A Product Design Path Decision Method for Multi-Source Design Requirements

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Abstract—As two design paths to meet the design needs, product change and product innovation adopt different technical methods and implementation characteristics. After the product design demand is put forward, if the product design path cannot be reasonably selected according to the demand characteristics, but blindly implement a certain path, it may affect the product design quality and produce additional production and manufacturing costs. This paper puts forward the method of product demand-oriented design. Firstly, according to the characteristics of design information domain in product design information association model, multi-source product design requirements are divided into functional requirements, structural requirements and parameter requirements, and the adaptability evaluation method of products to three types of requirements is proposed. Finally, a product design path decision method based on the evaluation results of three types of demand adaptability is proposed. As the evaluation standard of whether the product change can be implemented, this method can quickly enter the product design implementation stage, so as to speed up the response speed of enterprise demand and reduce the waste of unnecessary design resources.

Keywords: adaptability analysis of design requirements; design path decision

1 Introduction

After the design demand is generated, how to quickly determine the product design path to meet the demand according to the demand characteristics is an important premise and foundation to improve the demand response speed and design efficiency.

In the design requirement analysis in the field of research, scholars mostly by [1] the kano model and QFD (Quality Function Deployment) analysis method is rapid demand for products, complete product planning. Among them, Kuo et al.[2] divided customer requirements into several categories, such as function, appearance and environment, and used QFD to convert classified customer requirements into functional and technical requirements, so as to carry out function solving and product technical decomposition. Ramanathan et al.[3] conducted importance analysis and effectiveness analysis on functional and technical requirements sorted by QFD. In addition, Chung et al.[4] divided the design requirements of software products into

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functional requirements and non-functional requirements by combining the design characteristics of software products, and analyzed the characteristics and implementation means of the two types of requirements.

At the same time, scholar Altshuller[5] divides the problems to be solved in design into "conventional problems" and "invention problems" in the study of product design paths to meet demands, and the corresponding means to meet demands are divided into conventional design and innovative design. However, scholars Pahl and Beitz[6] divided product design methods to meet product design requirements into original design, adaptive design and variant design. In Pahl's research, the related design methods in variant design and adaptive design emphasize the demand-oriented modification of the original product. The related design methods in the initial design mainly focus on how to design and research and development of innovative products.

Generally speaking, different product characteristics and different demand division methods are all for better service product design. However, in the face of different types of product needs, enterprises can improve and upgrade existing products[7] or build creative and novel products to meet the needs by integrating new methods and technologies. In this paper, the two design paths are respectively called "product change" and "product innovation", which are two kinds of means to meet the design needs of enterprises, leading all kinds of design methods. Based on this concept, this paper combined with the characteristics of mechanical product design requirements, through demand classification and demand adaptability evaluation, design path decision, trying to improve the speed of product design demand response, and quickly enter the product design stage.

2 Feature Analysis of Design Path

In order to meet the original needs of customers, the design department constructs new products to meet the needs through the basic design process of demand analysis, functional design, structural design, parametric design, process design and so on, and the first batch of products are put into the market. However, with the progress of science and technology and the multi-source demand, new products that cannot be chosen by the market and have frequent failures will be abandoned, while high-quality products will evolve into "flagship" products, laying a foundation for the subsequent development of enterprise products. Even if a "flagship" product, is it in the process of operation, will face the change of running environment, performance requirements increase, equipment failures, such as new design requirements, design department by variant structure, parameter optimization and other means to meet these requirements, the "flagship" products will upgrade, gradually extended to the rich "series products. With the improvement of products and the continuous maturity of their functional modules, some products can even achieve rapid product change by means of module configuration and model call[8], saving a lot of costs for enterprises, as shown in Figure 1.

