, sustainable, and innovative. Figure 4 is the schematic diagram of the creative template method application.

The uniform function of low-temperature plasma gas distribution is the attractive attribute which is obtained by the KANO model corresponding to the structure of the gas distribution device, which is obtained from FBS mapping. Finally, the gas distribution device is designed according to the product function structure tree and the working environment by using the component control template in the creative template. In fact, the replaceable mesh-shaped wire is often set in the common low-temperature plasma deposition device as a gas distribution device to relieve and prevent the plasma from directly acting on the surface to be processed. However, this kind of gas distribution device still has the disadvantage of uneven film quality. A gas distribution device with a secondary distribution function is designed based on the replaceable mesh-shaped wire by the analysis of the functional structure tree (Figure 5) and the component control template. The gas distribution device adopts a sustainable modular innovative design. In conclusion, the first-stage gas distribution device mainly realizes the separation of low-temperature plasma into different regions of the reaction chamber, and the second-stage gas distribution device mainly realizes the flow and flow rate control of low-temperature plasma in different regions.

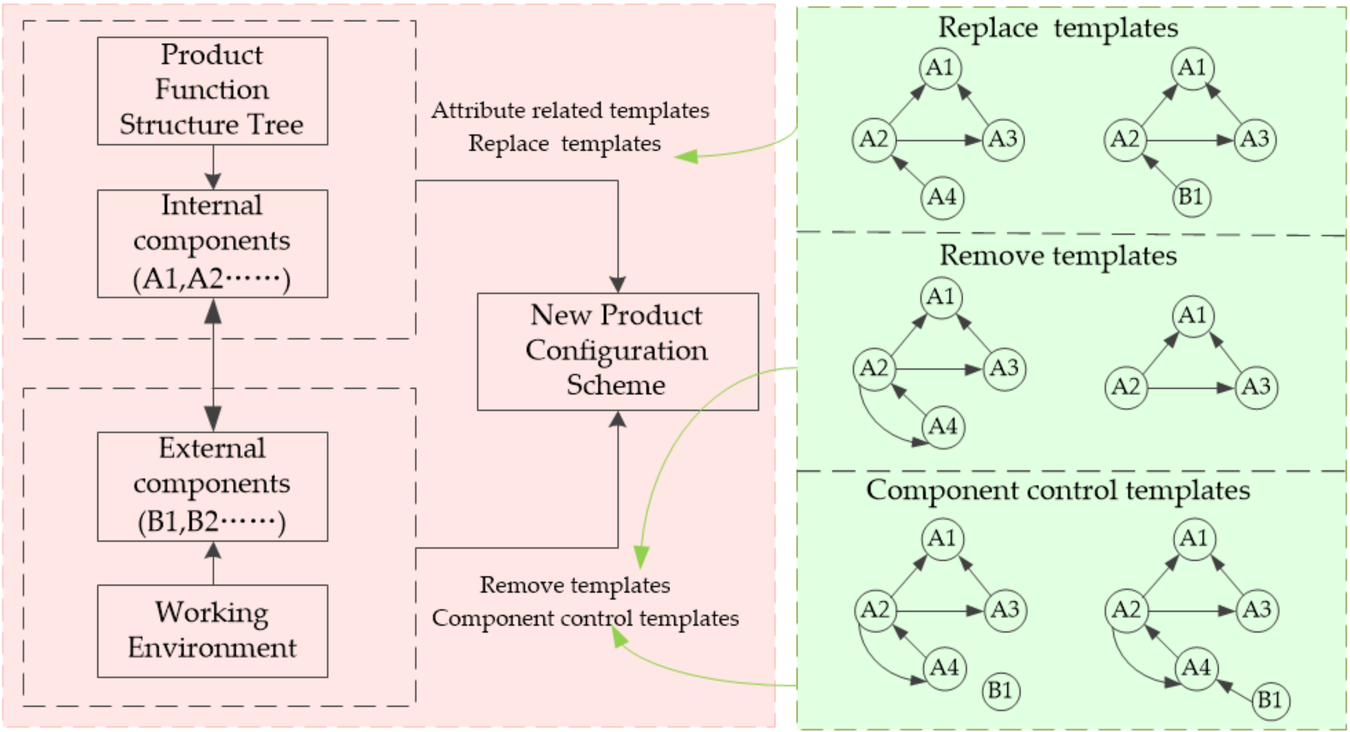


Figure 4. Schematic diagram of the creative template method application.

