Product Function Module Redesign Recognition Based on Fuzzy Clustering

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Abstract. To solve the existing pain points of the product, obtain a complete set of product functional module redesign identification methods, and enhance the company's competitiveness. In response to the issue of how to redesign product functional modules reasonably, this paper proposes a fuzzy clustering based method for product functional module redesign recognition. This method is based on user demand analysis and product function analysis. It first collects user demand information online, organizes and summarizes it, and then expresses it in professional terms to obtain the existing pain points of the product. Simultaneously collect and analyze product related information, abstract the redesigned object into a functional system, and decompose it into multiple levels of sub functions. Subsequently, a fuzzy evaluation was conducted on the degree of correlation between the input and output of subfunctions with different demand parameters. Taking into account each demand parameter, a correlation matrix was calculated, and then clustering analysis was used to analyze the results obtained. Functional modules were classified for the subfunctions, and the product was redesigned and identified from the perspective of product functional system integrity. Later, the snow rescue vehicle was used as a case study in this article to validate the proposed functional module redesign recognition method, and the results showed that the method was relatively reasonable.By analyzing the correlation between sub functions under the comprehensive consideration of all requirement parameters, and then dividing functional modules through cluster analysis, a feasible method for redesigning product functional modules was obtained and applied to design practice to solve the existing pain points of the product.

Keywords: Functional module redesign; Fuzzy evaluation; cluster analysis;

1 Introduction

Due to the transformation of production and operation methods, the product situation of enterprises is severe. Product function redesign is aimed at redesigning products that meet customer needs and have diverse functions. It has become one of the company's product strategies and a leading factor in winning the initiative. Module classification methods can be divided into the following categories: functional based, functional and architectural based, and several classification methods that face the entire product lifecycle. MICHAEL Mutini et al. [1] provide a criterion for evaluating modular design and a Fuzzy Grouping Genetic Algorithm (FGGA) for better allocation of modules during the modular design process. SUN Jian et al. [2] applied the redesign of product functional modules to the design of product systems, thereby meeting the unique requirements of customers and the customized design of products.

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Information mining technology can quickly and efficiently extract effective information from a large amount of data, so applying these information technologies to the redesign of product functional modules and designing products that better meet user needs will enhance the overall competitiveness of the industry.

2 Literature Review

In recent years, research on user needs has emerged endlessly. Mizuno S [3] and others have established a quality function extension method (QFD) based on customer needs many years ago to conduct customer demand analysis, starting from customer needs and developing new products; Some researchers have established Kano models [4] to represent the relationship between customer satisfaction and product quality; Wang Meiqing et al. [5] used network analysis to explore the relationship between user needs and quality characteristics; Zhang Lin[6] et al. explored the visual user requirement model; Zhang Qing[7] et al. analyzed the needs of users in the "functionality behavior structure" model to obtain the best user needs;Saaty et al. [8] proposed a nine level scoring criterion based on subjective evaluation of individuals, with ratings ranging from 1 to 9 based on the strength of emotions; Li Shichang et al. [9] studied the scenario demand analysis problem of autonomous transportation systems; Scholars such as Huang Jingwei [10], Bu Jiahui [11], and Yuan Jian [12] have used data mining methods to study the characteristics and needs of users.

There is also some research on the modularization of product functions. Jacobs [13] and Campagnolo [14] et al. have shown that modular design refers to the use of standardized interfaces for the combination of any two modules in a product. The separation freedom between each module is high, and it can be replaced according to specific needs without changing the overall functionality of the product. Li Anhu et al. [15] provided a modular design approach for ambulance boxes, thereby completing the classification of functional modules and modeling of product architecture. Jia Weiqiang et al. [16] provided a product module design method based on fuzzy correlation to address the uncertainty issues of signal transmission and conversion. Wang Xiangbing et al. [17] provided a modular design approach for flexible platforms based on the latest user needs, which is used to address module classification issues and product lifecycle issues.

Cluster analysis is one of the fundamental technologies for achieving different combinations of goods through data mining, which has been widely used in various fields such as mechanical learning, data mining, biology, and chemistry. Traditional clustering analysis is an unsupervised learning method that attempts to combine different combinations of goods through data mining based on the internal data structure of the dataset. It is widely used in various fields such as mechanical learning, data mining, biology, and chemistry. The core idea of fuzzy clustering algorithm is to place data points with the same features into the same category based on fuzzy membership, and data points with different features into different categories [18]. Traditional clustering analysis is an unsupervised learning method that attempts to transform the dataset $X = \{X_j | X_j \in R_p,\ j = 1,2,\dots,n\}$ based on its internal data structure,is divided into C ($1<c<n$) categories to minimize the distance between samples in the same cluster and maximize the distance between sample points in different clusters. Among all clustering methods, K-means clustering (K-means) [19] and fuzzy C-means clustering (FCM) [20] are the two most popular

clustering methods. It is widely used in multiple fields such as data representation [21], fuzzy control [22], and machine learning [23]. Chen Lin et al. [24] Applying fuzzy clustering analysis method to highway special project plans.

