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Research on Function Module Optimization Method of Smart Home Products Based on User Behavior Data Analysis

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Abstract As one of the important applications of modern technology, the research on optimization of smart home products' functional modules has been paid more and more attention. This paper constructs a knowledge model of smart home products based on user behavior data, uses the data as the basis for the functional design of smart home products, and applies the KANO model to analyze each demand in the user demand library. Based on the demand transformation method of QFD, the mapping relationship between personalized demands and product design parameters is established, and the correlation matrix of basic demand items and design parameters is constructed to realize the transformation of personalized demands. Applying the functional module optimization and design method proposed in this paper, we carry out the practice of optimizing the design of intelligent treadmill functional modules, and obtain the design requirements and design solutions of intelligent treadmill products. In terms of the review results, both experts and users rated the product within 4~5, which is a high overall rating.

Index Terms knowledge model, KANO model, quality house, smart home, function optimization

I. Introduction

The popularization and development of smart home products have brought great convenience and comfort to people's lives [1], [2]. With the continuous progress of technology, smart home products are becoming more and more intelligent and personalized [3]. The behaviors displayed by users when using smart home products are crucial for the optimization of product performance and the enhancement of user experience [4], [5].

In smart home products, user behavior can be divided into several different stages, including product selection, product operation, usage experience and feedback [6], [7]. First, users are influenced by several factors when choosing smart home products, such as product features, price, and brand reputation [8], [9]. Through the analysis and understanding of users' selection behavior, product manufacturers can understand the market demand, adjust product positioning, as well as provide products that better meet users' needs [10]-[12]. Second, in the process of product operation, users will have different behavioral habits and ways of use [13]. Smart home products can analyze user behavior through technical means and provide personalized services based on user preferences and habits [14], [15]. For example, by learning users' daily behaviors, smart home products can automatically adjust the temperature, lighting, and music [16]. By learning the user's usage frequency and time, smart home products can automatically remind users to replace consumables or perform maintenance [17], [18]. By analyzing user behavior, smart home products can form a closer and more intelligent interaction with users [19]. In order to improve the performance and user experience of smart home products, product function module optimization is an essential step [20], [21]. Through the analysis of user behavior data, user needs and preferences can be mined, which in turn guides the decision-making of product manufacturers [22], [23].

In order to accurately obtain users' personalized needs for smart home products and realize the optimization of functional modules of smart home products, this paper firstly forms the knowledge model of smart home products in four relative fields of demand, function, principle and structure, and obtains the data with the users of smart home products. Based on the principle of modular structure design of smart products, a comprehensive model of demand-function of smart home products is constructed, and the KANO model is used to analyze each user's demand in the user demand library. Based on the statistical data of the KANO questionnaire, a four-quadrant diagram is constructed and the initial importance of user requirements is calculated. The final importance of user requirements is calculated by increasing the importance adjustment coefficient K to indicate the importance of each user requirement. Using QFD theory to complete the mapping of user needs to product technical features, extract product technical features and establish the quality of smart products. The smart treadmill in smart home products is selected as the research subject to carry out the practice of optimization design of smart home product function module, and explore the effectiveness of the optimization method of smart home product function module related to this paper.

II. Smart Home Product Knowledge Model

One of the differences between the design method based on user behavior data and traditional design is the use of data as the basis of the design method, so we need to obtain user data and product data in the big data of smart home products, and effectively analyze them, and finally form the knowledge models of the four relative domains: demand, function, principle, and structure. After these knowledge models are stored and categorized, they can provide data support for the later research.

II. A.Requirements knowledge model

After obtaining user requirements, due to the differences in the user groups themselves, the differences in descriptions, and the differences in the functions of the requirements, the requirements can be categorized so as to obtain different levels and categories of requirements. The user requirement knowledge model can be represented by multivariate groups, so as to achieve the distinction between different levels and classes of requirement data, and to facilitate the subsequent analysis, the requirement knowledge model multivariate groups are represented as follows:

$$D = (D_{id}, D_n, D_c, D_d, D_f) \tag{1}$$

where D_{id} is the demand flag, indicating different levels of demand information; D_n is the name of the demand, i.e., it is the acquired user's need; D_c is the description of the user's demand, indicating the user's detailed description of his/her own demand; D_d is the expression of the demand, which indicates that the user expresses his/her demand with a connotation, and the real demand is expressed; and D_f is the function flag of the demand, indicating that the product should have the product functions corresponding to the user's demand. The D_f is the function flag of the demand, which indicates the product function that the user demand should have.

II. B.Functional Knowledge Model

In product design, the function of the product serves as a bridge connecting the user's needs to the structure required for the product to achieve the design goal, while the function of the product and the principle of product function are in correspondence, so there is a close connection between the knowledge of function and the knowledge of needs, principle and structure. The five-tuple knowledge model of function is expressed as:

$$F = (F_{id}, F_n, F_m, F_p, F_s) \tag{2}$$

where F_{id} for the function logo, expressed for different categories and levels of functional information; F_n for the function name, that is, the name of the function that the product needs to realize; F_m for the function of the main body logo, said that the function of the product is realized in the position of the main product or belongs to the parts; F_p for the principle of the function mark, indicating the knowledge principle that should be available in order to realize the target function; F_s is the structure mark of the function, indicating the structure information that the product should have in order to realize the target function under the support of the corresponding knowledge principle.

II. C.Principle Knowledge Model

Principle is a bridge connecting function and structure, and is a manifestation of the design knowledge level. Principle knowledge reflects the functional knowledge of the product, and at the same time can show the structural knowledge of the product, the five-tuple knowledge model of the principle is:

$$P = (P_{id}, P_n, P_d, P_f, P_s) \tag{3}$$

where P_{id} is the principle flag, indicating the classification of different principles; P_n is the name of the principle, indicating the name of the required design knowledge principle; P_d is the description of the principle, indicating the description of the principle's connotation; P_f is the principle's functional identity, indicating the function of the design product corresponding to the design knowledge principle; and P_s is the principle's structural identity, indicating the structure of the product design corresponding to the design knowledge principle. The P_s is the structural identifier of the principle, which is the structure of the product design corresponding to the design knowledge principle.