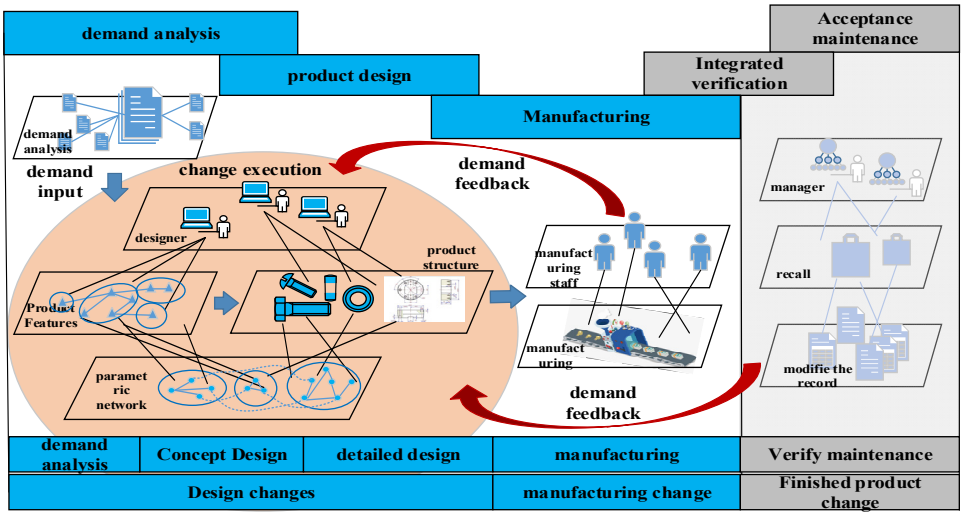

Fig.1 Logical view of product changes

Product innovation becomes the only way to meet design requirements that cannot be met by product change. Product innovation can not only "basically meet" the design needs of products, but also meet the "expectant needs" of customers, bringing additional "surprises" to consumers and enterprises, which are the advantages of product innovation. However, benefits and risks coexist, and the development and promotion of innovative products often consume a lot of human and material resources. Therefore, the innovative development of complex products has even become a part of the strategic decision-making of enterprises. Methods such as BCG Matrix and SWOT Analysis have been used in the strategic decision-making of innovative product development. The product innovation process generally starts from the basic functional requirements of the product, through the conceptual design and detailed design of the product, constructs the three-dimensional entity that the product meets the design requirements, among which the conceptual design of the product is the core step of the product innovation, as shown in Figure 2.

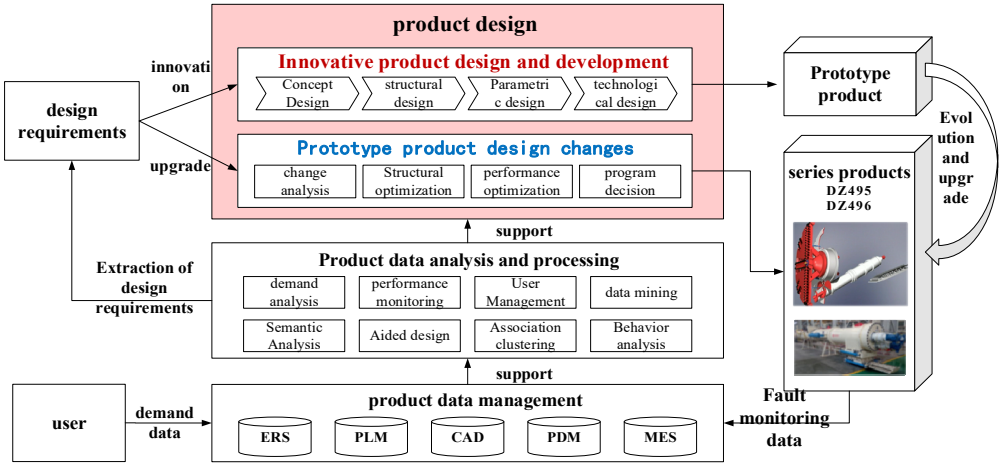

Fig.2 Evolution of a product based on design requirements

In fact, products exhibit different adaptations to different requirements, which we interpret as how easy it is to meet requirements through product change paths. If the product is highly adaptable to the demand, simple modification of the product can meet the demand, and it is appropriate to implement the product change. On the contrary, if the product has low adaptability to the demand and it is difficult to implement the change, it is not suitable to implement the product change and turn to product innovation, as shown in Figure 3.

For example, when the product needs to add a new function, if the design scheme of the product includes the interface of the function module, the product can realize the rapid configuration of the function module for the requirement without additional design cost. On the contrary, if a design requirement is to add a function that a prototype product does not have, and the product is difficult to integrate the function, it is not suitable to adopt the means of product change. Blindly carrying out product change can not only not well meet the design requirements, but also bring additional design and manufacturing costs to the enterprise. Therefore, how to combine design requirements with product attributes and choose a reasonable design path to guide subsequent product design is an important issue for enterprises.

