ORIGINAL ARTICLE

A spectral clustering method to improve importance rating accuracy of customer requirements in QFD

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Abstract

Quality function deployment (QFD) is a method commonly used in manufacturing industries to identify customer requirements (CRs) and the manufacturing capacity to meet CRs. Importance rate (IR) of CRs plays an important role in the QFD method. The existing methods in determining IR of CRs cannot consider all related factors of customer satisfaction, need importance, personal information, and relationship between customer satisfaction and function implementation. This paper proposes a method to improve the IR accuracy. Based on comments of customers for a product, importance rates of CRs are defined using integrated importance-performance analysis (IPA) and Kano models. IPA and Kano models are integrated by spectral clustering where a similarity matrix W is formed to balance the influence proportion between the IPA and Kano models considering comments of different customers for the product. IR of CRs is used in the QFD method to define functions and structures of the product. The proposed method is compared with several existing methods in case studies of designing an upper limb rehabilitation device and a feed drive system of the CNC machine. Results show that the proposed method has improved accuracy of IR of CRs for the product design and manufacturing.

Keywords Importance rating · IPA model · Kano model · Spectral clustering · QFD method

1 Introduction

It is essential for industry to develop product that meets customer requirements in the competitive market [1]. Quality function deployment (QFD) provides a guide for industry to transfer customer requirements (CRs) into engineering characteristics of product [2]. CRs are normally defined in QFD by manufacturing experts based on customer needs for a product [3]. Importance rate (IR) of CRs in the QFD method can be used to define the weight of function requirements (FRs) in product design and manufacturing [4]. Therefore, IR of CRs can guide manufacturing industries to produce a satisfied product for customers and improve competitiveness.

As the weight of FRs is defined based on IR of CRs and relationship between CRs and FRs in the QFD method [5], determination of the IR of CRs is a very important step after CRs are identified. Based on the accurate IR, a product can be designed and manufactured to match or exceed customer satisfactions in the target market to achieve competitive advantages [6].

There are two existing approaches to decide IR of CRs including expert evaluation and customer questionnaires. The expert evaluation includes methods of the additive ratio assessment (ARAS), techniques for preference order using similarity (TOPSIS), simple additive weighting (SAW), analytic hierarchy, and analytic network process [7]. Data used in these methods are from designers or experts in a manufacturing company. Solutions of these methods are subjective without considering customers' opinion. In addition, experts with a certain level of knowledge and experience are sometimes hardly available; conflict attitudes from different experts cannot be easily balanced [8]. Methods based on customer questionnaires include models of SERVQUAL, Kano, IPA, and customer satisfaction index [9]. These methods are based on collected comments of product users, which may sometimes be inaccurate if only based on the response from customers.

The Kano model uses the degree of implemented functions of a product to identify five types of customer requirements that influence ultimate customer satisfactions [10]. Must-be quality (M) is the requirement of customer expectations.

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One-dimensional quality (O) attributes a satisfaction when it is fulfilled and dissatisfaction when it cannot be fulfilled. Attractive quality (A) provides a satisfaction when CRs are met fully, without dissatisfaction when it is not fulfilled. Indifferent quality (I) refers to aspects that are neither good nor bad, which results in neither customer satisfaction nor dissatisfaction. Reverse quality (R) is for a high degree in dissatisfaction when not all customers are alike [11]. In the exiting research, most of researchers provide a fixed value for 5 types of CRs. However, values in M and A groups can also be influenced by current product performance for meeting CRs [12]. For example, IR of CRs will be very high if the CRs in the M group are not met. Meanwhile, IR of CRs will be normal if the CRs in the M group are fully met. Therefore, it is not accurate to define CRs as a fixed value in M and A groups. A weakness of using the Kano model to define IR of CRs is that the product performance from customer comments is ignored.

The IPA model is also commonly used for identifying customer satisfactions of different CRs of product. IPA is a simple and effective technique to assist practitioners in identifying improvement priorities of a product, which can guide designers to define IR of CRs. Product preference and importance of CRs from customers' survey can be considered in an IPA model. The IPA model prioritizes product attributes for improvement based on user evaluations. A matrix is used to represent the importance and performance of each quality attribute where the horizontal axis shows the degree of CRs' performance or satisfaction, and the vertical axis is the degree of the CRs importance [13]. In an IPA model, CRs are divided into 4 categories including concentrating area rated for a mark of 5, keeping up good work for a mark of 4, low priority for a mark of 3 and possible overkill for a mark of 2. The IPA model assumes that the improvement of a product function has a same linear promotion relationship with the overall customer satisfaction, which ignores the nonlinear relationship [14].