The design scheme of the secondary gas distribution device is formed through the further sustainable modular innovative design. Among them, the first-stage gas distribution device is composed of an upper gas distribution plate, a partition plate, and many throttle valves, which are used to control the plasma to enter different regions of the reaction chamber. The second-stage gas distribution device is composed of a lower gas distribution plate, sprinkler head devices, and many throttle valves, which are used to control the flow rate of the plasma to enter the reaction chamber. Ultimately, the plasma entering the reaction chamber becomes more uniform and the phenomenon of uneven film quality caused by gas recirculation is reduced through the control and adjustment of the plasma by the secondary gas distribution device. Figure 6 is a schematic diagram of the assembly of the secondary gas distribution plates.

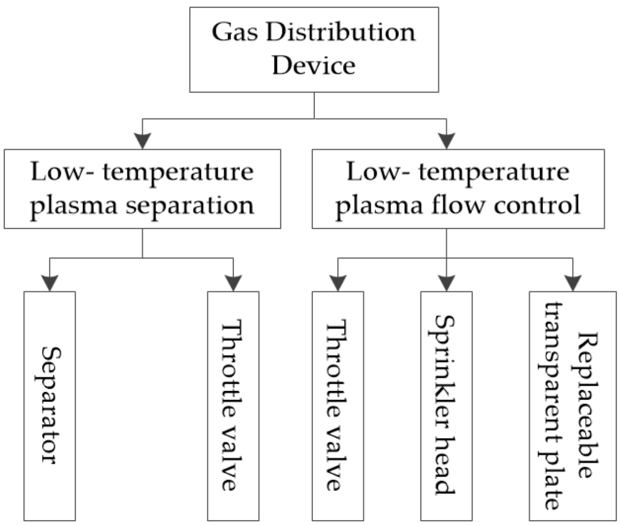


Figure 5. The functional structure tree of the gas distribution device.