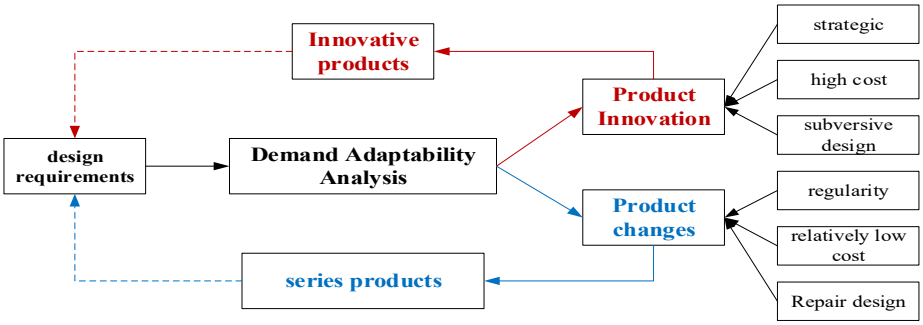

Fig.3 Method selection based on adaptive evaluation

3 Demand Adaptability Analysis

Product design requirements are multi-source and heterogeneous, such as functional requirements, performance requirements, quality requirements, operation requirements, maintenance requirements, external environment requirements, etc. Among them, operation and maintenance requirements, environmental requirements and other types of requirements will be updated over time and with the development of science and technology, and are unpredictable, dynamic and random. Design requirements that are dynamic, random and heterogeneous are ultimately design modification requirements for existing products[9]. In order to convert product design requirements into design information that can be modified, design requirements are transformed into functional requirements, structural requirements and parameter requirements in this paper, which correspond to the intermediate design information of functional domain, structural domain and parameter domain in the association model of general product design information, as shown in Figure 4. Through design information data call and data comparison, scientifically evaluate the adaptability of products to requirements.

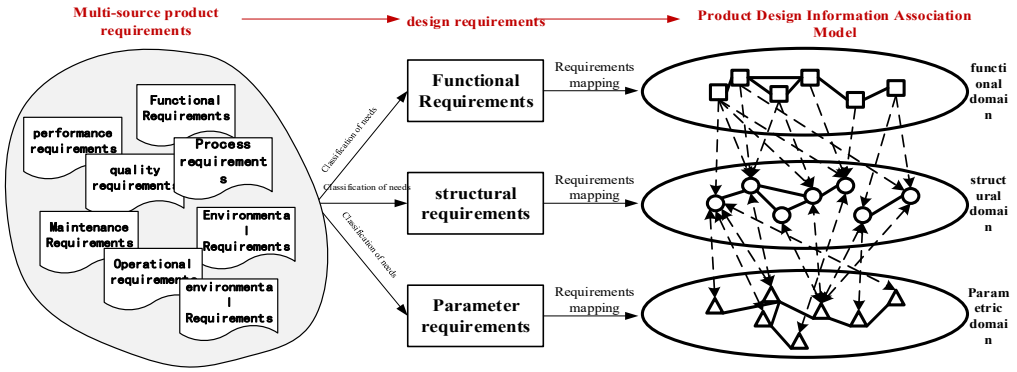

Fig. 4 Requirements adaptability analysis framework for prototype products

The adaptability analysis method of demand-oriented products varies with different types of requirements. Among them, functional requirements are the basic requirements of the product, which has dominance and fuzziness. Dominance is reflected in that functional requirements guide the subsequent design of the product. The satisfaction of functional requirements is the basic principle of the construction of the product entity structure, and functional requirements will be further transformed into structural requirements and parameter requirements. The fuzziness is mainly reflected in the fact that the functional requirements of the product cannot directly guide the product design. In the design requirements of the product, the functional requirements often do not appear alone, but will be accompanied by additional parameter requirements, such as performance parameter indicators, quality parameter indicators, etc. When evaluating product functional adaptability, it is necessary to base on structural and parameter adaptability. The demand of product structure is mainly reflected in the modification and deletion of product parts, which can also be transformed into parameter demand, such as the modification of dimension parameters, the increase and decrease of quantity parameters, etc. As the final form of product, the adaptability evaluation of product to structural requirements is

more intuitive, which is related to the modularity of product structure, configuration of structural interface and other factors, and can be reflected by the cost of structural change. Parameters are the lowest level of product design information, and the granularity of parameter requirements is also the smallest. For example, the improvement of performance parameters, the adjustment of structural parameters, and the change of environmental parameters can be met by parameter changes in the parameter information domain. At the same time, parameter requirements often exist as indicators of functional requirements and structural requirements. When the product has high adaptability to functional requirements and structural requirements, detailed product design can be carried out in the parameter information domain.