Kano and IPA models can be combined to define IR of CRs, which can improve the IPA model that considers only one-dimensional quality and reduce the limitation of the Kano model that neglects the attribute performance. However, the existing methods of combining Kano and IPA models cannot define IR of CRs accurately because of conflict requirements from different customers and too many levels for IR of CRs [15].

To improve accuracy of the IR of CRs in the QFD method, a new IR decision method using integrated IPA and Kano models is proposed using spectral clustering in this research. All factors from different customers in questionnaires are considered in the proposed model. Conflicted comments of customers are processed using the ANOVA method. By considering the type and actual function implementation of CRs, an improved Kano model is proposed to transfer categorical attributes to numerical attributes. A similarity matrix W is

proposed to integrate the influence factors in the IPA and Kano models. The final IR of CRs is used in the QFD method to improve the important rating of CRs in design cases of the upper limb rehabilitation and feed drive devices. The solution is verified by comparing with some existing methods.

The following parts of the paper are organized as follows. Literature review of related methods is discussed in Section 2. An improved IR determination method is proposed in Section 3 with an upper limb rehabilitation device design using the proposed IR determination method in defining IR of CRs. Section 4 discusses the design of upper limb rehabilitation devices and feed drive systems of the computer numerical control (CNC) lathe using different IR determination methods to verify the proposed method, followed by the research conclusion and further work in Section 5.

2 Literature review

2.1 Existing methods for combining Kano and IPA models

Integration of Kano and IPA models can improve the IR accuracy in the QFD method, for example, a combined model can balance the percentage of all factors or include more factors to improve the accuracy for IR of CRs. Wu et al. [16] identified key success factors to increase customer satisfactions by integrating Kano and IPA models using improved questionnaires. Tontini et al. [17] identified the impact of incremental innovations on customer satisfactions using a fusion method between IPA and Kano models. Deng et al. [18] combined Kano and IPA models to manage work with limited resources in competitive environments by a partial correlation analysis. Kuo et al. [14] retained original features of Kano and IPA models to comprehensively grasp user perceptions of all quality attributes and corresponding strategies by dividing CRs into 13 clusters based on the proposed IPA-Kano model.

The existing combination methods are mainly used in the service field such as the residence environment, restaurant, and airport services. Yin et al. [19] examined environmental correlations with the residential satisfaction by an IPA–Kano model. Pai et al. [20] combined Kano and IPA models to investigate critical service quality attributes to strengthen advantages of chain restaurants. Wang et al. [21] identified the customer retention for airline services by integrating fuzzy Kano with IPA models.

However, the existing methods for combing Kano and IPA models have following problems. (1) These models divide CRs into too many groups, which is ineffective and inaccurate to define IR of CRs in the process. (2) The existing models cannot combine different comments of customers. Average values of the product importance and performance are used

for evaluating comments of customers, which ignores differences of customers. (3) The influence of the function implementation in existing products is not considered in combined IPA and Kano models for defining IRs, Therefore, it is necessary to improve accuracy of the existing methods to combine Kano and IPA models.

2.2 Defining IR of CRs by clustering methods

As clustering methods can combine conflict comments of customers to improve IR accuracy, the existing clustering methods are reviewed for selecting the most suitable method to define IR of CRs. They include fuzzy clustering, K-mean clustering, and spectral clustering methods that are commonly used for the customer segmentation based on characters of customers such as age, income, and education [22].

Fuzzy clustering methods construct clusters with uncertain boundaries for the customer segmentation. Liu et al. [23] proposed a modified fuzzy clustering method to classify various importance groups of CRs, which improved the certainty and precision of QFD. Wang et al. [24] divided customer quality requirements into a hierarchical structure by the fuzzy clustering method to determine weights of the requirements for accurate and reliable information in quality control. Chan et al. [25] segmented the market based on CRs for new product design using fuzzy clustering methods.