II. D.Structural knowledge models

In the product design process structure as the final design results of the form, about the structure of many sources of knowledge, such as enterprise data, patent specifications, design drawings, product results model, modeling software library and so on. Access to this knowledge is categorized and organized and modeled into a database, and after obtaining the user requirements mapped to the product function and then to the design principle knowledge, the structural database can be used to directly get the target product design scheme, which greatly improves the design efficiency. The five-tuple knowledge model of the structure is:

$$S = (S_{id}, S_d, S_l, S_f, S_p) \tag{4}$$

where S_{id} is the structure identification, indicating the classification of the structure; S_d is the description of the structure, indicating the name of the structure of the product, the basic parameters of the use of the conditions and other aspects of the description; S_l is the use of the structure of the product qualifications, indicating the qualifications of the product's different structures, including the appearance of the structure of the color, material, size, weight, extensibility, etc.; S_f is the functional identification of the structure, which indicates the functional use of the different structures of the product; S_p is the principle identification of the structure, which indicates the design knowledge principle behind the structure of the designed product.

III. Smart Home Product Requirements - Functional Comprehensive Modeling

At present, the transformation process of user requirements to product functions in the smart home market is too dependent on designers' own experience and lacks scientific theoretical guidance. In order to optimize this problem this chapter will be based on the principle of modular structure design of smart products, introduce KANO model and importance adjustment coefficient in the link of demand analysis, and in the construction of the house of quality (HOQ), put forward the comprehensive model of demand-function of smart home product design research [24], [25].

III. A. Modularized Structure Design Principle for Intelligent Products

III. A. 1) Product design space

The traditional product design space is divided into functional space, behavioral space, structural space, and environmental attribute space, and many different studies of new product development methods have been generated for different product design spaces. This study takes the product design structure space as the research focus and seeks the realization method of product structure design.

In the process of new product development, the development cycle of new products is repeatedly compressed in order to meet the needs of enterprises. Product designers focus on the appearance design of the product at the early stage of the design process and pay insufficient attention to the structural design. In the middle and late stages of the product design process, it is very easy to produce potential hidden dangers due to the irrationality of the product structure, resulting in the inability to realize the product function. Therefore, how to take into account the reasonable development of product structure while developing new products oriented to customer needs has become an important direction for the research of new product development methods.

III. A. 2) Axiomatic design development process

Axiomatic design employs user, functional, structural and process domains to describe the product development process, and the four design domains correspond to their respective elements, i.e., user requirements (CAs), functional requirements (FRs), design parameters (DPs) and process variables (PVs) [26]. Among them, the process variables correspond to the product machining and assembly processes, which occur during the manufacturing and assembly phases of product production.

Axiomatic design theory establishes a top-down design process, forming a “Z” mapping relationship between design domains, which is divided into two aspects: mapping between the same level and different levels, and design expression in the form of judgment matrix.

In the axiomatic design theory, the mapping relationship between functional domains and structural domains is expressed as follows:

$$\{FR_s\} = A\{DP_s\} \tag{5}$$

where A denotes the design matrix, FR_s and DP_s are the set of functional requirements and the set of design parameters, respectively.

$\{FR_s\} = \{FR_1, FR_2, FR_3 ..., FR_n\}, \{DP_s\} = \{DP_1, DP_2, DP_3 ..., DP_n\}$, which can be described as follows:

$$\begin{bmatrix} FR_1 \\ FR_2 \\ \vdots \\ FR_n \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & a_{ij} & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ \vdots \\ DP_n \end{bmatrix} \tag{6}$$

where a_{ij} denotes the degree of association between the corresponding elements, which is usually denoted by X and O, with X denoting strong correlation and O denoting weak correlation or irrelevance.

For different forms of design matrices the designs are categorized into three types: independent, decoupled, and coupled.

III. A. 3) Axiomatic Design Theory Advantages

Axiomatic Design Theory (AD) has two design rules, the Axiom of Independence and the Axiom of Information. The two design axioms provide an effective evaluation standard for the new product development process, which can detect and deal with the design coupling as early as possible in the conceptual design stage and improve the efficiency of new product development.AD emphasizes the accuracy of product design at the beginning of the new product development, aiming at providing the thinking methods and tools based on logic and rationality, and guiding the designers to make a reasonable judgment in the design process.

AD “user needs - functional requirements - design parameters” mapping process, to realize the problem of what to do in the design process. Compared with the traditional new product conceptualization and generation method, it simplifies the new product development process and can quickly and reasonably realize the structural space design of new product development based on customers. However, the axiomatic design theory still has some shortcomings and needs to be integrated with other design theories or tools.

III. A. 4) Modular product architecture design

In modular design, each module serves as a constituent unit in the product system, and the product is constructed through the specific combination form between modules, and similarly, the product can be divided into different modules with independent functions through the modular design concept.

Modular product structure design, the modular design concept into the product structure design, that the product consists of a number of modular structure, can achieve mutual coordination within the product, in order to ensure that the product function is perfect on the basis of the product to achieve the optimal combination of the product as a whole.

Modular design process, the advantage is that you can add or delete different types of modules to achieve the overall performance of the product to improve and perfect, to achieve this advantage of the premise of the modular design system must have enough compatibility to ensure that the modular design of the product can continue to obtain the development of the space, axiomatic design theory and the integration of modular design ideas for the development of new products to provide infinite The integration of axiomatic design theory and modular design ideas provides infinite possibilities for new product development.

III. B. Requirements-functions synthesis model construction

The KANO model is used to analyze each user requirement in the user requirement library, which involves six parts: creation and distribution of the KANO questionnaire, analysis of the results of the KANO questionnaire, construction of the four-quadrant diagram, calculation of the initial importance of each requirement, introduction and calculation of the importance coefficient K, and calculation of the final importance.

III. B. 1) KANO questionnaire

According to the user requirements in the user requirements library, make corresponding KANO questionnaires from both positive and negative aspects, and select suitable target groups to distribute KANO questionnaires for target product research.

Count the number of people selecting each KANO category for each user requirement, and select based on the maximum value, i.e., for a certain user requirement, the KANO category with the largest number of people selecting it is the KANO category for that user requirement. The final KNAO category attribution table for each user need is obtained. In order to facilitate the subsequent construction of the four-quadrant diagram of user requirements, the reverse demand and suspicious demand are filtered out.

