Custom Product Design Method Based on the Kano-QFD Integrated Model

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Abstract. In response to the increasing prominence of heterogeneous customer demands in today's market and their impact on product development, researchers have shown interest in incorporating customer needs into product design. Quality Function Deployment (QFD) is a customer-centric approach to the process of designing products, but it has limitations in accurately understanding customer needs. The Kano model offers a qualitative framework for categorizing customer requirements and elucidating their influence on overall customer contentment. This research explores a product design method that integrates the Kano model with quantitative QFD. First, the quantification of the Kano model involves discerning the connection between customer requirements and the level of customer contentment. Then, considering the characteristics of mass customization, traditional Quality Houses are improved, and the integration of qualitative and quantitative findings from the Kano model is employed within the QFD framework to enhance the comprehension of customer requirements. Finally, while taking cost and technical constraints into account, a product planning model with maximizing customer satisfaction as the objective is established. Through applied analysis in the realm of personalized manufacturing, the proposed model's viability and efficacy are substantiated. The building of the Kano-QFD integrated model effectively identifies customer needs with a significant impact on customer satisfaction, thus preventing unnecessary errors. It also improves the methods for assessing product performance.

Keywords: Customer needs; Kano model; QFD; product development; planning model.

1 Introduction

With the escalating market competition, consumer demands are gradually becoming more personalized. Faced with an increasingly fragmented market and diversified customer needs, since the 1980s, some foreign manufacturers have been experimenting with large-scale customization production models to approximate the benefits and costs of mass production while offering products that cater to customers' personalized requirements [1]. Currently, the manufacturing industry faces challenges in meeting the diverse and uncertain product demands of customers within shorter product development cycles. On one hand, due to the shortened product life cycles, enterprises are actively pursuing strategies to shorten product development cycles and expedite market entry for their products. On the other hand, customers are demanding custom products while expecting faster fulfillment of their needs [2]. Therefore, effectively understanding and analyzing customer requirements (CRs) and integration of these elements into product design have become a necessary prerequisite for delivering customer-satisfying products. Numerous companies are making efforts to provide

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products that are tailored to customer preferences, aiming to set themselves apart from their rivals in the market [3]. Additionally, several methodologies and instruments have been devised to aid businesses in gaining deeper insights into CRs, thereby providing decision-making support to optimize product design and ultimately enhancing customer satisfaction (CS). Among the most recognized tools in customer-centric product design is the QFD. It is used to transform CRs into Engineering Characteristics (ECs) to plan and manage new product development and has been put to use in numerous studies to enhance design of products in alignment with CRs [4]. However, one of the primary challenges that QFD faces is the lack of clarity on how to understand CRs and link them to CS. The analysis of CRs serves as the pivotal launchpad for initiating QFD implementation. If this analysis fails to faithfully represent customer expectations, the model could potentially result in imprecise prognostications. The Kano model, on the other hand, classifies and prioritizes CRs based on their impact on CS, providing a more detailed identification of CRs and delivering a more precise representation "voice of the customer" as a basis for QFD analysis. To enhance QFD's capability to identify customer expectations, researchers have in the near past been connecting the Kano model with QFD (as detailed in the literature review). However, compared to QFD, the connection between CRs and CS in Kano model is frequently depicted qualitatively, with limited quantification. Presently, research concerning the amalgamation of these two methodologies is somewhat constrained.

In summary, there are several issues that need to be addressed in this research:

1) The Kano model acknowledges different types of relationships between CRs and CS, but it mainly focuses on categorizing and performing qualitative assessments of CRs within different Kano categories. Few scholars have conducted quantitative analyses of the Kano model [5].

2) The Kano model is extensively employed as a valuable instrument for comprehending and fulfilling customer requirements while assessing their influence on customer contentment. Nevertheless, the challenge lies in effectively incorporating the Kano model into Quality Function Deployment (QFD). Existing integration approaches primarily emphasize qualitative analysis, underscoring the urgent requirement for a unified and robust method to seamlessly integrate the quantified Kano model into QFD analysis.

3) In terms of product planning, the House of Quality (HOQ) is established according to identified customer needs and various components of the quality house. However, custom products are produced in light of customer demands, and the manufacturing procedure is guided by customer preferences. This makes it challenging for traditional HOQs to meet the requirements of custom product planning, requiring appropriate improvements.

4) When establishing QFD optimization models, setting target values for ECs is always a critical factor. Many studies define target values as the practical levels of ECs [6], but in some cases, the definitions of target values for ECs are not clear. Additionally, in the optimization model, most ECs are treated as continuous variables, but there are cases where certain ECs can only be considered as discrete variables. When determining target values, standardization needs to be performed separately for these two types of ECs.