3.1 Adaptability Analysis of Functional Requirements

Function realization is the starting point of product design, and new function requirements beyond the product function system have a great impact on prototype products. Some scholars even put forward the judgment criterion of product innovation design by judging whether there is conflict between functional models[10], which shows that the input of functional requirements and the change of functional models have a huge impact on products. Therefore, this paper proposes to realize the adaptability analysis of functional requirements based on whether the inherent functional system of the product can meet the requirements. Assume that the functional requirements set of the product is FR and the functional node set of the product is F.

(1) If $FR \cap F = FR$, the functional model of the product contains the functions described in the requirements, that is, the product can fully meet the functional requirements, which can be called the complete functional requirements, and the product is highly adaptable to the requirements, so there is no need to change the product.

(2) If $FR \cap F = \varnothing$, the functional structure of the product does not contain the functions described by the functional requirements, it is necessary to further determine whether the product has a functional extension interface, and if there is a functional extension interface, the functional requirements can be considered as complete functional requirements. If there is no function expansion interface, it indicates that the product cannot meet the functional requirement, which can be called missing functional requirement, and the product has weak adaptability to the requirement. In this case, it is not suitable to meet the requirement by means of product change, but by means of product innovation.

(3) If $FR \cap F \neq \varnothing$ and $FR \cup F \neq FR$, the original function of the product can meet some of the functional requirements, but cannot completely meet them, then such a requirement is called an adaptive functional requirement. At this point, the functional requirements of the product need to be further transformed into sub-requirements such as structural requirements and parameter requirements through functional decomposition. Only by modifying the design of the structure can the functional requirements be satisfied by adjusting parameters. Therefore, the adaptability of this kind of functional requirements needs to be judged according to the adaptability evaluation results of structural requirements and parameter requirements after decomposition.

3.2 Adaptability Analysis of Structural Requirements

Structural requirements include both those obtained directly from multi-source design requirements and those transformed from functional requirements. Structural requirements mainly include the addition and deletion of components in product structural modules, as well

as the modification of component characteristics. Because the product structure information domain takes parts as the basic unit, the design efficiency, quality, time, cost and other indicators are easy to obtain, so the adaptability assessment of product structure requirements is easy to quantify. This is also a typical feature that distinguishes structural domain from functional domain and parameter domain, and is an important reason why existing research on product change impact assessment focuses on product structural domain[11].In order to realize the adaptability analysis of product structure demand, this paper proposed SA_{needs}, an adaptability factor of product structure demand, as the adaptability evaluation index of prototype product:

$$SA_{needs(i)} = \frac{Cost_{(zero \to s\_states)} - Cost_{(c\_states \to s\_states)}}{Cost_{(zero \to s\_states)}} = 1 - \frac{Cost_{(c\_states \to s\_states)}}{Cost_{(zero \to s\_states)}}$$

$SA_{needs(i)}$ was the adaptability evaluation factor of the product to structural demand *i*. $Cost_{(c\_states \to s\_states)}$ refers to the cost consumed by building products to meet requirements by means of design changes based on the current product state. $Cost_{(zero \to s\_states)}$ refers to the cost of building a new product to meet requirements through product innovation after abandoning the existing product. Generally speaking, product innovation needs to redesign and manufacture products, while product change is a variant and upgrade of existing product structure, saving the $Cost_{c\_state}$ of existing product construction. The cost of structural change of prototype product mainly includes: 3d structural design cost of change, material cost of product change, manufacturing cost, etc. These costs are also closely related to the structural attributes of product structure expansibility, module configurability and so on. Product innovation needs to consider innovative design cost, material cost of product construction, processing and manufacturing cost, etc. Design cost is closely related to the innovation ability of the enterprise team.

Cost estimation to meet structural requirements still depends on modification records and expert experience. To achieve accurate structural change cost estimation, it can only be calculated through trial production of prototype products or small batch production. After the structural cost estimation was completed, the size of the structural demand adaptability assessment factor $SA_{needs(i)}$ could be calculated according to the relationship between $Cost_{(c\_states \to s\_states)}$ and $Cost_{(zero \to s\_states)}$, and the product's adaptability to structural demand could be further analyzed, as shown in Figure 5.