III. B. 2) Construction of four-quadrant diagrams

Based on the statistical data of KANO questionnaire, the value of user relative satisfaction Si and the value of user relative dissatisfaction Di for each demand are calculated separately. Taking the absolute value of Di as the horizontal coordinate, Si as the vertical coordinate, and the mean value of Si and the mean value of absolute value of Di as the quadrant division points, a four-quadrant diagram of Si - Di is constructed. In this way, we can determine the attribution category of user needs. The specific calculation of Si and Di is as follows:

$$Si = \frac{Ai + Oi}{Ai + Oi + Mi + Ii} \tag{7}$$

$$Di = \frac{Mi + Oi}{Ai + Oi + Mi + Ii} * (-1) \tag{8}$$

The Si coefficient denotes the satisfaction of the user when a need is satisfied, and the Di coefficient denotes the dissatisfaction of the user when a need is not satisfied. The Ai coefficients represent the total number of users who chose the charismatic needs in the questionnaire survey for the i -item of needs; Oi represents the total number of users who chose the expected needs in the questionnaire survey for the i -item of needs; Mi represents the total number of users who chose the basic needs in the questionnaire survey for the i -item of needs; Ii denotes the total number of users who chose the undifferentiated need during the questionnaire survey for the i th need.

III. B. 3) Calculation of Initial Importance of User Requirements

The initial importance of each user requirement is mainly obtained by means of a questionnaire. That is, target users are invited to score the importance of each user requirement, which is divided into five levels: very unimportant, unimportant, general, important, and very important, and the corresponding scores for each level are 1, 2, 3, 4, and 5, respectively. The mean of each user requirement score is the initial importance of each user requirement.

III. B. 4) Introduction and calculation of the importance factor K

Different types of user needs have different degrees of influence on user satisfaction. Therefore, it is necessary to add a demand importance adjustment coefficient K to indicate the importance degree of each user demand. In the KANO model, for basic needs, the increase ratio of user satisfaction is smaller than the increase ratio of product quality; for charm needs, the increase ratio of user satisfaction is larger than the increase ratio of product quality; for expectation needs, the increase ratio of user satisfaction is equal to the increase ratio of product quality. Among them, user satisfaction refers to the degree of user satisfaction with the product function, and product quality refers to the degree of realization of the product function. Q represents user satisfaction, P represents product quality, and ΔQ and ΔP represent the amount of change in user satisfaction and product quality, respectively. Then the KANO model can be simply expressed by the following formula:

Basic Demand:

$$\mathrm{D}Q / Q < \mathrm{D}P / P \tag{9}$$

Charming needs:

$$\mathrm{D}Q / Q > \mathrm{D}P / P \tag{10}$$

Expected demand:

$$\mathrm{D}Q / Q = \mathrm{D}P / P \tag{11}$$

For the sake of simplicity of the study, the relationship between user satisfaction and product quality is linear by default. Increasing the user demand importance adjustment coefficient K, the three relationships above can be expressed in a single expression, i.e.:

$$\mathrm{D}Q / Q = K\mathrm{D}P / P \tag{12}$$

Equation (12) can be further transformed:

$$Q = CP^{K} \tag{13}$$

where C is a constant. In general, $K > 1$ for charismatic needs, $K = 1$ for desired needs, and $K < 1$ for basic needs.

Assuming that Q_0 and P_0 are the user satisfaction and product quality of the current product, and Q_1 and P_1 are the product user satisfaction target and product quality target, it can be obtained according to equation (13):

$$Q_0 = CP_0K \tag{14}$$

$$Q_1 = CP_1^K \tag{15}$$

can be derived from Eqs. (14) and (15):

$$Q_1 / Q_0 = CP_1^K / CP_0^K = (P_1 / P_0)^K \tag{16}$$

Further derivation leads to the formula for the user satisfaction adjustment factor K, i.e.:

$$K = \log_{P_1 / P_0} Q_1 / Q_0 \tag{17}$$

As can be seen from equation (17), to get the value of the user importance adjustment factor K, it is necessary to get the values of current product user satisfaction, current product quality, target product user satisfaction, and target product quality. Current product satisfaction refers to the degree of user satisfaction with the current product, and target product user satisfaction refers to the degree of satisfaction that the user expects the product to achieve. Current product quality refers to the degree of realization of current product functions, and target product quality refers to the degree of realization of desired product functions. Its value can be obtained by issuing the product user satisfaction survey to the questionnaire and product quality questionnaire, and its value is the average of the scores. The score of the product user satisfaction questionnaire is divided into five levels: very dissatisfied, dissatisfied, general, satisfied, very satisfied. The corresponding values of each grade are: 1, 2, 3, 4, 5. The product quality questionnaire scores are divided into five grades: very low, low, general, high, very high, the corresponding values of each grade are: 1, 2, 3, 4, 5. It should be noted that the two questionnaires are targeted at different groups of people, the product user satisfaction questionnaire's object of investigation is to have experience in the use of the product, the product quality questionnaire's object of investigation is to have relevant experience in the use of the product, and the product quality questionnaire's object of investigation is to have relevant experience in the use of the product. The target group of the questionnaire is designers with relevant product design experience.

III. B. 5) Calculation of Final Importance of User Requirements

Through the preliminary research of the relevant questionnaires to obtain the value of the initial importance of user needs and the importance of user needs to adjust the coefficient K, the product of the two values for the final importance of user needs. That is:

$$W = KR \tag{18}$$

where W is the final importance of user demand, K is the adjustment coefficient of user demand importance, and R is the initial importance of user demand.

IV. Fuzzy QFD-based personalized demand transformation methodology

In the previous chapter, the comprehensive demand-function model for smart home product design research is proposed, QFD theory is used to complete the mapping of user demand to product technical features, and the House of Quality (HOQ) is constructed to obtain the importance and ranking among technical features. This chapter will take the demand-function comprehensive model of smart home products proposed in this paper as the basis, and use the demand conversion method based on fuzzy QFD to establish the mapping relationship between personalized demand and product design parameters, and realize the conversion of user's personalized demand for home products [27].