Taking into consideration the aforementioned issues, this paper introduces a product design approach that utilizes the integrated Kano-QFD model as its foundation. Firstly, it quantitatively analyzes the Kano model by identifying the relationship between CRs and CS. Subsequently, with the characteristics of mass customization in mind, it enhances the traditional HOQ. Then, based on the quantified relationships, CRs are integrated into the QFD of a customized product's nonlinear programming model. The objective of this model is to establish the desired benchmarks for CRs and ECs in order to maximize CS under various constraints, ultimately achieving the optimal design. In summary, the construction of the integrated models for both the Kano model and QFD expands their applicability and assists businesses in better pinpointing CRs with a substantial influence on CS. It also aids designers in effectively connecting CRs to CS using both qualitative and quantitative results, ultimately outlining products that satisfy customer needs.

2 Literature review

2.1 Integrating CRs into product design

Incorporating CRs into effective designing products strategies is of significant importance [7], and in recent years, there has been a considerable amount of research on product design. Numerous techniques for configuration design have been suggested in the field of engineering design with the objective of revealing unexpressed customer requirements, emphasizing the importance of customer involvement in product design [8]. Zhou et al. [9] adopted a customer-driven product configuration optimization approach, which was established as a foundation for addressing the diversity of customer demands. To further enhance customer satisfaction, Wang [10] incorporated customer satisfaction factors into product design. Jiang et al. [11] introduced an adaptive neural-fuzzy inference system based on rough sets and particle swarm optimization with the aim of enhancing the precision of customer satisfaction modeling in the process of product design. In order to address a variety of individualized demands, Wang and Tseng [12] utilized product variations as category labels and employed a naive Bayesian approach to classify product variants into different categories. However, viewing product design solely from a customer perspective may lead to designs that depart from design principles and fundamental paradigms, and could potentially conflict with the product design strategy of the manufacturer. As a result, certain research endeavors focus on optimizing product design through the lens of manufacturers or experienced designers. [7].

2.2 Kano model

The Kano model [13] explores CRs and offers a more effective means of CR categorization. This categorization is facilitated through the utilization of survey data, allowing for the classification of CRs. Customer preferences are segmented into three primary categories, determined by attribute priority and their impact on customer satisfaction (refer to Figure 1):

1.Must-Be Quality (M): Must-Be quality preferences represent the customer's baseline expectations, and if their expectations are met, they consider these attributes as a given. However, if the product fails to meet their expectations, they become dissatisfied.

2.One-Dimensional Quality (O): Customer satisfaction with One-Dimensional quality preferences correlate positively and linearly with the fulfillment of their expectations.

3.Attractive Quality (A): Attractive Quality preferences are typically unanticipated, implying that their presence results in a higher proportion of customer satisfaction without causing dissatisfaction.

Apart from the M, O, and A categories, CRs can also be sorted into three additional groups: Indifferent (I), Reverse (R), and Questionable (Q). (I) signifies that customers are not interested in a specific attribute of the product, (R) indicates that customers dislike the attribute, whereas (Q) implies that the attribute falls short of meeting the customer's expectations.

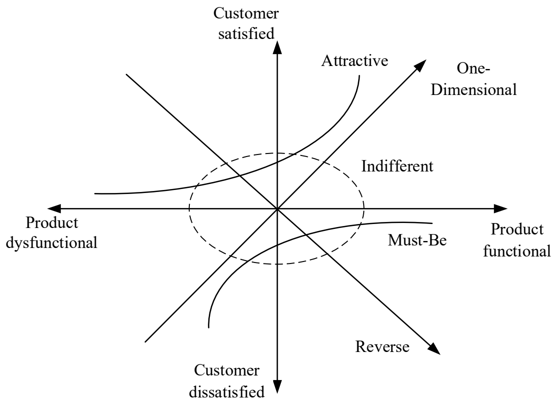

Fig. 1. Kano’s diagram.

Certain investigations have incorporated the Kano model into the realm of product design, enhancing designs by identifying and analyzing potential elements that impact customer contentment [14]. To attain product development objectives aligned with the market's demands, it is imperative to seamlessly integrate customer contentment within the decision-making process for product configuration. Wang et al. [10] introduced a combined framework designed to tackle two essential aspects of new product development: ensuring customer contentment and managing product configuration. The Kano model predominantly emphasizes qualitative depictions of categorization techniques and diverse relationship curves, offering a solely qualitative method for discerning the varied connections between CRs and CS. [15]. Wang and Ji [16] performed a quantitative assessment of the conventional Kano model to gain deeper insights into CRs. They demonstrated that the proposed method excelled not only excelled in precisely delineating the connections between CRs and customer contentment but also in effecting a more extensive transformation within the customer demand domain, even when operating under particular design constraints.