In summary, the above research results have more or less conducted qualitative and quantitative research on the division of product design system modules. However, few people have started to delve into the modular design of product design functions from the overall perspective of product design, which is also the main focus of this article's research. The commonly used module partitioning methods currently include functional analysis and component analysis, while this article uses functional analysis to redesign and identify product functional modules. On the basis of functional decomposition of the entire functional system, user needs are treated as parameters for correlation analysis between product subfunctions, in order to obtain product functional module layout results that meet user needs and are reasonably allocated within the functional domain.

3 Example of Redesign and Identification of Product Function Modules

3.1 Case Selection and Needs Analysis

With the rapid development of the economy in recent years, more and more people enjoy exploring and adventuring in polar regions. However, due to the increasingly harsh global ecological environment and the changing climate, natural disasters such as snow and freezing occur frequently. Therefore, there are a large number of unpredictable safety hazards hidden in polar regions, especially safety accidents caused by snow disasters, which are high incidence events. Therefore, it is necessary to continuously improve and innovate the existing snow rescue vehicles in China. Therefore, this article selects the existing snow rescue vehicles in China for functional module redesign and identification. After conducting online research, collecting relevant literature and news, as well as conducting online interviews with 20 snow rescue vehicle users, demand information was collected and sorted using the KJ method. Professional terminology was used to express the pain points and issues that users encountered during the use of the product.

The first layer of requirements that are summarized and organized through the KJ method and expressed in professional terms are: good mobility, complete rescue functions, and an artistic appearance. This article mainly focuses on the redesign and identification of product functional modules. The requirement parameter of artistic appearance is not within the scope of this article's research. Therefore, in the following analysis, the requirement parameters used for redesign and identification are: good mobility and complete rescue function, namely: U={Good maneuverability, complete rescue function}.

$$U = \{u_1, u_2, \dots, u_k, \dots, u_m\} \quad (1)$$

Among them, "u_k" represents the k-th demand parameter; "M" represents the number of requirement parameters.

3.2 Functional breakdown of snow rescue vehicles

Firstly, review and collect relevant information on existing snow rescue vehicles in China,think of it as an abstract functional system and then decompose it into functions. Its overall function is to be able to drive normally in snow, adapt to the natural environment of snow, and have rescue functions. The secondary sub functions decomposed are driving function, control function, driving function, rescue function, etc. Organize the sub function set $F = \{f_1, f_2, \dots, f_{14}\}$ of the snow rescue vehicle, and the sub functions represented by each element in the set are shown in the following Table 1:

Table 1. Subfunction set.

parameter	Functional content	parameter	Functional content
f_1	Energy transfer and distribution	f_8	Rescue equipment carrying function
f_2	Energy conversion function	f_9	Rescue search function
f_3	Braking function	f_{10}	Patient Placement Function
f_4	Steering function	f_{11}	Energy storage function
f_5	Circuit control function	f_{12}	Structural connection function
f_6	Variable speed driving function	f_{13}	Lighting function
f_7	Rescue item storage function	f_{14}	Visual communication function

3.3 correlation analysis

3.3.1 Fuzzy evaluation

The evaluation set V obtained through online expert interviews and pre evaluation is as follows:

$$\mathrm{V} = \{\mathrm{v}_1, \mathrm{v}_2, \mathrm{v}_3, \mathrm{v}_4, \mathrm{v}_5, \mathrm{v}_6\} \tag{2}$$

Among them: v_1={completely unrelated}; v_2={Relatively weak}; v_3={general correlation}; v_4={Moderate correlation}; v_5={Strong correlation}; v_6={completely correlated}.