IV. A. Description of the Personalized Demand Transformation Method

QFD from the perspective of ensuring product quality, through the quality house method to decompose personalized needs into various stages and modules of the product, so that the product can meet the customer's personalized needs. The essence of OFD theory is to effectively connect the personalized needs description and product design parameters, that is, to achieve the conversion of the user's personalized needs to the index parameters of the product module parts and components. The QFD-based personalized demand conversion method mainly includes demand acquisition and processing, demand importance determination, product design parameter determination, construction of relationship matrix, design parameter importance determination and other aspects. In this paper, the QFD-based demand conversion method is used to establish the mapping relationship between personalized demand and product design parameters. The requirement importance and design parameter importance are solved separately to derive the core design parameters that must be considered in the product design process.The core of OFD is to establish the quality house of the correlation matrix between basic requirement items and design parameters. The traditional quality house method does not support the transformation of unstructured requirements, so this paper proposes a fuzzy QFD requirement transformation method to solve the above problems by introducing fuzzy numbers and gray correlation analysis.

IV. B. Demand-switching quality house establishment

The purpose of establishing the demand transformation quality house is to realize the mapping of personalized demand to product design parameters and analyze the correlation relationship in the mapping process, as shown in Fig. 1. On the left side of the figure is the customer's personalized demand CR and demand importance W_{CR}, on the top is the product design parameter TP, on the bottom is the importance of the design parameter W_{TP}, and in the middle is the correlation matrix between personalized demand and design parameter r_{ij}.

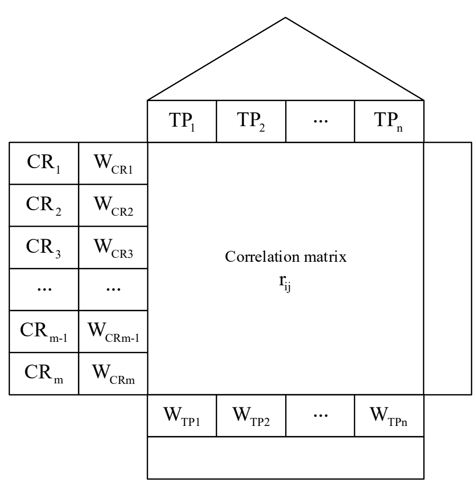

Figure 1: Demand Transformation Quality House

IV. C. Demand transformation algorithm steps

The subsequent key steps such as requirement importance determination, relationship matrix construction, and design parameter importance are explained.

(1) Determination of requirement importance degree

The set of basic requirement items obtained by classification after pre-processing is denoted as $\bar{R} = \{r_1, r_2, \ldots, r_m\}$.

where: r_i denotes the basic customer demand item $(i = 1, 2, \ldots, m)$, w_i denotes the absolute importance of the i th demand item, $w_i = \sum_{j=1}^{m} z_{ij}$ represents the degree of influence of this demand item on the overall product performance, z_{ij} represents the importance of the impact of the i th demand item on the product performance compared to the j th demand item, which is determined using the reciprocal 1-9 scale.

The importance values z_{ij} in the matrix $\bar{R}$ are transformed into rough number form by geometric averaging in order to obtain the rough group decision matrix R. The lower approximation $\underline{Lim}(r_i^k)$ and the upper approximation $\overline{Lim}(r_i^k)$ of the rough number are obtained from the obtained by the following equations:

$$\underline{Lim}(r_{ij}^k) = \left(\prod_{m=1}^{N_{ij}L} x_{ij}\right)^{1/N_{ij}L} \tag{19}$$

$$\overline{Lim}(r_{ij}^k) = \left(\prod_{m=1}^{N_{ij}U} y_{ij}\right)^{1/N_{ij}U} \tag{20}$$

x_{ij} and y_{ij} are the elements contained in the upper approximation and lower approximation of the rough number. From Eqs. (19) and (20), the rough number expression $RN(r_i^k)$ for z, and $N_{ij}U$ and $N_{ij}L$ are the number of objects included in the upper bound approximation and lower bound approximation. This creates the rough group demand evaluation matrix R:

$$R = \begin{bmatrix} [1,1] & [r_{12}^L, r_{12}^U] & \cdots & [r_{1n}^L, r_{1n}^U] \\ [r_{21}^L, r_{21}^U] & [1,1] & \cdots & [r_{2n}^L, r_{2n}^U] \\ \vdots & \vdots & \ddots & \vdots \\ [r_{n1}^L, r_{n1}^U] & [r_{n2}^L, r_{n2}^U] & \cdots & [1,1] \end{bmatrix} \tag{21}$$

In order to achieve the unification of demand importance metrics, Equation (22) is used to convert absolute demand importance w_i to relative demand importance w_i:

$$w_i' = \frac{w_i}{\max(w_i)} \tag{22}$$

(2) Construction of parameter importance matrix

The parameter importance matrix is constructed by analyzing the correspondence between the customer's basic demand items and the product module component design parameters to realize the importance ranking of the component design parameters, and the three correspondences are as follows:

1) For a customer basic requirement item, there exists a unique product component design parameter corresponding to it.

2) For a customer basic requirement item, there are multiple product component design parameters corresponding to it.

3) For multiple customer basic requirements, there exists only one product component design parameter corresponding to it.

r_i denotes the basic requirement item;

r_{ij} denotes the product design parameter requirement;

s_{ij} denotes the degree of correlation between the i th item of demand and the j th item of design parameter requirement, determined by the reciprocal inversion 1-9 scale method.

(3) Design parameter importance degree determination

The design parameter importance degree w^a can be calculated according to equation (23):

$$w_j^{la} = \sum_{i=1}^{m} w_i^r s_{ij} \tag{23}$$

The relative importance of design parameter requirements can be calculated according to equation (24):

$$w_j^{tr} = \frac{w_j^{ta}}{\max(w^{ta})} \tag{24}$$

V. Smart home product function module optimization design practice

There are a wide variety of smart home products that cover all aspects of family life. This chapter will take the smart treadmill in the health and care module of smart home products as the object of this research. Combined with the functional module optimization method of smart home products proposed in this paper, the design of the smart treadmill is completed based on functional module optimization.