2.3 Integrated research of the Kano model and QFD

In recent years, many scholars have explored the incorporation of the Kano model into QFD. Generally, the Kano model is often linked with QFD as an initial reference point for collecting and analyzing CRs during the QFD process. Based on the Kano model, Matzler et al. [17] proposed categorizing CRs into distinct categories, alongside the assessment of their strategic significance through the computation of customer satisfaction (CS) and customer dissatisfaction (DS) metrics. This categorization of CRs serves as the foundational framework for subsequent QFD analysis. Sireli et al. [18] employed a widely accepted rating method to incorporate the Kano model into QFD, conducting statistical significance tests to further advance the method described in [17]. However, these methods are still qualitative descriptions of the Kano model and involve limited quantitative analysis.

In order to resolve the uncertainty in product development, a fuzzy nonlinear model was constructed for the assessment of the performance levels associated with each design requirement. In this approach, Kano's design requirement categories were considered to maximize CS [19]. Shen et al. [20] introduced an integrated methodology that employed the Kano model for creating an approximate transformation function, facilitating the evaluation of the significance of individual CR within the planning matrix. Nevertheless, it's worth noting that this approach tends to be subjective and somewhat indistinct, primarily since the selection of parameters for various Kano categories in the transformation function heavily relies on the expertise and familiarity of QFD practitioners. Lai et al. [21] applied QFD and the Kano model to formulate a mathematical optimization model for product design by inferring the contribution of different CRs to CS.

3 The construction of a quantitative Kano-QFD integrated model

3.1 Quantitative analysis of the Kano model

With an insight into the conventional Kano model, Wang and Ji [16] introduced a novel approach to broaden the scope of the Kano model, shifting from qualitative descriptions to quantitative analysis, thus achieving a more exact comprehension of CRs. By analyzing customer survey results, the Kano model classifies various CRs into three primary categories. The quantitative evaluation of the Kano model employs these classifications to identify the relationship functions of different CRs. The procedure for ascertaining these quantitative functions is as follows:

(1) Calculate the values of CS and DS. To represent the average level of customer satisfaction, Berger [22] proposed a method for calculating two coefficients, where CS_i represents customer satisfaction with CR_i and DS represents customer dissatisfaction with CR_i. The corresponding expressions are shown in Equations (1) and (2):

$$CS_i = \frac{f_A + f_O}{f_A + f_O + f_M + f_I} \tag{1}$$

$$DS_i = -\frac{f_O + f_M}{f_A + f_O + f_M + f_I} \tag{2}$$

Here, f_A, f_o, f_M, and f_I stand for the quantities of Attractive, One-Dimensional, Must-Be, and Indifferent requirements, respectively. Based on this, this paper determines the absolute importance of each CR as the maximum value among them, resulting in the importance weight for CR_i as follows [18]:

$$\rho_i = \max\left\{\frac{CS_i}{\sum_{i=1}^{m} CS_i}, \frac{DS_i}{\sum_{i=1}^{m} DS_i}\right\} \tag{3}$$

(2) Identify the CS and DS positions and construct the linkage curve. To define the values of CS and DS, as well as the corresponding specific levels of CRs, based on the assumptions presented in article [16]: Assuming that customer satisfaction for fully implemented CRs is 1, and customer satisfaction for CRs not implemented at all is 0. Underlying this hypothesis, the CS and DS positions are stipulated. For the CS point of the ith customer requirement CR_i, denoted as $(1, \mathrm{CS_i})$, it represents the degree of CS_i when CR_i is entirely met. As for the DS point of CR_i, expressed as $(0, \mathrm{DS_i})$, it indicates the level of customer DS_i where CR_i is completely unsatisfied. By integrating these two positions into the Kano model, the relationship between the level of CR implementation and CS can be achieved accurately. The curves representing various categories (One-Dimensional, Attractive, and Must-Be requirements) exhibit an exponential curve pattern as they traverse through the CS and DS points, as depicted in Figure 1, and can be plotted as shown in Figure 2.

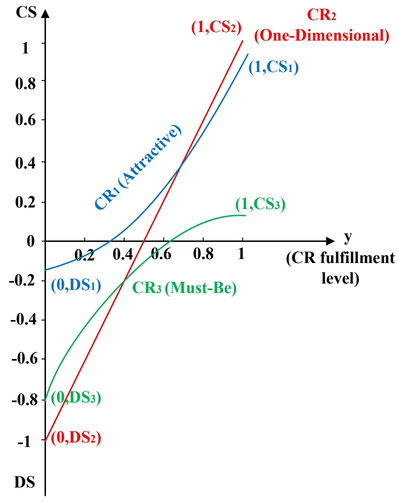

Fig. 2. Relationship curves of customer satisfaction and CR fulfillment.