The K-mean clustering is an efficient method for the customer segmentation. Alvandi et al. [26] clustered customers based on their contributions to profitability in banking services using a K-mean clustering method. Ho et al. [27] proposed a GA-based K-mean algorithm to cluster customers for developing approximate optimal solutions. Wang et al. [28] proposed improved K-mean algorithms for the market segmentation using silhouette coefficient.

The spectral clustering method uses a similarity matrix to extract important information for improving the clustering accuracy. Wu et al. [29] clustered customers based on their online shopping behaviors, service satisfaction, and internet usage using this method. Sagar et al. [30] proposed a user segmentation model for clustering user trajectories using a feature matrix in the spectral clustering method. Chang et al. [31] applied a spectral clustering technique to cluster customers for determining characters of loyal customers in adjusting a promotion strategy to gain more benefits.

Comparing with other clustering methods, the spectral clustering method can process a huge amount of data easily because a similarity matrix can be used to extract important information and reduce the effect of useless information. In addition, the Laplacian matrix in the spectral clustering method can combine categorical attributes and numerical attributes for clustering, which increases accuracy of clustering. Therefore, the spectral clustering method is selected in our proposed IR determination method to combine all the important factors to cluster CRs, which can solve the three problems in the existing methods for combined IPA and Kano models.
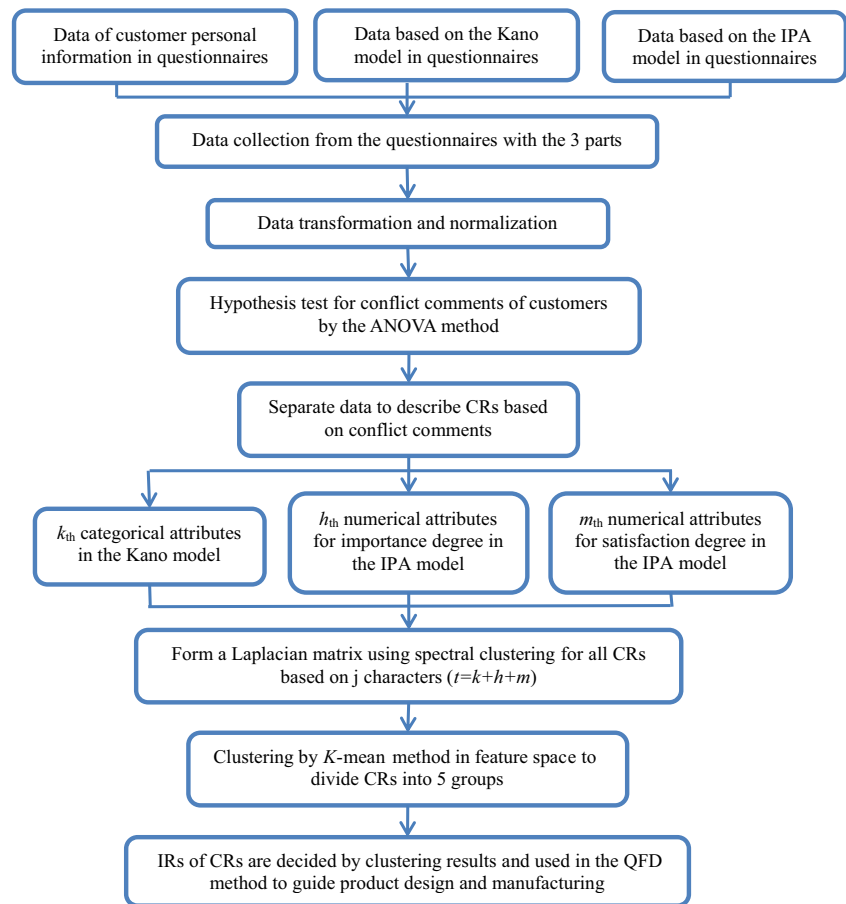
3 Proposed IR method

Raw data used in the proposed method were obtained through a questionnaire survey for customer personal information, data for Kano, and IPA models. Collected raw data are normalized for eliminating the influence of dimensions. The categorical attributes in the Kano model are transferred to numerical attributes by integrating the current function implementation of CRs and categorical attributes of CRs in the Kano model. Conflict comments from different customers are processed using the ANOVA method. A database is created by separating data of conflict comments into different groups to show all important comments of customers.