V. A. Smart Treadmill Demand Questionnaire

This subsection focuses on the questionnaire survey method to understand users' suggestions and expectations of smart treadmills and to collect the user needs of smart home treadmill users.

V. A. 1) Importance Self-Assessment Questionnaire Design and Implementation

This questionnaire uses a five-level Likert scale to determine the user's self-rating level of the importance of the need, and its purpose is mainly the following two points: first, according to the user's self-rated importance level, to understand the information of the user group and their views on the demand, and to verify the authenticity of the collected demand; Second, the importance of the user's self-rating here will be used as a reference for the calculation of the comprehensive score of the importance of the need in the following.

The self-assessment questionnaire consists of two parts, the first part is the basic information of the research object, and you can check the options. The second part is the survey of the needs of the middle portal, this part is designed as a scale option, and the survey subjects are selected according to the recognition of the needs given, "strongly agree" corresponds to 5 points, "agree" corresponds to 4 points, "general" corresponds to 3 points, "disagree" corresponds to 2 points, and "strongly disagrees" corresponds to 1 point.

V. A. 2) Reliability analysis of the self-assessment questionnaire on importance

This subsection will be based on the design of the questionnaire to fill out the questionnaire, using SPSSAU tools to analyze the reliability and validity of the questionnaire, specifically as shown in Table 1, it can be seen that the questionnaire's a coefficients and the KMO value of 0.871, 0.845, respectively, are greater than 0.8, which indicates that the reliability of this research is high.

Table 1: Reliability and validity of importance self-assessment questionnaire

KMO sampling suitability quantity		0.845
Bartlett sphericity test	Approximate chi-square	394.765
	Freedom	55
	Significance	0.000
Cronbach a coefficient	0.871	

V. B. Sorting user requirements

In this section, we will combine the comprehensive model of smart home product requirements-functions constructed in this paper, collect the ratings of users on the positive and negative aspects of product requirements through questionnaires, and then use the obtained ratings to figure out which aspect of the requirements is more important to the users, and then re-categorize them after correcting the weights, so as to calculate the importance of the individual requirements, and then sort the importance, and finally get the comprehensive importance of all the requirements.

V. B. 1) Kano questionnaire design

The needs in this questionnaire are transformed from the real needs of the target group, and are designed from the content of the demand table obtained from the research, which is also the basis for the design of the Kano questionnaire model. In this paper, we have analyzed the results of the questionnaire research and obtained the real needs of the target group. In order to improve the validity of the research results, the options of Kano questionnaire are composed of the first-level needs of the previous research.

V. B. 2) Kano Requirements Revision and Categorization

In order to avoid the situation that the proportion of several attributes is close to each other and the users are more oriented when filling out the questionnaire, which leads to the overall results of the questionnaire survey being biased, the Better-Worse coefficient is used to correct the results of the questionnaire survey and to re-determine the final attributes of the requirements. Let F_i be the Better coefficient, D_i be the Worse coefficient, and the attribution degree of basic need for each need be M_i, that of charismatic need be A_i, that of aspirational need be O_i, and that of irrelevant need be I_i, and the calculation formulas are shown in Eq. (25) and Eq. (26):

$$Better\ coefficient\ F_i = (A_i + O_i)/(A_i + O_i + M_i + I_i) \tag{25}$$

$$Worse\ coefficient\ D_i = (M_i + O_i)/(A_i + O_i + M_i + I_i) \tag{26}$$

F_i is the Better coefficient, which indicates the index of the degree of positive influence on the overall satisfaction of the user when a specific demand is satisfied F_i is a positive number between 0 and 1. The closer the value of the F_i coefficient is to 1, it means that if the satisfaction of the demand is positively influenced on the user's overall satisfaction the more significant the positive effect is on the The greater the enhancement effect on the user's overall satisfaction. D_i is the Worse coefficient, which represents the index of the degree of negative influence on the overall user satisfaction when a specific demand is not met, D_i is a negative number between -1 and 0, and the closer the value of it is to -1, the more significant the negative effect is on the overall user satisfaction if the demand is not met. The closer it is to -1, the more significant the negative effect on overall user satisfaction and the greater the effect on the reduction of satisfaction. The data obtained from the research were calculated in this way, and the percentage of each demand in each dimension and the value of Better-Worse coefficient were obtained as shown in Table 2.

After finding out the F_i coefficient and D_i coefficient of each demand, take the average of the two numbers with the highest and the lowest absolute values of Better coefficient F_i and Worse coefficient D_i and take the average of the two numbers as the origin of the axes to establish the coordinate system. Each demand falls into the corresponding quadrant according to its own Better-Worse coefficient to determine the final attributes of the demand attributes, one, two, three and four quadrants correspond to the demand attributes of the desired demand, charming demand, irrelevant demand, basic demand. According to the data obtained from the research to build such a coordinate system: x-axis of the mid-point of the demand among the Better coefficient F_i coefficient of the minimum value of 0.09 and the maximum value of 0.72 of the average of 0.41, y-axis focus on the position of the Worse coefficient D_i coefficient of the absolute value of the minimum value of 0.19 and the maximum value of 0.84 of the average of 0.52, the demand will fall into the constructed quadrant to determine the final attributes of the demand attributes. The demand is dropped into the constructed coordinate system separately as shown in Figure 2. As can be seen from the figure, there are five requirements within the charismatic requirement interval: there are demand management, product attention, product recommendation, information filtering, and application cases; the desired requirements are data display; the basic requirements are information feedback, product details, product usage, and product dynamics; and the irrelevant requirements are message notification.