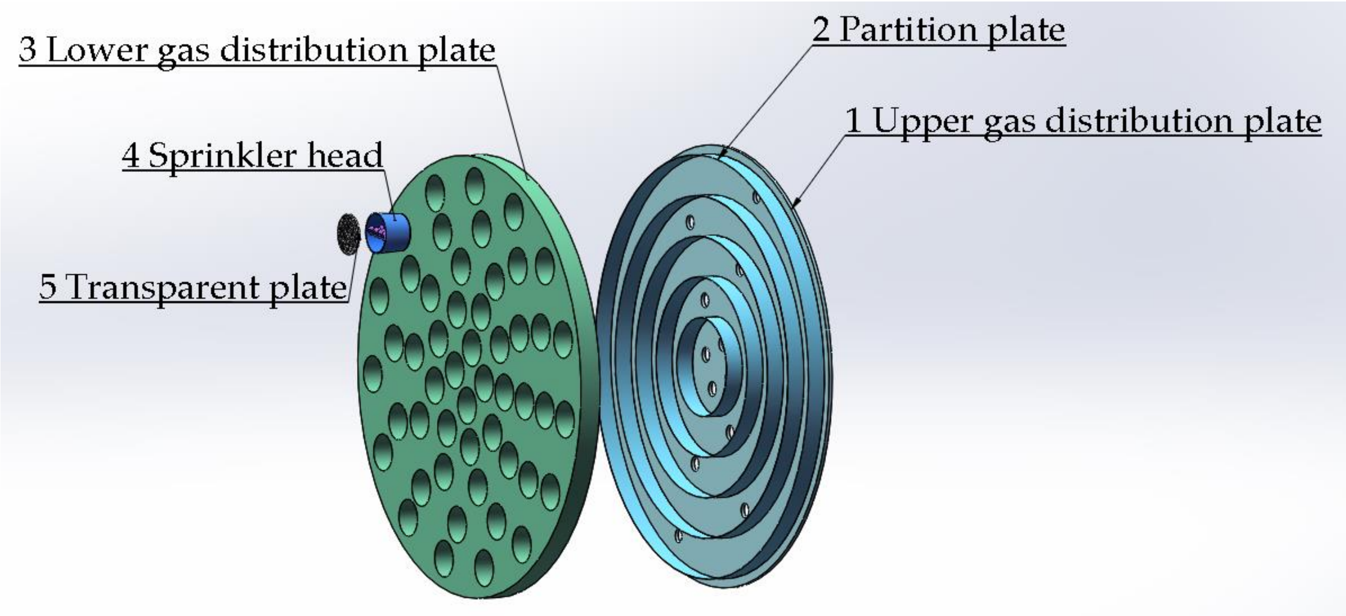
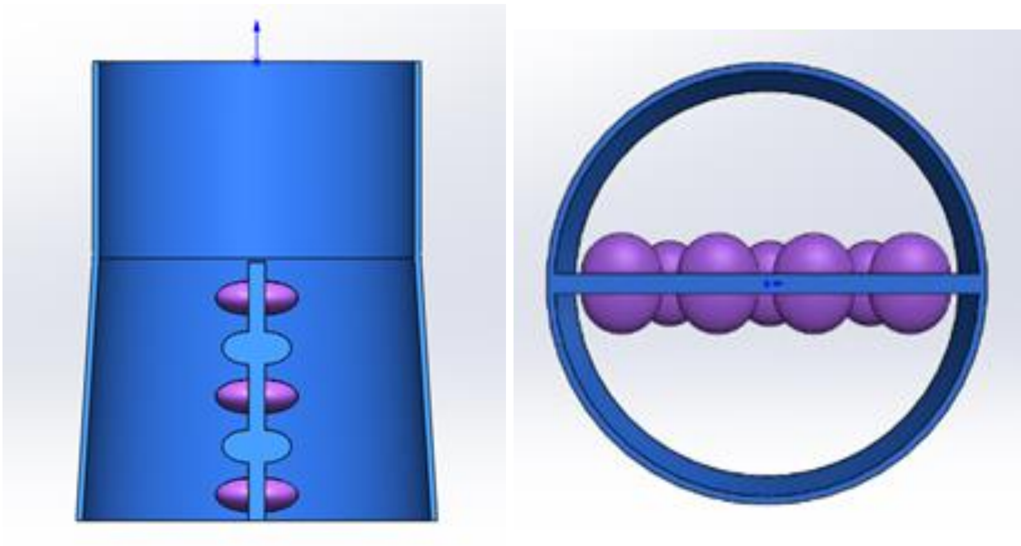


Figure 6. Schematic diagram of the assembly of the secondary gas distribution device.

To further ensure the uniform flow rate of plasma entering the reaction chamber, the structure of the sprinkler head device is improved by using the component control template method. Figure 7 is the design diagram of the plasma sprinkler head. The key point of the sprinkler head design is to set a partition plate with multiple hemispherical protrusions inside the sprinkler. The function of partition plate with hemispherical protrusion is to ensure that the flow rate of the plasma is buffered and dispersed to a certain extent after entering the sprinkler head. At the same time, a replaceable mesh-shaped transparent plate is set at the bottom of the sprinkler head to further guarantee the plasma flow out of the sprinkler evenly.



(**a**) (**b**)

Figure 7. (**a**) The cross-sectional drawing of the sprinkler head; (**b**) The vertical view of the sprinkler head.

The gas distribution device is innovative and sustainably designed by using the creative template method. Finally, the secondary gas distribution device is obtained that the first and second stage gas distribution devices are convenient to disassemble from the overall structure. Among them, the transparent plate and the sprinkler head in the second-stage gas distribution device also can be replaced easily. Figure 8 is the assembly diagram of the secondary gas distribution device.