A spectral clustering method is used to form a Laplacian matrix for combining kth categorical attributes in the Kano model, hth numerical attributes for importance degree, and mth numerical attributes for satisfaction degrees in the IPA model. Based on characters of CRs, the CRs are clustered into 5 groups by the K-mean method in the feature space. IRs of CRs are defined based on clustering results and then used in the QFD method. Steps of the proposed IR decision method are shown in Fig. 1.

3.1 Collection of raw data using questionnaires based on IPA and Kano models

A questionnaire with three parts is created to conduct a user survey for collecting raw data. The first part is customer personal data related to the use of product. The second part is used for the Kano model. Based on each CR, there are two questions for customers. The first question is the positive question to find the customer feeling if a CR can be met. The second question is the negative question to get the customer comment if the CR cannot be met. The third part is for the IPA model. The current satisfaction degree and importance degree for each CR are defined based on the average value of importance and satisfactory degrees from responses of the questionnaire. Based on requirements of the quantitative evaluation in the design process using the QFD method, five levels of the importance degree (ID) and satisfaction degree (SD) are defined.

Fig. 1 Proposed IR steps


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┌─────────────────────┐  ┌─────────────────────┐  ┌─────────────────────┐
│ Data of customer    │  │ Data based on the   │  │ Data based on the   │
│ personal            │  │ Kano model in       │  │ IPA model in        │
│ information in      │  │ questionnaires      │  │ questionnaires      │
│ questionnaires      │  │                     │  │                     │
└─────────────────────┘  └─────────────────────┘  └─────────────────────┘
            │                      │                      │
            └──────────────────────┼──────────────────────┘
                                   │
              ┌────────────────────────────────────────────┐
              │ Data collection from the questionnaires     │
              │ with the 3 parts                            │
              └────────────────────────────────────────────┘
                                   │
              ┌────────────────────────────────────────────┐
              │ Data transformation and normalization       │
              └────────────────────────────────────────────┘
                                   │
              ┌────────────────────────────────────────────┐
              │ Hypothesis test for conflict comments of    │
              │ customers by the ANOVA method               │
              └────────────────────────────────────────────┘
                                   │
              ┌────────────────────────────────────────────┐
              │ Separate data to describe CRs based on      │
              │ conflict comments                           │
              └────────────────────────────────────────────┘
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k_{th} categorical attributes in the Kano model

h_{th} numerical attributes for importance degree in the IPA model

m_{th} numerical attributes for satisfaction degree in the IPA model

Form a Laplacian matrix using spectral clustering for all CRs based on j characters ($t=k+h+m$)

Clustering by K-mean method in feature space to divide CRs into 5 groups

IRs of CRs are decided by clustering results and used in the QFD method to guide product design and manufacturing

3.2 Data transformation

Raw data values of ID and SD with 5 levels in the IPA model are defined and normalized. Values of an ID have 5 levels including very importance (5 marks), importance (4 marks), normal (3 marks), unimportance (2 marks), and very unimportance (1 mark). Values of a SD have 5 levels including very satisfaction (5 marks), satisfaction (4 marks), normal (3 marks), dissatisfaction (2 marks), and very dissatisfaction (1 mark). Dimensions in Kano and IPA models are from 0 to 1 and from 1 to 5, respectively. For comparing data with different dimensions in Kano and IPA models, data in the IPA model are transferred into interval from 0 to 1 using Eq. (1).

Table 1 Values of x

Value of x	Description
0	Current product does not have any function to meet CRs
1	Current product only has the very basic function to meet CRs
2	Current product has the function to meet CRs, but it needs huge improvement
3	Current product has the function to meet CRs with some improvement space
4	Current product has functions to meet CRs with little improvement required
5	Current product has all functions to fully meet CRs