(3) To identify the S-CR relationship functions. Derived from the preceding diagram, it reveals that the relationship between CS and CR implementation (S-CR) can be approximated using a fitting function. Typically, the function describing the S-CR relationship can be denoted as S=f(x,a,b), with CS representing customer satisfaction, and S-CR indicating the extent of CRs implementation concerning the product, varying between 0 and 1. For One-Dimensional requirements, this relationship function can be explicitly quantified as $S_O=a_1x+b_1$, given two points $(1,CS_i)$ and $(0,DS_i)$, the parameters $a_1=CS_i-DS_i$ and $b_1=DS_i$ can be determined. For Attractive requirements, their curves can be approximated using an exponential function, where $S_A=a_2e^x+b_2$, with parameters a_2 and b_2 adjusting the slope and intercept, respectively. By the same reasoning, we can derive $a_2=\frac{CS_i-DS_i}{e-1}$, $b_2=-\frac{CS_i-eDS_i}{e-1}$. For Must-Be requirements, their curve can be approximated through an exponential function $S_M=a_3e^{-x}+b_3$ as well, resulting in $a_3=-\frac{e(CS_i-DS_i)}{e-1}$, $b_3=\frac{eCS_i-DS_i}{e-1}$. Therefore, the relationship functions between S-CR and various CR categories, along with customer satisfaction, can be described as follows::

$$s_i = \begin{cases} (CS_i - DS_i)y + DS_i & (O) \\ \frac{CS_i - DS_i}{e-1}e^y - \frac{CS_i - eDS_i}{e-1} & (A) \\ -\frac{e(CS_i - DS_i)}{e-1}e^{-y} + \frac{eCS_i - DS_i}{e-1} & (M) \end{cases} \tag{4}$$

3.2 Integrating the Kano model into QFD

In this stage, firstly, the traditional HOQ is improved to align with the characteristics of mass customization. Subsequently, the qualitative and quantitative findings derived from the Kano model are fused with the QFD process. An optimization model is constructed based on the improved HOQ to ascertain the desired values for a set of ECs. This model aims to maximize CS by translating CRs into ECs.

3.2.1 The construction of the customized product HOQ

The traditional HOQ consist of six main components, as shown in Figure 3, with each element focusing on how to determine product engineering characteristics based on customer requirements. In contrast, in mass customization manufacturing, production processes are customer-driven, aiming to quickly meet customer demands. This makes it challenging for traditional quality houses to meet the requirements of mass customization product planning, requiring appropriate modifications to the traditional quality house components.

In the case of customer-centric customization, all mass-customized products are unique to each specific customer's requirements. Customization means producing according to the specific customer's demands, where each customer can purchase a unique product or service. Therefore, the assessment of mass-customized products in comparison to competing products can be disregarded. In this regard, this paper removes the two elements from the traditional quality house: market competitiveness evaluation and technical competitiveness evaluation, significantly simplifying the related influencing factors [23].

With these two elements removed, considering mass customization entails rapid tailoring, which necessitates swift responses to CRs. Customers also have clear expectations regarding the price and delivery timelines of the products. While fulfilling personalized customer needs, companies must also consider their existing resource conditions – in other words, how to leverage their current resources to optimally meet customer demands [24]. Therefore, given limited resources, businesses must thoroughly consider product development costs and technological specification limits when planning products.

Based on this, this paper has pruned and supplemented the elements of the traditional quality house. It has eliminated the original market competitiveness evaluation and technical competitiveness evaluation elements and added product development costs and technological constraint limits as new elements. The improved quality house not only simplifies the influencing factors but also enables a swift response to customers' personalized needs. Moreover, it takes into account the current state of the company's resources, determining product development costs and technological constraint limits based on the enterprise's existing resources. The improved quality house is shown in Figure 4.

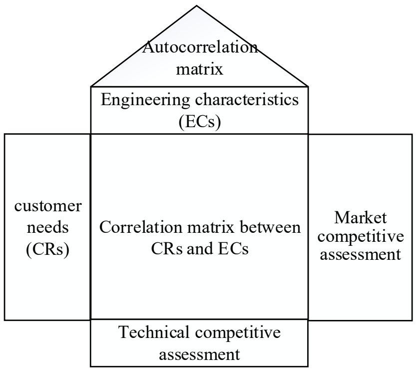

Fig. 3. Traditional House of Quality.

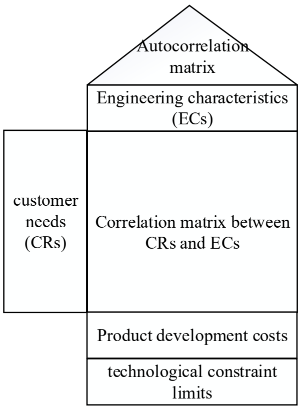

Fig. 4. Improved House of Quality.