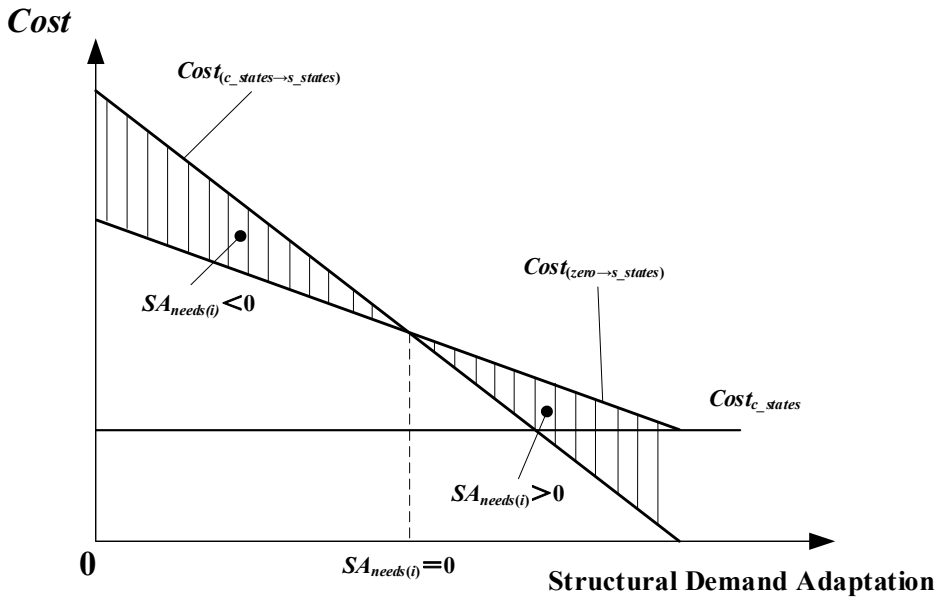

Fig.5 Evaluation method for adaptability of product design change

$SA_{needs(i)}$, the adaptability factor of structural demand, was represented by the ratio of product change cost to meet structural demand and product innovation cost, which was used as the evaluation basis of structural demand adaptability.

(1) When the cost of product innovation to meet the structural demand *i* is higher than that of product change, the adaptability factor $SA_{needs(i)} > 0$, the product has high adaptability to the structural demand, and it is suitable to use product change to meet the structural demand. However, when the structural demand involves parameter change, it needs to be further judged according to the parameter demand adaptability evaluation method.

(2) When the cost of product innovation to meet the structural demand *i* is lower than the cost of product change, the adaptability factor $SA_{needs(i)} < 0$, the adaptability of the product to the structural demand is low, and it is suitable for product innovation. It can be seen that the implementation cost of not all product innovation is higher than that of product change. When the prototype product structure is greatly modified to meet the structural requirements or some structural requirements deviate from the basic principles of prototype product design, improving the structure through product change is a worse choice.

(3) In a very special case, when the cost of product innovation to meet the structural demand *i* is equal to the cost of product change, the adaptability factor $SA_{needs(i)} = 0$, the adaptability of product structural demand is moderate, and the enterprise's innovation ability, design change implementation level and other factors can be considered to comprehensively judge whether to implement product design change.

3.3 Adaptability Analysis of Parameter Requirements

As the lowest design information in the product design process, parameters determine whether

the product function and product structure can meet the design requirements. Due to the wide variety of parameters, the demand for parameter change is also diverse, such as the improvement of performance parameters, the adjustment of structural parameters, the change of environmental parameters, etc.

There are three sources of parameter requirements: parameter requirements for functional requirements transformation, parameter requirements for structural requirements transformation, and parameter requirements contained in product design requirements. Parameter requirements come from different sources and contain different types of requirements. For example, parameter requirements obtained from the transformation of functional requirements generally include performance parameter requirements, quality parameter requirements, etc. The parameter requirements transformed from structural requirements generally include geometric parameter requirements, process parameter requirements, etc. the transformed parameter requirements exist in the form of functional demand indicators and structural demand indicators; The parameter requirements directly obtained from the product design requirements are diverse.

When the parameter requirements are mapped to the parameter association constraint network, the parameter requirements are generally expressed as limiting the parameter values. However, the threshold range of product design parameters is not unlimited. According to the different requirements of parameter requirements on parameter values, products show different adaptability to parameter requirements. When a requirement has too high requirements for parameter modification, violates the product design principle or exceeds the threshold conditions, it will lead to too high cost of prototype product change and modification, and then cannot meet the parameter requirements. If the change value of the parameter is relatively reasonable, it has high adaptability to the demand.