Table 2: Demand attribute attribution table

Serial number	Demand	Attribute rating				Better coefficient	Worse coefficient
		Basic M_i	Charm A_i	Irrelevant I_i	Expectation O_i	F_i	D_i
U1	Information feedback	45%	7%	31%	17%	0.24	-0.62
U2	Management needs	6%	54%	22%	18%	0.72	-0.24
U3	Focus on products	16%	34%	25%	26%	0.6	-0.42
U4	Message notification	15%	34%	47%	4%	0.38	-0.19
U5	Product recommendation	9%	40%	29%	21%	0.62	-0.3
U6	Information filtering	12%	36%	22%	29%	0.65	-0.42
U7	Product introduction	67%	4%	24%	4%	0.09	-0.72
U8	Product use method	70%	1%	15%	15%	0.16	-0.84
U9	Learn about the data	17%	28%	21%	34%	0.62	-0.51
U10	Product dynamics	51%	6%	35%	9%	0.15	-0.6
U11	Application scenarios	11%	38%	38%	12%	0.51	-0.24

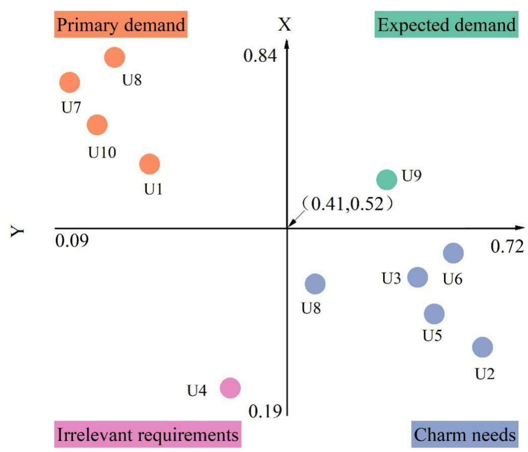

Figure 2: Distribution of the Better-Worse coefficient

V. B. 3) Calculation of demand importance

According to the Better-Worse coefficient of each demand derived in the previous subsection, the value of Better coefficient F_i and Worse coefficient D_i can be used to determine the impact index of the demand, and set the maximum value of the user impact index as T_i, and the formula for calculating the formula is shown in equation (27):

$$Maximum\ impact\ index\ T_i = Max(|F_i|, |D_i|) \tag{27}$$

In order to avoid the problem of non-objective data due to the strong personal emotions or subjective preferences of different users. The value of the adjustment coefficient determined according to the attribution category of the requirement K and the user's self-rating of the importance of the requirement H_i and the maximum value of the user's influence index T_i are proposed to calculate the final composite rating of the importance of each requirement W_i, which is calculated in Eq. (28):

$$\text{Comprehensive score of importance } W_i = (1+T_i)^k H_i \tag{28}$$

Different values of adjustment coefficients are introduced to the categorized attributes of different needs in Eq. (28), and the values of K corresponding to charismatic, aspirational, and basic needs are 0.5, 1, and 1.5, respectively, while the values of K for the needs categorized by other types are 0. H_i is the value of the self-assessment questionnaire of the user's importance obtained from the user's self-assessment questionnaire above, and the user's importance for each of his/her needs is obtained by this method. The composite score data is shown in Table 3 below.

Table 3: The index values of the demand in the kano model

Serial number	Demand	Maximum impact index T_i	Importance self-rating H_i	Adjustment coefficient K	Importance self-rating W_i
U1	Information feedback	0.62	4.17	1.5	8.6
U2	Management needs	0.72	3.97	0.5	5.21
U3	Focus on products	0.6	3.89	0.5	4.92
U4	Message notification	0.38	3.81	0	3.81
U5	Product recommendation	0.62	3.58	0.5	4.56
U6	Information filtering	0.65	3.78	0.5	4.86
U7	Product introduction	0.72	4.51	1.5	10.17
U8	Product use method	0.84	4.36	1.5	10.88
U9	Learn about the data	0.62	3.83	1	6.2
U10	Product dynamics	0.6	3.86	0.5	4.88
U11	Application scenarios	0.51	4.24	1.5	7.87

From the data obtained in the above table, it can be seen that the requirements obtained are prioritized according to the combined importance score. In order to visualize the order of importance of each requirement, the data in the table are counted in a bar chart as shown in Figure 3. From the information in the figure, it can be analyzed that:

1) Among the top five requirements of U8, U7, U1, U11 and U9 in terms of importance, four of them are requirements in the dimension of information display, especially the most important ones, U7 and U8, which are the requirements of product introduction and how to use the product respectively, which shows that users are most concerned about the information level during the process of using the product, and therefore, we should pay attention to this kind of requirements in the subsequent functional design process. Therefore, in the subsequent functional design process, we should focus on this type of demand, and conduct in-depth analysis and optimization of the design of this part of the functional page.

2) U4 message notification is the least important requirement, probably because users have been deeply disturbed by various product messages, and therefore have emotional resistance to this requirement.

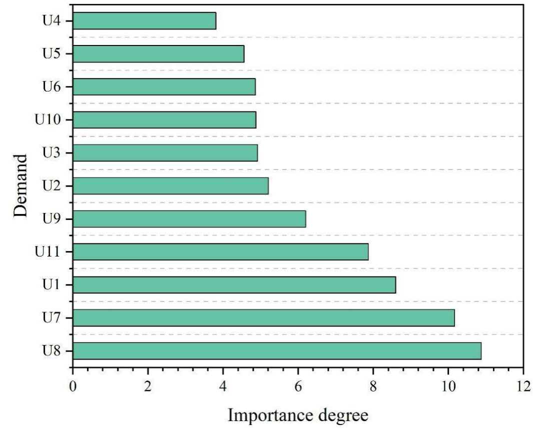

Figure 3: Comprehensive score of demand importance

V. C. Quality house construction

V. C. 1) Identify product design elements

The QFD team converted the acquired user requirements into product design requirements, and the development of the design requirements is shown in Table 4.

Table 4: Intelligent treadmill product design requirements to start.