By evaluating t evaluation definitions in set V, convert each evaluation definition into a corresponding equal difference array A, where each value represents the corresponding degree of correlation, and take the equal difference value within the range of [0,1]. As follows:

$$\mathrm{A} = \{0, \mathrm{a}_2, \dots, \mathrm{a}_i, \dots, \mathrm{a}_{t-1}, 1\} \tag{3}$$

$$\mathrm{A}_i = 1/(\mathrm{t} - 1) + \mathrm{a}_{i-1} \tag{4}$$

Among them, 0 represents complete irrelevance between two subfunctions, and the larger the value, the greater the degree of correlation between subfunctions; 1 indicates a complete correlation between the subfunctions of the two.Convert each fuzzy evaluation definition into corresponding numerical values for further research in the future. The fuzzy correlation between sub functions is defined in the Table 2 below:

Table 2. Fuzzy Correlation Definition.

Evaluation semantics	Relevance	Related Types	Correlation Descriptionv
v_1	0	completely unrelated	The sub functions are independent of each other
v_2	0.2	weak correlation	The sub-functions are basically independent
v_3	0.4	general correlation	The interaction between subfunctions is not obvious
v_4	0.6	moderately relevant	There are certain interactions and associations between sub-functions
v_5	0.8	strong correlation	The sub-functions are closely related and highly related
v_6	1	perfect correlation	The sub-functions are closely related and cannot be split

The following is the calculation formula for the correlation degree "r_{ij}"between the i-th and j-th subfunctions:

$$r_{ij} = \begin{cases} \sum_{k=1}^{m} w_k \quad \times C\left[(f_I, f_j)_k \quad + (f_j, f_j)_k\right] & i \neq j \\ 1 & i = j \end{cases} \tag{5}$$

Among them, "C"is to ensure that the ratio of "r_{ij}" values between [0, 1] is constant;"w_k"refers to the coefficient of influence of the correlation of any demand parameter on the total correlation ($\sum_{k=1}^{m} W_k \quad = 1$).The fuzzy evaluation value matrix between subfunctions "F_1"and "F_2"are as follows:

$$F_1 = \begin{bmatrix} 1 & 0.8 & 0.8 & 0.8 & 0.6 & 0.6 & 0.4 & 0.2 & 0.6 & 0.2 & 0.2 & 0.4 & 0.6 & 0.2 \\ 0.6 & 1 & 0.4 & 0.2 & 0.2 & 0.6 & 0.2 & 0.2 & 0.6 & 0.2 & 0.4 & 0.2 & 0.6 & 0.2 \\ 0.4 & 0.4 & 1 & 0.6 & 0.4 & 0.6 & 0.2 & 0.2 & 0.6 & 0.2 & 0.4 & 0.4 & 0.4 & 0.4 \\ 0.4 & 0.4 & 0.6 & 1 & 0.2 & 0.6 & 0.2 & 0.2 & 0.6 & 0.2 & 0.2 & 0.6 & 0.2 & 0.2 \\ 0.2 & 0.2 & 0.4 & 0.4 & 1 & 0.4 & 0.2 & 0.4 & 0.4 & 0.2 & 0.4 & 0.2 & 0.2 & 0.2 \\ 0.4 & 0.6 & 0.4 & 0.4 & 0.4 & 1 & 0.4 & 0.2 & 0.8 & 0.2 & 0.4 & 0.6 & 0.4 & 0.4 \\ 0.2 & 0.2 & 0.4 & 0.2 & 0.4 & 0.4 & 1 & 0.2 & 0.6 & 0.2 & 0.4 & 0.4 & 0.2 & 0.2 \\ 0.2 & 0.2 & 0.2 & 0.4 & 0.4 & 0.2 & 0.2 & 1 & 0.2 & 0.4 & 0.4 & 0.4 & 0.2 & 0.2 \\ 0.4 & 0.6 & 0.6 & 0.8 & 0.6 & 0.8 & 0.4 & 0.2 & 1 & 0.2 & 0.2 & 0.6 & 0.8 & 0.6 \\ 0.2 & 0.4 & 0.2 & 0.2 & 0.4 & 0.2 & 0.6 & 0.6 & 0.4 & 1 & 0.2 & 0.4 & 0.6 & 0.4 \\ 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.4 & 0.6 & 0.2 & 0.4 & 0.2 & 1 & 0.4 & 0.2 & 0.2 \\ 0.6 & 0.4 & 0.6 & 0.6 & 0.4 & 0.6 & 0.2 & 0.4 & 0.4 & 0.2 & 0.2 & 1 & 0.4 & 0.2 \\ 0.4 & 0.6 & 0.6 & 0.6 & 0.4 & 0.8 & 0.2 & 0.2 & 0.8 & 0.2 & 0.2 & 0.2 & 1 & 0.6 \\ 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.6 & 0.2 & 0.2 & 0.8 & 0.2 & 0.4 & 0.4 & 0.4 & 1 \end{bmatrix} \tag{6}$$