Therefore, the adaptive threshold range of parameter requirements (δ, θ) is proposed in this paper as a standard for evaluating the adaptability of parameter requirements, where δ Is the lower limit of the parameter threshold range, θ Is the upper limit of the parameter threshold range. The adaptive threshold range of product design parameters, which is the threshold condition set by the designer according to the design standard and design experience after the completion of product design. Suppose that the parameter value of a design requirement should be adjusted to $P\_ value$, when the parameter value $P\_value \in (\delta, \theta)$, the product has high adaptability to the requirements of this parameter, and it is suitable for product design change. When the parameter value $P\_value \notin (\delta, \theta)$, the adaptability of the product to the parameter requirements is low, and it is not suitable to adopt the means of product change to meet the parameter requirements.

It is worth noting that due to the large number of product design parameters, it is impossible for designers to evaluate and formulate the adaptability threshold range of all parameters. For example, some parameters are related to the size of some standard parts or the basic functions of products. As constant parameters, these parameters cannot be changed, and there is no need to formulate the adaptive threshold range; Some parameters are product customization parameters provided to customers, and some parameters are variant parameters closely related to structural selection in the design process. These parameters need to strictly formulate the adaptive threshold range to ensure the enforceability of parameter design changes. Other parameters are public parameters with large variable momentum, which can help meet the constraints of some parameter requirements. Such parameters do not need to strictly formulate

the adaptive threshold range. Through the classification of multi parameters and the formulation of adaptive threshold, not only the ability of adaptive analysis of product parameter requirements is improved, but also the parameter configurability of product change is improved.

4 Product Design Path Decision Method based on Demand Adaptability

Through the adaptability analysis of products to three types of design requirements, a product design path decision-making method is proposed. The basic process of this method is shown in Figure 6.

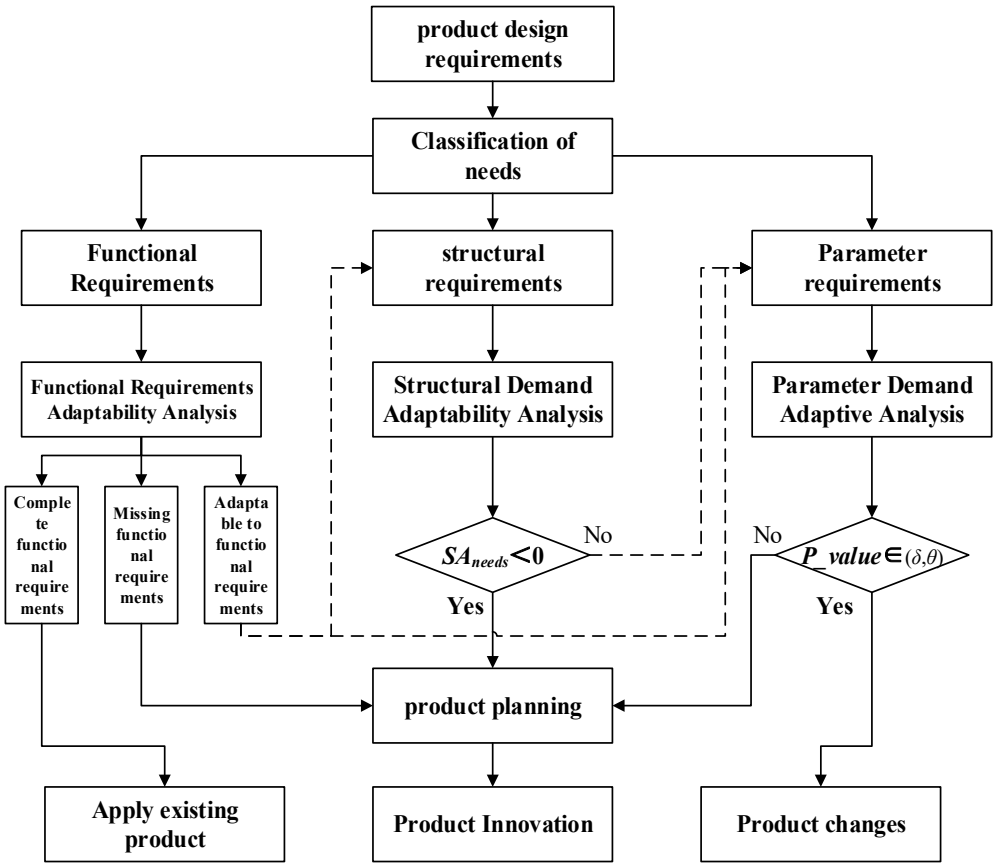

Fig.6 Evaluation method for adaptability of product design change

(1) Demand classification. After obtaining the product design requirements, firstly, according to the requirements description, the future design requirements from the whole product life cycle are divided into functional requirements, structural requirements and parameter requirements,

and the requirements are accurately mapped to the product design information association model.