The process of establishing the quality house includes capturing CR from the Kano questionnaire results, listing the EC related to CR, establishing a correlation matrix among CR and EC, deploying relevant matrices among EC, and determining product development costs and technical constraint conditions. In order to provide a more accurate representation of the connections between CR and EC, it is essential to standardize the relationship matrix within the quality house. Therefore, this study adopted Wasserman's standardization method [25] as follows:

$$R_{ij}^{norm} = \frac{\sum_{k=1}^{n} R_{ik} \cdot \gamma_{kj}}{\sum_{j=1}^{n}\sum_{k=1}^{n} R_{ij} \cdot \gamma_{jk}}, \quad i = 1,2,...m\,; \;\; j = 1,2,...,n \tag{5}$$

In this equation, R_{ij} and γ_{jk} represent elements of the relationship matrix within the HOQ and the autocorrelation matrix, respectively. Multiplying the importance weights of CRs, as calculated by equation (3), with the normalized relationship matrix allows for the conversion of these weights into the importance weights of ECs.

$$\mu_j = \sum_{i=1}^{m} \rho_i R_{ij} \tag{6}$$

3.2.2 The standardization of EC values

In the context of various QFD optimization models, it is typically assumed that EC values fall within a continuous range, where any value within that range is considered a feasible solution [21]. Nonetheless, certain technical limitations may necessitate that specific ECs assume discrete values rather than continuous ones. For example, the dimensions of a laptop are typically considered continuous variables with minimum and maximum values, whereas the computer CPU is regarded as a discrete value. In such cases, there are certain challenges for QFD optimization models as the obtained optimal solutions might not be feasible for product development and manufacturing processes. To address this issue, this paper employs different standardization methods for discrete ECs and continuous ECs.

Regarding continuous ECs, they can be further categorized into favorable characteristic values and unfavorable characteristic values. Favorable characteristic values indicate that increased EC values lead to improved performance, whereas unfavorable characteristic values suggest that higher EC values result in degraded performance. The standardization formulas for these are as follows:

$$x_j = \frac{\left(X_j^* - X_{\min}\right)}{\left(X_{\max} - X_{\min}\right)} \quad , \quad x_j = \frac{\left(X_{\max} - X_j^*\right)}{\left(X_{\max} - X_{\min}\right)} \tag{7}$$

In these equations, X_j^* represents the particular numerical value of the j th engineering characteristic, $X_{\max}$ and $X_{\min}$ are the maximum and minimum values of the corresponding engineering characteristic. For discrete ECs, this paper follows the method from reference [16], standardizing discrete ECs by introducing binary variables x_{jk} . Each discrete EC has a collection of available discrete values and is assigned a satisfaction level d_{jk}. When the value of EC_j is k, then x_{jk} equals 1. EC_j aligns with the x_j level associated with the chosen EC value, as expressed in equation (8). The discrete EC values are subsequently linked to the fulfillment degree to create the mathematical programming model.

$$x_j = \sum_{k=1}^{p} x_{jk} d_{jk} \tag{8}$$

3.2.3 The establishment of the QFD optimization model

Establish a customized product planning model based on the existing improved quality house. In the market environment of mass customization, maximizing customer satisfaction is the goal pursued by businesses. Therefore, a nonlinear programming model based on QFD is established with the maximization of satisfaction as the objective function. To classify various CRs into Kano categories based on questionnaire analysis, we use the quantitative analysis of the S-CR relationship function from section 3.1 as the objective function during the decision-making phase. The overall CS, reflecting the extent to which the designed product is addressed, is considered a mathematical set of CRs' implementation levels, i.e., $S(y_1, y_2, \ldots, y_m)$. This paper uses the sum of the satisfaction of each CR to express:

$$S\left(y_1, y_2, \ldots, y_m\right) = \sum_{i=1}^{m} \rho_i s_i \quad (9)$$

Therefore, by amalgamating the S-CR relationship functions, the objective function can be articulated as follows:

$$max \sum_{i=1}^{m} w_i s_i \quad (10)$$

$$s_i = \begin{cases} \left(CS_i - DS_i\right) y + DS_i & (O) \\ \dfrac{CS_i - DS_i}{e-1} e^{y} - \dfrac{CS_i - eDS_i}{e-1} & (A) \\ -\dfrac{e\left(CS_i - DS_i\right)}{e-1} e^{-y} + \dfrac{eCS_i - DS_i}{e-1} & (M) \end{cases}$$

Through the multiplication of the standardized relationship matrix, we can convert the satisfaction levels of ECs into those of CRs, as demonstrated in Equation (11). Equation (12) represents the normalization of discrete ECs, and Equation (13) illustrates the constraint for discrete values, where only one EC value can be chosen.