$$F_2=\begin{bmatrix} 1 & 0.6 & 0.2 & 0.2 & 0.2 & 0.6 & 0.2 & 0.8 & 0.6 & 0.8 & 0.4 & 0.2 & 0.2 & 0.2 \\ 0.8 & 1 & 0.2 & 0.2 & 0.2 & 0.6 & 0.2 & 0.6 & 0.2 & 0.2 & 0.2 & 0.4 & 0.4 & 0.2 \\ 0.2 & 0.4 & 1 & 0.4 & 0.2 & 0.4 & 0.6 & 0.6 & 0.8 & 0.4 & 0.2 & 0.4 & 0.2 & 0.2 \\ 0.4 & 0.2 & 0.4 & 1 & 0.2 & 0.6 & 0.2 & 0.2 & 0.6 & 0.2 & 0.2 & 0.4 & 0.2 & 0.2 \\ 0.2 & 0.2 & 0.2 & 0.2 & 1 & 0.4 & 0.2 & 0.2 & 0.4 & 0.4 & 0.4 & 0.4 & 0.4 & 0.2 \\ 0.6 & 0.6 & 0.6 & 0.8 & 0.4 & 1 & 0.4 & 0.6 & 0.8 & 0.4 & 0.2 & 0.4 & 0.4 & 0.4 \\ 0.4 & 0.4 & 0.2 & 0.2 & 0.2 & 0.4 & 1 & 0.4 & 0.2 & 0.4 & 0.6 & 0.4 & 0.2 & 0.2 \\ 0.6 & 0.8 & 0.4 & 0.4 & 0.2 & 0.2 & 0.6 & 1 & 0.8 & 0.8 & 0.6 & 0.6 & 0.2 & 0.2 \\ 0.2 & 0.2 & 0.6 & 0.6 & 0.4 & 0.8 & 0.6 & 0.4 & 1 & 0.4 & 0.4 & 0.4 & 0.4 & 0.8 \\ 0.4 & 0.2 & 0.2 & 0.2 & 0.4 & 0.6 & 0.8 & 0.8 & 0.4 & 1 & 0.8 & 0.8 & 0.4 & 0.4 \\ 0.2 & 0.8 & 0.4 & 0.4 & 0.2 & 0.6 & 0.6 & 0.4 & 0.2 & 0.4 & 1 & 0.4 & 0.2 & 0.4 \\ 0.2 & 0.2 & 0.6 & 0.8 & 0.2 & 0.6 & 0.6 & 0.8 & 0.4 & 0.4 & 0.2 & 1 & 0.2 & 0.2 \\ 0.4 & 0.2 & 0.6 & 0.6 & 0.2 & 0.6 & 0.2 & 0.2 & 0.8 & 0.2 & 0.2 & 0.2 & 1 & 0.4 \\ 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.4 & 0.2 & 0.2 & 0.6 & 0.2 & 0.2 & 0.2 & 0.2 & 1 \end{bmatrix} \tag{7}$$

3.3.2 Establishment of correlation matrix

Based on two requirement parameters: good maneuverability, complete rescue function, and the relative equal importance of the two requirement parameters, $W_1=W_2=0.5$ is taken. According to equation (5), the correlation is calculated in MATLAB software when considering various parameters comprehensively. Calculated correlation matrix R:

$$\begin{bmatrix} 1 & 0.70 & 0.40 & 0.45 & 0.30 & 0.55 & 0.30 & 0.45 & 0.50 & 0.30 & 0.25 & 0.35 & 0.40 & 0.20 \\ & 1 & 0.35 & 0.25 & 0.20 & 0.60 & 0.25 & 0.45 & 0.40 & 0.25 & 0.25 & 0.40 & 0.45 & 0.20 \\ & & 1 & 0.50 & 0.30 & 0.55 & 0.35 & 0.35 & 0.65 & 0.25 & 0.30 & 0.50 & 0.45 & 0.25 \\ & & & 1 & 0.25 & 0.60 & 0.20 & 0.30 & 0.65 & 0.20 & 0.25 & 0.65 & 0.40 & 0.20 \\ & & & & 1 & 0.40 & 0.25 & 0.30 & 0.45 & 0.35 & 0.30 & 0.30 & 0.30 & 0.20 \\ & & & & & 1 & 0.40 & 0.30 & 0.80 & 0.35 & 0.40 & 0.55 & 0.55 & 0.45 \\ & & & & & & 1 & 0.35 & 0.45 & 0.50 & 0.55 & 0.40 & 0.20 & 0.20 \\ & & & & & & & 1 & 0.40 & 0.65 & 0.40 & 0.55 & 0.20 & 0.20 \\ & & & & & & & & 1 & 0.35 & 0.30 & 0.50 & 0.70 & 0.70 \\ & & & & & & & & & 1 & 0.40 & 0.45 & 0.40 & 0.30 \\ & & & & & & & & & & 1 & 0.30 & 0.20 & 0.30 \\ & & & & & & & & & & & 1 & 0.25 & 0.25 \\ & & & & & & & & & & & & 1 & 0.40 \\ & & & & & & & & & & & & & 1 \end{bmatrix} \tag{8}$$