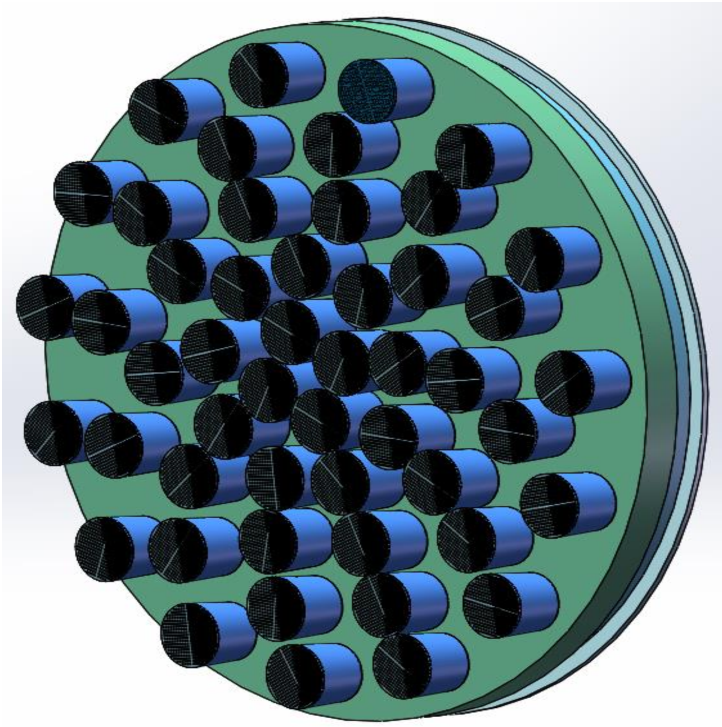


Figure 8. Assembly diagram of the secondary gas distribution device.

The preliminary conceptual design scheme of the product is obtained through the structure of the deposition device obtained from the FBS model combined with the creative template method. The preliminary configuration scheme of the product is as follows:

S1: A gas-mixing device is set to ensure that the gas is fully mixed before being accessed to the low-temperature plasma generator. Moreover, the design of multiple gas paths is adopted in the gas mixing system to strictly control the flow of each path gas into the deposition device. The design of the gas mixing device has the following advantages: shorten the processing time; lessen the gas consumption; high applicability; and satisfy the different working requirements of single or multiple gases.

S2: The vacuum pump with good performance is adopted to ensure that the air in the chamber is completely replaced before the experimental gas is introduced. Thus, the vacuum degree in the chamber can be guaranteed all the time during the deposition process by using the good performance vacuum pump. The maintenance of the vacuum degree can greatly improve the quality of deposited films and ensure that the deposition variables are not disturbed by external factors.

S3: A device of stably generated low-temperature plasma is adopted to ensure the quality of plasma reaction during the processing. The adequate and smooth operation of the low-temperature plasma generator has outstanding effects in improving deposition efficiency, reducing exhaust gas emission, and ensuring the quality of deposited films.

S4: The gas distribution device is designed to ensure the uniform gas flow of low-temperature plasma entering the reaction chamber. The secondary flow control design of the gas distribution device is completed by using the component control template. In summary, the design of secondary gas distribution is to ensure that the low-temperature plasma exists in all parts of the reaction chamber and the flow rate of the plasma is uniform and controllable.

S5: The plasma deposition device is designed with a Langmuir probe to monitor the plasma parameters in the reaction chamber in real time to ensure the visualization of data during the experiment. The design of a Langmuir probe can detect and collect the plasma parameters at different positions in the chamber. The visual design of the deposition process can greatly increase the operability. Among them, the design of a visual reaction chamber is convenient for the experimenter to observe the deposition in the chamber.

S6: The flow rate of gas emission after the experiment needs to be controlled to ensure the quality of the film after depositing. The reason is that the reaction chamber is in a vacuum state. If the flow rate of the gas emission is not controlled, it is easily to generate gas vortex that affects the quality of deposited films. In the meantime, the exhaust gas needs to be reasonably disposed to ensure the safety operation of the staff and the protection of the environment. Finally, sustainable innovative design in exhaust gas disposal based on PECVD technology is realized.