$$y_j = \sum_{j=1}^{n} R_{ij}^{norm} x_j \,, \quad i = 1, 2, \ldots, m \quad (11)$$

$$x_j = \sum_{k=1}^{p} x_{jk} d_{jk} \quad (12)$$

$$\sum_{k=1}^{p} x_{jk} = 1 \quad (13)$$

$$x_{jk} \in \left(0\,, 1\right) \quad (14)$$

In addition to considering customer satisfaction, the development of new products demands a range of resources for support. These resources include product development time, development costs, manufacturing costs, human resources, and more. The total cost depends on the implementation level of EC_j (x_j), and Equation (15) indicates that the total cost of the established product design model cannot exceed the cost budget.

$$\sum_{j=1}^{n} c_j x_j \le C \quad (15)$$

For certain ECs, some technical constraints might restrict the number of product developments. In other words, there might be lower or upper technical limits on the EC achievement level, depending on the specific circumstances. Equation (16) specifies further constraints on the attainable levels of specific Ecs, and equation (17) signifies that the achievement level of EC_j is between 0 and 1.

$$ECL_j \le x_j \le ECH_j \,, \quad j = 1, 2, \ldots, n \quad (16)$$

$$0 \le x_j \le 1\,, \quad j = 1, 2, \ldots, n \quad (17)$$

4 Case analysis

Combining the aforementioned analyses, this section uses the example of a company's condenser design to illustrate the process of constructing an optimization model for manufacturing custom products and decision analysis. Through interviews with the company and customer surveys, the following section lists some of the CRs and ECs of the product. The Kano questionnaire was used to investigate the five CRs of the condenser, including safe and reliable(CR_1), stable operation(CR_2), low energy consumption(CR_3), rational structure(CR_4) and high heat effciency(CR_5). A dataset of 125 questionnaire responses were gathered from the company's customer base. Based on the statistics, the Kano categorization, CS and DS values for each CR were derived. Subsequently, through the applied quantitative analysis approach, the S-CR relationship functions were approximated, as shown in Table 1.

Table 1. S-CR functions for different CRs.

CRs	Kano classification	CS	DS	S-CR function
CR_1	M	0.3871	−0.7742	$s=-1.8371e^{-y}+1.0629$
CR_2	A	0.7073	−0.3902	$s=0.6387e^{y}-1.0289$
CR_3	O	0.6829	−0.7886	s=1.4715y-0.7886
CR_4	A	0.7097	−0.3468	$s=0.6149e^{y}-0.9617$
CR_5	O	0.7787	−0.7049	s=1.4836y-0.7049

Based on the survey results, it was found that there were no indifferent-type requirements. Therefore, all five requirements mentioned above were included in the subsequent analysis. Using Equation (3), the determination of importance weights for each customer requirement can be conducted as follows:

$$\rho_1 = 0.216,\ \rho_2 = 0.182,\ \rho_3 = 0.220,\ \rho_4 = 0.182,\ \rho_5 = 0.200$$

The ECs presented in this paper are those that typically align with the most prevalent customer concerns in product development, such as liquid oxygen level stability(EC_1), monitoring point categories(EC_2), structural hierarchy(EC_3), installation form(. EC_4 .), cycle ratio(EC_5), and design margin(EC_6). After reviewing relevant literature, an expert rating method is used to score the relationship matrix and the autocorrelation matrix. The scores were then standardized using Equation (5), resulting in the standardized relationship matrix (R) as follows:

$$R = \begin{bmatrix} 0.1589 & 0.1674 & 0.1886 & 0.1377 & 0.1631 & 0.1843 \\ 0.1841 & 0.1639 & 0.2010 & 0.1368 & 0.1334 & 0.1807 \\ 0.1603 & 0.1603 & 0.1987 & 0.1603 & 0.1517 & 0.1688 \\ 0.1391 & 0.1593 & 0.1996 & 0.1673 & 0.1593 & 0.1754 \\ 0.1599 & 0.1537 & 0.1972 & 0.1506 & 0.1413 & 0.1972 \end{bmatrix}$$

At this point, the calculation of the significance coefficients for ECs can be achieved through the utilization of equation (6), which is as follows:

$$\mu_1 = 0.1604,\ \mu_2 = 0.1610,\ \mu_3 = 0.1968,\ \mu_4 = 0.1505,\ \mu_5 = 0.1501,\ \mu_6 = 0.1812$$

In this paper, all six engineering characteristics have discrete values. They need to be processed by adding a binary variable x_{jk}. x_{jk} takes on values of 0 or 1, with 1 indicating that an EC value is chosen, and 0 indicating that it's not selected. For this paper, experts from the company were consulted using a brainstorming method to assume several sets of satisfaction levels for EC values. These assumptions are detailed in Table 2.