(2) Functional requirements adaptability analysis. If the design requirements are functional requirements, they are divided into complete functional requirements, missing functional requirements and adaptive functional requirements through the adaptability analysis of functional requirements. If the functional requirements of the prototype are complete, the product can be applied directly; If the functional requirements are the missing functional requirements of the prototype product, product innovation is required; If the functional requirements are the adaptable functional requirements of the prototype product, the adaptability of product design change needs to be further evaluated.

(3) Adaptive functional requirements decomposition. Transform adaptable functional requirements into structural requirements and parameter requirements. This step mainly determines which structure of the product needs to be changed and which parameters need to be adjusted when meeting the functional requirements.

(4) Structural demand adaptability analysis. Carry out adaptability analysis on the structural requirements transformed from functional requirements and the structural requirements extracted from design requirements. When the structural adaptability factor $SA_{needs(i)} < 0$, implement product innovation. When $SA_{needs(i)} > 0$, it is necessary to further evaluate the adaptability of parameter requirements.

(5) Decomposition of structural requirements. When $SA_{needs(i)} > 0$, the structural requirements i of the product are transformed into parameter requirements to determine which design parameters need to be modified to meet the structural requirements.

(6) Adaptability evaluation of parameter requirements. This step mainly analyzes the adaptability of the parameter requirements decomposed in the functional requirements and structural requirements and the parameter requirements extracted from the design requirements. When $P\_value \notin (\delta, \theta)$, it indicates that the adaptability of product design change is low, the parameter requirements cannot be met through product change, and product innovation needs to be carried out. Conversely, when $P\_value \in (\delta, \theta)$, the adaptability of product design change is high, which is suitable for the design change of prototype product.

Whether to implement product change or product innovation is determined by both demand characteristics and product design characteristics. When the product can fully meet the functional requirements, the existing products can be directly applied. When the functional requirements are not met, innovative product design is needed. Whether the adaptable functional requirements can implement design changes is mainly determined by the adaptability of the structural requirements and parameter requirements of the functional requirements decomposition. The adaptability of structural requirements is determined by the adaptability factor of structural requirements. When the adaptability factor is less than 0, the design change should not be implemented; When it is greater than 0, it is determined by the parameter demand adaptability of structural demand transformation. Design parameters are the lowest design information in the design process. When the parameter requirements are met, whether the design change can be implemented is related to the adaptability threshold range of the parameters. The parameter value defined by the parameter requirements is within the threshold range. If the prototype product has high adaptability to the parameter requirements, the design change can be implemented.

For enterprises producing and developing a series of products, product innovation, a subversive and high-cost means of demand satisfaction, is often accompanied by high risks. Before implementing product innovation, they must go through product planning processes such as market analysis, project evaluation, resource allocation, planning time, preliminary planning and process development.

5 Case Analysis

The screw conveyor of shield machine is a typical complex mechanical product. The demand of its life cycle is dynamic, random and heterogeneous. When it is fed back to the design stage of the product, it is expressed as the design demand of the product. When evaluating the adaptability of screw conveyor design change, first classify the product design requirements, determine which type of product design requirements belong to functional requirements, structural requirements and parameter requirements, and decide whether to implement the product change according to the design change adaptability evaluation method. This paper sorts out the design requirements and classification of some screw conveyors, as shown in Table 1:

Table1 Classification of design requirements

Design requirements	**Demand classification**
1. transport slag with maximum particle size of 12cm	● functional requirement: slagging ● parameter requirement: maximum particle size H = 12cm
2. maximum conveying capacity $Q_2 \geq 350$ m^3/h	● functional requirement: slagging ● parameter requirement: maximum slag discharge capacity $Q_2 \geq 350$ m^3/h
3. maximum torque $220kN \cdot m$	● parameter requirement: maximum torque $T_L \leq 220kN \cdot m$
4. realize the telescopic movement of the screw of the screw machine	● structural requirement: expansion device for adding screw
5. the speed of spiral shaft can be adjusted continuously at 0 ~ 22rpm	● functional requirement: screw shaft speed regulation ● parameter requirement: screw shaft speed $n_i \in [0,22] rpm$
6. variable speed reversing of screw conveyor	● functional requirement: variable speed reverse ● structural requirement: add speed regulating, direction changing devices
7. the propulsion speed of shield machine is increased by 20%	● parameter requirement: propulsion speed v_2 increased by 20%