Numbering	First-level design requirements	Numbering	Secondary design requirements
D1	Appearance design	D11	Modeling
		D12	Color matching
		D13	Material
		D14	Size
D2	Interaction design	D21	Function module design
		D22	Interface design
D3	Components and performance design	D31	Bracket design
		D32	Treadmill design
		D33	Security
		D34	Audio and video entertainment
		D35	Damping noise reduction
		D36	Motion data recording
		D37	Multiple running modes
		D38	Data connection

V. C. 2) Determine the correlation between user needs and design elements

The "user demand - functional features" quality house was constructed, and the expanded user needs and expanded functional features were used as the "left wall" and "roof" of the quality house in the QFD method, respectively, and the user needs and product quality characteristics of intelligent treadmill products were constructed. The interrelationships between the secondary indicators and the intermediate of the secondary level requirements were scored as 9 (scored as ●, representing strong correlation), 5 (scored as ○, representing correlation), 1 (scored as △, representing weak correlation), and 0 (scored as null, representing irrelevance). The QFD team is invited to evaluate the relationship between user requirements and product features. Let CRi be the importance of the i th demand, Rij be the numerical value corresponding to the correlation between the i th demand and the j th quality characteristic (0,1,5,9), and TIR_j be the importance of the j th quality characteristic, then:

$$TIR_j = \sum_{i=1}^{n} CIR_i \times R_{ij}, j = 1,2,3,\ldots,m \tag{29}$$

Using the independent matching point method, the importance of each design requirement was calculated and the results were obtained as shown in Table 5.

Table 5: Weight of product characteristic index

-	Corrected importance	D11	D12	D13	D14	D21	D22	D31	D32	D33	D34	D35	D36	D37	D38
CR1	6.31									○				●	
CR2	4.12	△												●	
CR3	7.95										●				●
CR4	4.43											●			
CR5	5.12												●		●
CR6	8.71				●	○	○								
CR7	9.01									●					
CR8	7.59										●		●		
CR9	9.55														
CR10	3.99												●		●
CR11	7.98										●				●
CR12	8.38	●		△	●			●	○						
CR13	11.99				●				●						
CR14	4.6	●	●	●											
CR15	6.11			●						●					
CR16	8.94		△		△	●	●								
Secondary design requirements score		120.94	50.34	104.77	270.66	124.01	124.01	75.42	149.81	167.63	211.68	39.87	150.3	93.78	225.36
Weight of the secondary design requirements index		0.06	0.03	0.05	0.14	0.06	0.06	0.04	0.08	0.09	0.11	0.02	0.08	0.05	0.12

Organize the intelligent treadmill product design requirement weights, as shown in Table 6. As can be seen from the table:

1) Size design the highest weight of all the design requirements, the importance of the user demand item running deck size wide is very high, but the size of the smart treadmill and the limitations of the home environment, so in the running deck design of the smart treadmill products, the optimization of the product design dimensions under the premise of ensuring the user's good use experience.

2) The priority of data connection is located in the second place, and the demand items related to data connection are audio/video entertainment, data logging, Wifi/Bluetooth connection, and cell phone movement to control the treadmill speed, which indicate that the design of smart treadmill should focus on the design of IoT functions, and how to make the product design more intelligent is the focus of the design of smart treadmill.

3) Audio/video entertainment is in the third place, but the decision of whether audio/video entertainment is prioritized in the design of smart treadmill should be made according to the positioning of the product design and the selling price of the product.

4) Safety is in the fourth place, in the research of the importance of user needs, the weight of safety is equally important, therefore, there should be a safety emergency stop button or safety buckle design in the design of intelligent treadmill.

V. D. Smart Treadmill Design Evaluation

Combined with the intelligent treadmill design requirements obtained from the analysis above, the design practice of the intelligent treadmill is completed, and a comprehensive design evaluation of the designed product is carried out to demonstrate the effectiveness of the smart home product design method in this paper. The six items of ease of use, functionality, comfort, durability and intelligence are taken as the product design evaluation indexes. Eight designers with treadmill design experience and 20 treadmill users were invited to evaluate the satisfaction of the designed smart treadmill. The evaluation score ranges from 1 to 5, with 5 representing very satisfied and 1 representing very dissatisfied, and the sum of the ratings of the designers and users was averaged respectively, and the statistical results are shown in Table 7. From the evaluation results, the overall evaluation of the design program is high, and the expert and user evaluation results are within the range of reasonable expectations, and the average rating is within the range of 4~5. This also proves the reasonableness of this design practice, and also proves the effectiveness of the intelligent product function module optimization and design method proposed in this paper.

Table 6: Weight of product design requirements

Product design requirements	Weight
Modeling	0.06
Color matching	0.03
Materials	0.05
Size	0.14
Function module design	0.06
Treadmill interface design	0.06
Bracket design	0.04
Treadmill design	0.08
Security	0.09
Audio and video entertainment	0.11
Damping noise reduction	0.02
Motion data recording	0.08
Multiple running modes	0.05
Data link	0.12

Table 7: Design evaluation table

Evaluation perspective	Designer rating	User rating
Ease of use	4.63	4.65
Functionality	4.13	4.4
Comfort	4.25	4.45
Security	4.5	4.55
Durability	4.38	4.45
Intelligence	4.38	4.5

VI. Conclusion

This paper collects user behavior data by constructing smart home product knowledge model, then proposes smart home product demand-function synthesis model, analyzes each user demand in the user demand library by using KANO model, proposes personalized demand conversion algorithm based on fuzzy QFD, completes the mapping of user demand to product technical characteristics, obtains the smart home product design demand, and realizes the optimization of the functional modules of smart home products. Product function module optimization.

In order to prove the effectiveness of the above methods related to the optimization of smart home product function modules, this paper takes the smart treadmill in smart home products as the main research body, and carries out the practice of optimizing the design of smart home product function modules. The importance self-assessment questionnaire is designed to understand users' suggestions and expectations of smart treadmill, and the a coefficients and KMO values of the questionnaire are 0.871 and 0.845 respectively, which are all greater than 0.8, with high reliability and validity of the questionnaire. With the help of KANO model to correct and categorize the user requirements, the requirements fall into the constructed coordinate system respectively, in which the requirements in the charismatic requirement interval are requirement management, product attention, product recommendation, information filtering, application cases, requirement management, product attention, product recommendation, information filtering, application cases, the desired requirement is only data display, and the message notification is the only irrelevant requirement. Further calculating the importance of the requirements of smart treadmill, four of the top five requirements are in the dimension of information display, and message notification is the least important requirement. The acquired user requirements are converted into product design requirements, and a “user requirements-functional features” quality house is constructed to organize the weights of product design requirements for smart treadmills. The top four design requirements with the highest weights are size design, data connection, audio/video entertainment and safety. According to the product design requirements of the intelligent treadmill derived from this paper, the design of the intelligent treadmill is completed, and 8 designers with treadmill design experience and 20 treadmill users are invited to evaluate the satisfaction of the intelligent treadmill designed in this paper. The results show that all the expert and user ratings are in the range of 4~5, which verifies the reasonableness of the design practice of this intelligent treadmill and proves the validity of the optimization and design method of this paper's intelligent product function module.