Table 2. Standardized EC values.

Discrete EC values	Option1	Option2	Option3	Option4	Option5
EC_1	d_{11}=0.25	d_{12}=0.5	d_{13}=0.8	d_{14}=1	
EC_2	d_{21}=0.25	d_{22}=0.5	d_{23}=0.75	d_{24}=1	
EC_3	d_{31}=0.2	d_{32}=0.4	d_{33}=0.6	d_{34}=0.8	d_{35}=1
EC_4	d_{41}=0.33	d_{42}=0.66	d_{43}=1		
EC_5	d_{51}=0.33	d_{52}=0.66	d_{53}=1		
EC_6	d_{61}=0.2	d_{62}=0.4	d_{63}=0.6	d_{64}=0.8	d_{65}=1

Through interviews with company experts, the cost index (c_j) for each EC is obtained. This paper determined a set of c_j values by taking into account the one-time investment cost for providing that feature and the net present value of the company's operational costs over the past three years.

$$c_j = [c_1, c_2, c_3, c_4, c_5, c_6] = [19.8, 17.5, 15.5, 14.0, 16.5, 14.5]$$

For each EC, there may be technical lower bounds (ECL_j) or upper bounds (ECH_j) for their satisfaction levels, which need to be determined based on actual circumstances. In this study, by reviewing relevant literature and investigating the specifics of the company's product, we set $ECL_1 = 0.65$ and $ECH_3 = 0.85$, meaning that the first EC has a lower technical limit of 0.65, and the third EC has an upper technical limit of 0.85, while there are no technical limits for the other ECs.

Based on the above analysis, the quality house for the condenser evaporator is constructed as follows table 3:

Table 3. House of Quality for Condenser Evaporator Design.

	EC_j	EC_1	EC_2	EC_3	EC_4	EC_5	EC_6
CR_i	ρ_i	standardized relationship matrix R_{ij}^{norm}					
CR_1	0.216	0.1589	0.1674	0.1886	0.1377	0.1631	0.1843
CR_2	0.182	0.1841	0.1639	0.2010	0.1368	0.1334	0.1807
CR_3	0.220	0.1603	0.1603	0.1987	0.1603	0.1517	0.1688
CR_4	0.182	0.1391	0.1593	0.1996	0.1673	0.1593	0.1754
CR_5	0.200	0.1599	0.1537	0.1972	0.1506	0.1413	0.1972
	μ_j	0.1604	0.1610	0.1968	0.1505	0.1501	0.1812
	c_j	19.8	17.5	15.5	14.0	16.5	14.5
	ECL_j	0.65	—	—	—	—	—
	ECH_j	—	—	0.85	—	—	—

Let $X = [x_1, x_2, x_3, x_4, x_5, x_6]^T$ represent the level of implementation for each EC, and $Y = [y_1, y_2, y_3, y_4, y_5]^T$ represent the level of implementation for each CR. Now, the company is considering investing 1 million to improve the product quality of the condenser evaporator. The expression of the QFD optimization model is as follows:

$$\max = 0.216s_1 + 0.182s_2 + 0.22s_3 + 0.182s_4 + 0.2s_5$$

$$s_1 = -1.8371e^{-y_1} + 1.0629$$

$$s_2 = 0.6387e^{y_2} - 1.0289$$

$$s_3 = 1.4715y_3 - 0.7886$$

$$s_4 = 0.6149e^{y_4} - 0.9617$$

$$s_5 = 1.4836y_5 - 0.7049$$

$$\begin{cases} 19.8x_1+17.5x_2+14.5x_3+14x_4+16.5x_5+15.5x_6 \le 100 \\ x_1=0.25x_{11}+0.5x_{12}+0.8x_{13}+x_{14} \\ x_2=0.25x_{21}+0.5x_{22}+0.75x_{23}+x_{24} \\ x_3=0.2x_{31}+0.4x_{32}+0.6x_{33}+0.8x_{34}+x_{35} \\ x_4=0.33x_{41}+0.66x_{42}+x_{43} \\ x_5=0.33x_{51}+0.66x_{52}+x_{53} \\ x_6=0.2x_{61}+0.4x_{62}+0.6x_{63}+0.8x_{64}+x_{65} \\ x_{11}+x_{12}+x_{13}+x_{14}=1 \\ x_{21}+x_{22}+x_{23}+x_{24}=1 \\ x_{31}+x_{32}+x_{33}+x_{34}+x_{35}=1 \\ x_{41}+x_{42}+x_{43}=1 \\ x_{51}+x_{52}+x_{53}=1 \\ x_{61}+x_{62}+x_{63}+x_{64}+x_{65}=1 \\ Y=RX \\ 0 \le x_j \le 1, \quad j=1,2,\ldots,n \\ x_{jk} \in (0,1), \quad j=1,2,\ldots,n; k=1,2,\ldots,p \\ x_1 \ge 0.65, \quad x_3 \le 0.85 \end{cases}$$

The model can be characterized as a nonlinear programming model with mixed-integer components, and it was solved using Lingo software. The results obtained are shown in Tables 4 and 5 below.