3.4 Cluster analysis

In cluster analysis, taking λ= 0.6. The cutoff matrix value of the correlation matrix formula R is:

$$R_{ij}\ (0.6)=1;\ \text{When } r_{ij} \geq 0.6\ (\text{fi is related to fj}) \tag{9}$$

$$R_{ij}\ (0.6)=0;\ \text{When } r_{ij}<0.6\ (\text{fi is not related to fj}) \tag{10}$$

The following results were obtained through cluster analysis: $r_{12}, r_{26}, r_{39}, r_{46}, r_{49}$, $r_{412}, r_{513}, r_{514}$, r_{69}, r_{810} , r_{913} , r_{914} are all greater than or equal to λ, based on the transitivity of the correlation degree, it can be concluded that there is a strong correlation between subfunctions $f_1, f_2, f_3, f_4, f_5, f_6, f_9, f_{12}, f_{13}, f_{14}$, Therefore, assign it to the same functional module.The subfunctions f_8 and f_{10} are interrelated, but have strong independence from other subfunctions.

3.5 Functional module redesign identification

From a practical perspective, taking into account the practical factors of modular design, the integrity of module functions, and the required auxiliary functions, the following functional modules are divided:Module 1: $\{f_1, f_2, f_3, f_4, f_5, f_6, f_9, f_{11}, f_{12}, f_{13}, f_{14}\}$;Module 2: $\{f_7, f_8, f_{13}, f_{14}\}$.

The partition scheme of Module1 meets one main requirement parameter: good maneuverability. Module1 has strong relative independence. When used alone, during the journey to the rescue cabin (Module 2), it can travel quickly in the snow, saving the total time required to arrive at the accident site and carrying out efficient and fast rescue tasks.The partition scheme of Module 2 meets another main requirement parameter: complete rescue function. This module also has relative independence, which can be designed as a self-service rescue warehouse waiting to be combined with module 1 at any time. Its space can be expanded and rescue facilities can be added, and it can be placed near accident prone areas for a long time, which relatively enhances the rescue function.In summary,Module 1 and Module 2 can also be interactively combined, and when combined, they still maintain their complete functional characteristics. In the event of a safety accident, Module 1 quickly travels to Module 2, which is closest to the accident site, and interacts with it to rush to the accident site, thereby efficiently and quickly completing rescue tasks. By redesigning the product functional modules, all subfunctions were divided into two relatively independent product functional modules, resulting in three solutions that fully demonstrate the advantages of product modularity.

4 Conclusions

This article proposes a functional module redesign identification method based on user demand analysis and product function decomposition, which addresses the issue of how to redesign product functional modules reasonably. By analyzing the correlation between subfunctions under the comprehensive consideration of all requirement parameters, and then dividing functional modules through clustering analysis, the existing pain points of the product are solved, A feasible method for redesigning product functional modules was obtained and applied to design practice. Finally, the rationality of this method was verified by using a snow rescue vehicle as a case study in this article.The main conclusions of this study are as follows:(1) This article uses the KJ method to effectively collect and professionally express complex information, effectively grasp the essence, and find solutions. However, due to the use of online user demand collection in this article and the randomness of social network platform speeches, the results are not objective and rigorous enough, which also brings some interference to subsequent data analysis work and reduces reliability.(2) The functional decomposition method can effectively decompose a complex product functional system into a well organized functional decomposition diagram, and then establish sub functional sets for correlation analysis and product functional module division. Compared to the component decomposition method, this method is more suitable for decomposing the functional structure of complex products.(3) By conducting correlation analysis and clustering analysis on the input and output between subfunctions of different demand parameters, user needs and product functional module partitioning are effectively linked, thereby solving the existing pain points of the product.

The limitation is that it is currently not possible to conduct a more in-depth analysis and design of product functional modules, and there may be various factors that have not been taken into account, so it may be more idealized compared to reality.

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