The preliminary design of the plasma deposition device is formed according to the conceptual design scheme of the product. Among them, the working process of the low-temperature plasma deposition device is as follows: Firstly, the working gas enters the gas mixing chamber through three-path gas inlet. A fan is set in order to ensure that the working gas is fully and evenly mixed. Then, the high-performance vacuum pumps (Non-Evaporable Getter (NEG) pump and turbomolecular pump) are selected to ensure that the vacuum degree of the reaction chamber. Secondly, a throttle valve is set between the gas-mixing chamber and the plasma generation device. The low-temperature plasma is generated by Radio Frequency (RF) excitation. Afterwards, the plasma is ejected from the gas sprinkler heads to the reaction chamber through the gas distribution device at different flow rates and flows. Finally, a monitoring device is set in the reaction chamber to ensure the digitization and visualization of low-temperature plasma flow in the reaction process. Among them, the throttle valve is used to control the rate of the emission plasma after processing, and the plasma discharged from the vacuum chamber needs exhaust treatment.

The design of low-temperature plasma deposition device is obtained based on the new product conceptual design scheme, which is generated by the S-KFCF iterative conceptual design process. The innovative design of each functional module is completed according to the sustainable design requirements of the device. At the same time, the innovative optimization design of the plasma flow uniform function of the attractive attribute is completed. Eventually, the overall structure design of the low-temperature plasma deposition device is completed under the guidance of the S-KFCF process.

4.4. FAHP Scheme Evaluation

The FAHP is used to qualitatively and quantitatively evaluate the new product conceptual design scheme, which is obtained by the creative template method. Then, the problem of sustainable innovative design of low-temperature plasma deposition device is divided into target layer, standard layer, and scheme layer (Figure 9). The evaluation indicators and weights are designed (Table A2 in Appendix B) to complete the collection of basic data for this design problem through the multiple expert score. Furthermore, the fuzzy consistency judgment matrix B is completed after the group synthesis primitive matrix A is establishment. The Formulas (1) and (2) are used to complete the weight calculation of each factor. Table 1 shows the weight value of each factor by using the formulas calculated. Ultimately, the evaluation of the product conceptual design scheme is completed by calculating the weight of each scheme.

$$\alpha = (n - 1)/2, \quad (1)$$

$$W_i = 1/n - 1/2\alpha + b_i/n\alpha, \quad (2)$$

where α is an intermediate variable, n is the matrix dimension, W_i is the weights, and b_i are the fuzzy consistency matrix sums determinant values by row.