Table 4. Selected EC values and predicted allocation.

Discrete EC values	Selected EC point	Satisfaction level of ECj (x_j)	Cost allocation （ten thousand）
EC_1	x_{14}	1	19.8
EC_2	x_{24}	1	17.5
EC_3	x_{34}	0.8	12.4
EC_4	x_{43}	1	14.0
EC_5	x_{53}	1	16.5
EC_6	x_{65}	1	14.5

Table 4 presents the implementation status of ECs and the corresponding resource allocation results. Based on the selected normalized EC values, the actual satisfaction level for each EC can be determined. Multiplying the actual satisfaction level of every EC by the cost index of each engineering characteristic results in the actual cost allocation for each engineering characteristic.

Table 5. Implementation Level of CRs and customer satisfaction.

CRs	Satisfaction levels (y_i)	Customer satisfaction (s_i)	Complete customer satisfaction (CS_i)	Customer satisfaction level (%)
CR_1	0.9623	0.3611	0.3871	93.28
CR_2	0.9597	0.6387	0.7073	90.30
CR_3	0.9604	0.6246	0.6829	91.46
CR_4	0.9601	0.6444	0.7098	90.79
CR_5	0.9605	0.6768	0.7787	86.91
Overall		0.5843	0.6475	90.24

Table 5 presents the satisfaction levels (y_i) and customer satisfaction (s_i) for each customer requirement. It can be observed that under the constraint of a total cost of 1 million, the satisfaction levels for all customer requirements reach 0.9. Utilizing the S-CR relationship functions provided in table 1, the actual customer satisfaction (s_i) for each requirement can be calculated. CS_i represents the customer satisfaction brought by each requirement when the satisfaction level y_i is 1. Dividing the actual customer satisfaction s_i by the complete customer satisfaction CS_i results in a customer satisfaction level. It can be seen that CR_1, 'safe and reliable,' reaches the maximum customer satisfaction level, and its satisfaction level is also the highest. This suggests that the chosen ECs exhibit strong optimization performance and result in a relatively high degree of customer satisfaction. Furthermore, by substituting the weight for each customer requirement, denoted as ρ_i, overall customer satisfaction and complete customer satisfaction can be calculated. Overall, the product design achieves a customer satisfaction of 0.5843, with a complete customer satisfaction of 0.6475, resulting in a customer satisfaction level of 90.24%. Furthermore, in this case, it can be observed that the customer requirement satisfaction level y_i is close to 1, but the customer satisfaction s_i is rather moderate. This results from its calculation using the quantitative Kano model, and defining si values using the Kano model provides a more objective measure. Even when a customer requirement is completely satisfied, there's no assurance that a customer will find it entirely satisfying, as some engineering characteristics may be unnecessary.

5 Conclusions

Based on the issues existing in the Kano model and QFD theory, this study proposes a product design method that combines the Kano model with QFD quantitatively enhance the comprehension of customer requirements for product design. The main contributions are summarized as follows:

1. This method not only quantifies the Kano model and objectifies the classification of customer requirements but also effectively integrates the Kano model with QFD, allowing for a thorough exploration of customer needs. It eliminates the heavy reliance

on translating explicit customer specifications for product attributes but also facilitates the identification of critical CRs that significantly influence CS. This approach aids companies in steering clear of the error of allocating excessive resources to CRs of lesser significance.

2. To meet the needs of large-scale customized production, improvements have been made to the traditional quality house, introducing an optimized QFD model tailored to custom product planning.

3. There is an enhancement in the evaluation of product performance. Compared to traditional methods that use linear functions, mapping CR achievement levels to CS based on Kano classification allows for a more objective assessment of the product.

Future research can focus on the following improvements: First, the paper approximated the relationship functions between attractive, must-be requirements, and customer satisfaction using an exponential function based on literature assumptions. In the future, it is imperative to concentrate on enhancing these assumptions to achieve more objective derivation of the relationship functions. Additionally, a substantial amount of data should be used for objective validation. Second, this study only improved the traditional quality function deployment in a customized environment. Future research can focus on enhancing the analysis of quality function deployment itself, particularly the relationship between CRs and ECs. Third, additional case studies addressing product design challenges are needed to verify the practical suitability of the proposed approaches.

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