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References

[1] Shin, J., Park, Y., & Lee, D. (2018). Who will be smart home users? An analysis of adoption and diffusion of smart homes. Technological Forecasting and Social Change, 134, 246-253.

[2] Balakrishnan, S., Vasudavan, H., & Murugesan, R. K. (2018, December). Smart home technologies: A preliminary review. In Proceedings of the 6th International Conference on Information Technology: IoT and Smart City (pp. 120-127).

[3] Guo, X., Shen, Z., Zhang, Y., & Wu, T. (2019). Review on the application of artificial intelligence in smart homes. Smart Cities, 2(3), 402-420.

[4] Shank, D. B., Wright, D., Lulham, R., & Thurgood, C. (2021). Knowledge, perceived benefits, adoption, and use of smart home products. International Journal of Human–Computer Interaction, 37(10), 922-937.

[5] Nacer, A., Marhic, B., & Delahoche, L. (2017, May). Smart Home, Smart HEMS, Smart heating: An overview of the latest products and trends. In 2017 6th international conference on systems and control (ICSC) (pp. 90-95). IEEE.

[6] Liang, T., Zeng, B., Liu, J., Ye, L., & Zou, C. (2018). An unsupervised user behavior prediction algorithm based on machine learning and neural network for smart home. IEEE Access, 6, 49237-49247.

[7] Jose, A. C., & Malekian, R. (2017). Improving smart home security: Integrating logical sensing into smart home. IEEE Sensors Journal, 17(13), 4269-4286.

[8] Yamauchi, M., Ohsita, Y., Murata, M., Ueda, K., & Kato, Y. (2020). Anomaly detection in smart home operation from user behaviors and home conditions. IEEE Transactions on Consumer Electronics, 66(2), 183-192.

[9] Jalali, N., Sahu, K. S., Oetomo, A., & Morita, P. P. (2020). Understanding user behavior through the use of unsupervised anomaly detection: proof of concept using internet of things smart home thermostat data for improving public health surveillance. JMIR mHealth and uHealth, 8(11), e21209.

[10] Zhai, S., Wang, Z., Yan, X., & He, G. (2018). Appliance flexibility analysis considering user behavior in home energy management system using smart plugs. IEEE Transactions on Industrial Electronics, 66(2), 1391-1401.

[11] Yang, H., Lee, H., & Zo, H. (2017). User acceptance of smart home services: an extension of the theory of planned behavior. Industrial Management & Data Systems, 117(1), 68-89.

[12] Amraoui, N., & Zouari, B. (2022). Anomalous behavior detection-based approach for authenticating smart home system users. International Journal of Information Security, 1-26.

[13] Coppers, S., Vanacken, D., & Luyten, K. (2020). Fortniot: Intelligible predictions to improve user understanding of smart home behavior. Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, 4(4), 1-24.

[14] Zhang, N., Yan, Y., Zhu, X., & Wang, J. (2022). A novel user behavior prediction model based on automatic annotated behavior recognition in smart home systems. China Communications, 19(9), 116-132.

[15] Jose, A. C., Malekian, R., & Letswamotse, B. B. (2018). Improving smart home security; integrating behaviour prediction into smart home. International Journal of Sensor Networks, 28(4), 253-269.

[16] Zhang, J., Shan, Y., & Huang, K. (2015). ISEE Smart Home (ISH): Smart video analysis for home security. Neurocomputing, 149, 752-766.

[17] Kim, S., Christiaans, H., & Baek, J. S. (2019). Smart homes as product-service systems: Two focal areas for developing competitive smart home appliances. Service Science, 11(4), 292-310.

[18] Kim, E., Helal, S., Nugent, C., & Beattie, M. (2015). Analyzing activity recognition uncertainties in smart home environments. ACM Transactions on Intelligent Systems and Technology (TIST), 6(4), 1-28.

[19] Zou, Q., Li, Q., Li, R., Huang, Y., Tyson, G., Xiao, J., & Jiang, Y. (2023). Iotbeholder: A privacy snooping attack on user habitual behaviors from smart home wi-fi traffic. Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, 7(1), 1-26.

[20] Hong, A., Nam, C., & Kim, S. (2020). What will be the possible barriers to consumers' adoption of smart home services?. Telecommunications Policy, 44(2), 101867.

[21] Lesani, F. S., Fotouhi Ghazvini, F., & Amirkhani, H. (2021). Smart home resident identification based on behavioral patterns using ambient sensors. Personal and Ubiquitous Computing, 25, 151-162.

[22] Debes, C., Merentitis, A., Sukhanov, S., Niessen, M., Frangiadakis, N., & Bauer, A. (2016). Monitoring activities of daily living in smart homes: Understanding human behavior. IEEE Signal Processing Magazine, 33(2), 81-94.

[23] Sadikoglu-Asan, H. (2022). 'User-Home relationship'regarding user experience of smart home products. Intelligent Buildings International, 14(1), 114-130.

[24] Li Xue,Meng Mei,Ren Xiang Fang & Shen Lei. (2025). A customization design platform for school uniforms using the Kano model. International Journal of Clothing Science and Technology,37(2),355-373.

[25] Dian Retno Sari Dewi,Dini Endah Setyo Rahaju,Maureen Angela,Irene Karijadi & Luh Juni Asrini. (2024). Determining Optimal Design Specification in the House of Quality. Mathematical Modelling of Engineering Problems,11(6).

[26] Kai Gryczycha,Maik Pannok & Stefan Lier. (2025). Planning modular intralogistic systems in the chemical industry by axiomatic design. International Journal on Interactive Design and Manufacturing (IJIDeM),(prepublish),1-21.

[27] Zongming Liu,Xinan Liang,Xuhui Chen & Xinmiao Wen. (2024). Design of a sweeping robot based on fuzzy QFD and ARIZ algorithms. Heliyon,10(19),e38319-e38319.