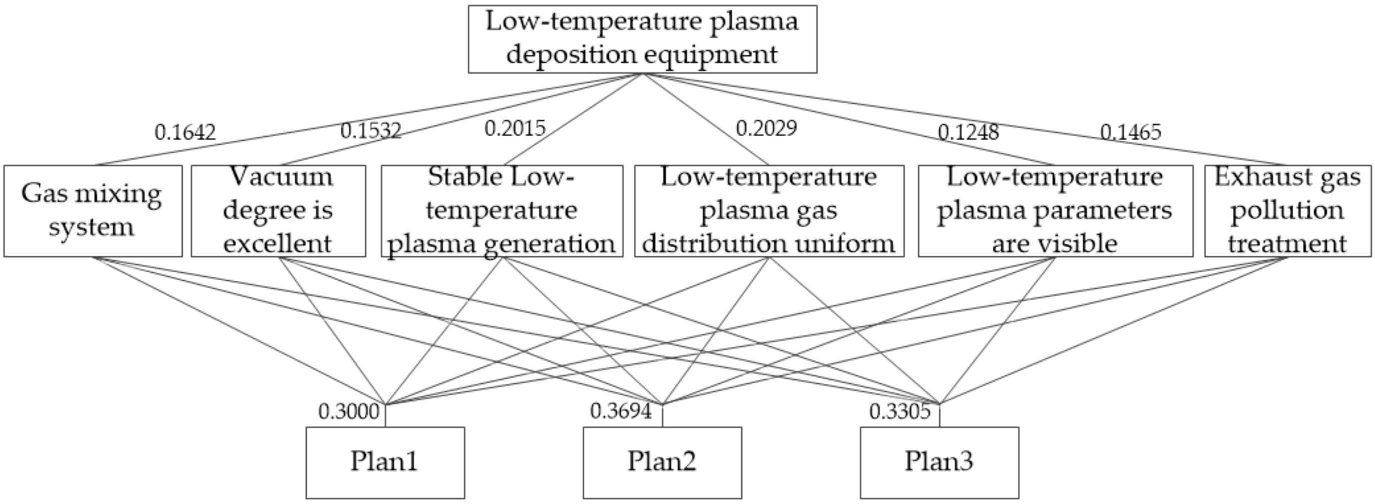


Figure 9. Target, standard and scheme layer of FAHP.

Table 1. FAHP weight value of each factor.

Serial No.	Factor	Weights
1	Gas mixing system	0.1642
2	Vacuum degree is excellent	0.1532
3	Stable low-temperature plasma generation	0.2015
4	Low-temperature plasma gas distribution uniform	0.2029
5	Low-temperature plasma parameters are visible	0.1248
6	Exhaust gas pollution treatment	1.1465

This iterative conceptual design process can generate product conceptual design schemes that can better meet user requirements by collecting users' feedback and opinions of the previous scheme continuously. At the same time, the design time can be shortened, and the design cost can be reduced under the guidance of the S-KFCF design process. PECVD technology, as a new type of green film preparation process, has been widely used in the preparation of nano-films and other fields compared with other processing methods for depositing films [39]. Hence, the iterative conceptual design process is used to complete the product sustainable innovative modular design in order to further ensure that no harmful effects are generated during the production process and guaranteed the industrial application of the deposition device. The product iterative conceptual design schemes can achieve the following functions: guided by user requirements, realized modular design while reducing material energy consumption, easily recyclable, and reusable.

5. Discussion

The thinking stereotypes of the traditional product design leads to the disadvantages of product designers having weak awareness of environmental protection and an insufficient understanding of sustainable design. Meanwhile, the enterprises have the disadvantages of weak product independent development ability and lack of innovation consciousness. In summary, these disadvantages lead to the lack of systematic sustainable and innovative modular design concepts and methods for product design [4]. Innovation is the driving force for enterprises to break through development difficulties and solve existing challenges and promote development. Products are the carrier of user requirements and are fundamental to the existence of the enterprises. The innovative modular design of products is the inevitable choice for the survival and sustainable development of enterprises. In general, innovative methods are the basis for achieving technological innovation.

Advanced technological innovation methods can effectively improve the efficiency of product innovation; thus, the realization of product innovation design needs to be guided by the corresponding technological innovation methods. At the same time, the application of the technological innovation methods can greatly shorten the research and development cycle of new products, accelerate the update of products, and improve the market competitiveness of enterprises. The proposal of sustainable development is not only a measure to deal with global warming, resource shortage, and other serious problems affecting human development, but also a new awareness of social development. The product design method has experienced the stages of green design [40], ecological design [41], low-carbon design [42], and environmental design [43] under the guidance of the sustainable design. Hence, an iterative conceptual design process is formed by the innovative design method combined with the sustainable analysis according to the design problems of mechanical products. Kamala et al. proposed to integrate the ECQFD, TRIZ, and AHP methods to establish a method for sustainable product design [44]. Bai et al. used the Bio TRIZ method to provide the satisfactory solutions for innovative design of green products [11].

A S-KFCF iterative conceptual design process for modular product is presented in this paper. The process not only meets the sustainability of user requirements, but also completes the modular innovative design for products. The advantages of using the S-KFCF iterative conceptual design process is to reduce design cost, shorten the design cycle and improve product processing quality under the premise of ensuring sustainable product design. Afterwards, the iterative conceptual design process is applied to the design improvement of a low-temperature plasma deposition device. Ultimately, the product conceptual design scheme obtained by the iterative conceptual design process meets the requirements of users and the sustainable innovative design, which verifies the feasibility of S-KFCF iterative conceptual design process.