Due to the change of geological environment, when the diameter of materials transported by screw conveyor changes, it brings the design demand: "transporting slag with maximum particle size of 12cm". Take this requirement as an example to evaluate the adaptability of design change. The design requirements include functional requirements: conveying slag and soil. The functional requirements belong to the complete functional requirements of screw conveyor

products, which can be directly applied to the existing products to meet the requirements, but the requirements still include parameter requirements as the limiting conditions for the functional requirements. The parameter requirements are "the design parameters of screw conveyor products, and the maximum particle size H of materials is increased to 12cm". According to the designer's analysis, the adaptability threshold of this parameter is 1-15cm, so the parameter demand is within the adaptability threshold. Through the parametric design calculation of screw conveyor difference, the design improvement of screw conveyor products can be completed to meet the design demand, as shown in Figure 7. Due to space constraints, this paper does not carry out adaptability analysis on all design requirements, but only carries out feasibility analysis and elaboration on the above requirements.

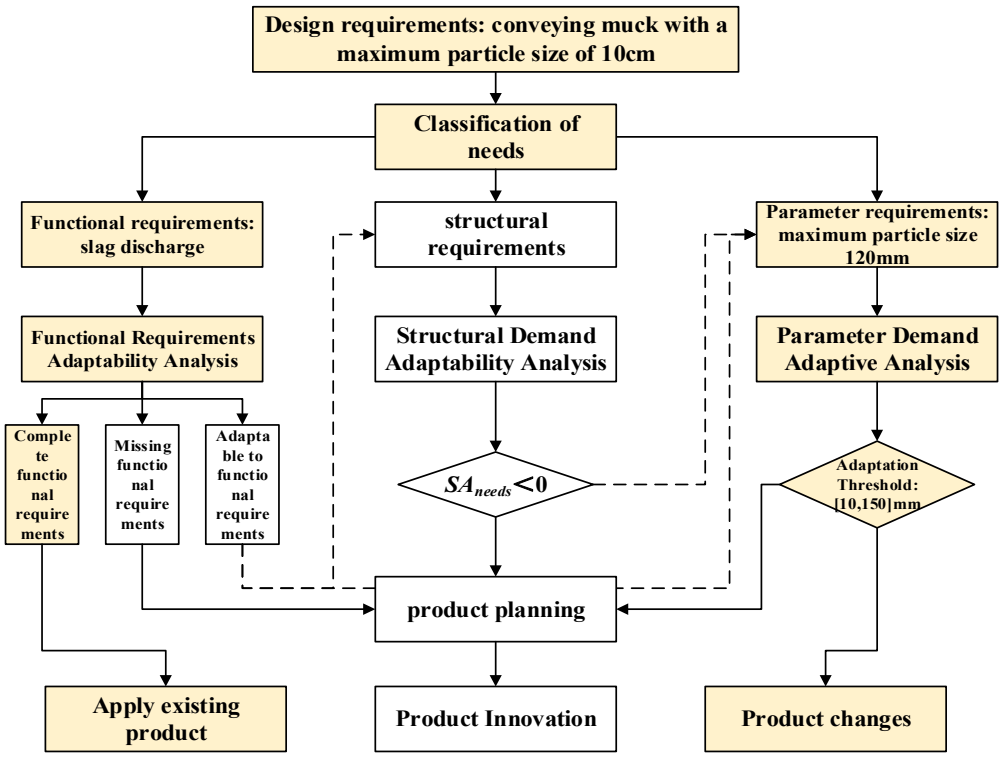

Fig.7 Adaptability evaluation of product design change oriented to change requirement

6 Conclusion

Through the classification of design requirements and the mapping and transformation of design requirements to function structure parameter design information, combined with product characteristics, this paper carries out demand adaptability evaluation. Finally, based on the adaptability evaluation results, this paper makes a decision on the design path to judge whether

the design requirements can be met through the design improvement and upgrading of existing products.

Through the above work, a new idea is provided for the research of demand based design method and path decision-making. It is scientific to carry out demand classification based on product function information, structure information and parameter information, and match with the actual product design pattern. At the same time, the demand adaptability evaluation method closely combined with the product design information attribute conforms to the actual design idea of the enterprise and is reasonable. The design path decision-making method combined with the results of adaptability evaluation can help the design department quickly complete the demand analysis, improve the response speed of demand, and enter the link of product design. Facing the design requirements, through scientific and reasonable design path selection, it can effectively reduce the follow-up development cost of products and ensure the product quality, which has high guiding value for the design work of enterprises.

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