In this paper, a sustainable and feasible design scheme is provided for the innovative design of mechanical engineering devices. However, the sustainable innovative design process proposed in this paper has limits, such as incomplete selection of user groups in the acquisition of user requirements, and the designers must have perfect relevant professional knowledge and experience. In future research, the user requirements of the product life cycle can be obtained [45], and a perfect demand acquisition mechanism can be established. At the same time, the domain knowledge bases such as expert systems are introduced to assist and guide designers to better complete the sustainable innovative design of mechanical engineering devices in the design process.

6. Conclusions

Iterative conceptual design plays a role in improving the ability of enterprises to adapt to changes in user requirements and to reduce the cost of design. In this present study, we outline a process and methodology to support iterative conceptual design using sustainable analysis and the creative template method. Our contributions are twofold. Firstly, a structure design process is proposed to help standardize designers in their design iterations of modular products. Secondly, the modular conceptual design is completed with the assistance of sustainable analysis of requirements and generation of innovative solutions. To demonstrate iterative conceptual design process, a case study of low-temperature plasma distribution device is presented. Results have shown that a suitable iterative conceptual design process for different modular product cases can be identified while satisfying the sustainable requirements of users. Such a scheme of iterative conceptual design enables deposition devices to mitigate the negative effects of plasma flow rate on film surface quality.

The sustainable design is characterized by greening of design materials, energy-efficient production processes, healthy consumption patterns, and humanization to consumers. In this paper, the problems of traditional mechanical design and manufacturing are solved by focusing on the concept of sustainable and innovative modular design. First of all, the user requirements are collected and classified by the KANO model. Secondly, the FBS model is used to complete the map of the function-behavior-structure and the modular design of the initial design elements. Then, the creative template method is used to generate the innovative and sustainable design scheme. Finally, the FAHP is used to complete the evaluation of the product conceptual design scheme. Therefore, the iterative conceptual design process for mechanical engineering devices with sustainable innovative modular design requirements is obtained eventually.

The thin film that is deposited by PECVD technology has a wide range of applications, such as the fields of ultra-large-scale integrated circuits, optical device, and micro-electromechanical systems (MEMS). However, the continuous industrial application of the deposition device is restricted due to the disadvantages of PECVD technology such as high gas consumption, high cost, and difficulty in controlling the uniformity of film quality. Therefore, the product iterative conceptual design process that is proposed in this paper is applied to the design of a low-temperature plasma deposition device. In general, the working performance of the low-temperature plasma deposition device has significantly improved by using the S-KFCF iterative conceptual design process. The application of the S-KFCF process can realize the requirements of energy saving in production, humanization of users, and greening production of film. The sustainable innovative modular design of the plasma deposition device can realize the characteristic of shortening the design time, reducing the emission of harmful substances, and better uniformity of the thickness of the deposited film compared with the existing deposition device. Consequently, the application of iterative conceptual design process to the design of plasma deposition device has significantly advantages. The feasibility of the S-KFCF iterative conceptual design process that is described in this article is proved.

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Appendix A

Table A1. The satisfaction questionnaire for low-temperature plasma deposition device.

Question	Enjoyed It	As It Should Be	No Matter	Reluctantly Accepted	Disgusted
The device adopts gas mixing system, your review is: Without this feature, your review is:					
The device can maintain a good vacuum degree, your review is: Without this feature, your review is:					
The device can generate stable low-temperature plasma, your review is: Without this feature, your review is:					
The device adopts a low-temperature plasma gas distribution uniform device. Your review is: Without this feature, your review is:					
The device adopts the visual design of low-temperature plasma parameters. Your review is: Without this feature, your review is:					
The device adopts exhaust gas pollution treatment device. Your review is: Without this feature, your review is:					

Appendix B

Table A2. The design of evaluation indicators and weights.

Grading Criteria	Description
0.1	The latter is extremely important than the former
0.3	The latter is obviously more important than the former
0.5	The latter is equally important than the former
0.7	The former is obviously more important than the latter
0.9	The former is extremely important than the latter
0.2/0.4/0.6/0.8 are intermediate values	

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