Table 2 CRs result based on Kano and IPA models

	Kano model			IPA model					
CRs	1. Kano model of character 1	2. Kano model of character 2	3. Kano model of character k	4. ID for character 1	5. ID for character 2	6. ID for character h	7. SD for character 1	8. SD for character 2	9. SD for character m
CR.1	x_{11}	x_{12}	x_{1k}	x_{14}	x_{15}	x_{1h}	x_{17}	x_{18}	x_{1m}
CR.2	x_{21}	x_{22}	x_{2k}	x_{24}	x_{25}	x_{2h}	x_{27}	x_{28}	x_{2m}
CR.n	x_{n1}	x_{n2}	x_{nk}	x_{n4}	x_{n5}	x_{nh}	x_{n7}	x_{n8}	x_{nm}

$$x_{ij}^{n} = \frac{x'_{ij} - \min_{1 \leq i \leq n}\{x'_{ij}\}}{\max_{1 \leq i \leq n}\{x'_{ij}\} - \min_{1 \leq i \leq n}\{x'_{ij}\}} \quad (j = 1, 2, \ldots, h) \tag{1}$$

Values of CRs in the Kano model are also normalized. As categorical attributes cannot be directly used to search similarity, the categorical attributes are transferred into numerical attributes. The interval for 0 to 1 is suitable for the definition of weight in the field of product design. As categories of O, I, and R are not influenced by the current function implementation degree of CRs, values for CRs in these 3 categories are defined based on characters of product design [10]. The value is stable for CRs in O, I, and R groups. The value of O is assigned as "0.6" as the one-dimensional CRs can promote the product preference when CRs are satisfied. The value of I is defined as "0.2" when indifferent CRs cannot influence the customer satisfaction. The value of R is assigned as "0.1" when the reversed CRs can reduce the customer satisfaction.

Values for CRs belonging to A and M groups are relative to the current function implementation degree of CRs. Based on the slope of characters in the Kano model [10], values of categories A and M are proposed in Eqs. (2) and (3), respectively, where x is the current function implementation degree of CRs for a product. For product design, the x value can be defined into 6 levels as shown in Table 1.

V_A is a value of CRs in A group in the Kano model. Based on Eq. (2), values of CRs are higher if a current product from a manufacturing company cannot provide a satisfied function (x is 0, 1, or 2). Values of CRs are lower if the current product provides a satisfied function (x is 3, 4, or 5) as follows.

$$\begin{cases} V_A = \frac{1}{5} \times 5^{0.5x} & (x = 0, 1, 2) \\ V_A = 2 \times \frac{1}{5}^{0.2x} & (x = 3, 4, 5) \end{cases} \tag{2}$$

V_M is a value of CRs in M group in the Kano model. Based on Eq. (3), values of CRs have a higher importance if the current product from a manufacturing company cannot provide a satisfied function. For example, V_M is very high (V_M is

equal to 1.0) if current product does not have any function to meet CRs (x is equal to 0).

$$V_M = 0.4 + 0.6 \times \left(\frac{1}{5}\right)^{0.2x} \tag{3}$$

The average value of all customers' responses in Kano and IPA models can be determined using results of data transformation from Eqs. (1), (2), and (3).

3.3 Hypothesis testing by the ANOVA method for separating data to describe CRs

Some factors of the demographic and personal information such as customers' background, expectation, and preference on product can affect results. Thus, the analysis of variance (ANOVA) techniques is used to detail CRs in different conditions [18]. Z score is used to test the data statistical significance by Eq. (4) to decide whether a null hypothesis should be rejected.

$$z = (x - \mu)/\sigma \tag{4}$$

where z is the standard score (Z score), x is the raw score of standardization, μ is the mean of data, σ is the standard deviation of the data. Based on z value in Eq. (4), the relationship between p and z values is found using a Z table in the reference [18].

The p value is the probability that falsely rejects the null hypothesis. For a typical analysis, using the standard $\alpha = 0.05$ cutoff, the null hypothesis is rejected when $p < 0.05$. The p value of customers' data from each CR is calculated by the Z table. The number of CRs based on each factor that p value is lower than 0.05 is recorded as shown in Table 2.

If more than 30% of CRs related to the personal information are refused, raw data for describing CRs will be determined separately in Kano and IPA models because customers with different conditions have different comments for requirements of the product. Raw data for defining IR of CRs are shown in Table 2. The characters show factors with conflict comments of different customers. n is the number of CRs for the product.

Algorithm 1 is developed for the data transformation to describe the process descried in Sections 3.1–3.3 as follows.

Algorithm 1 Data transformation

1: **for** i =1 **to** number of CRs
2:     **for** j=1 **to** number of characters in IPA model
3:         Transfer data x'_{ij} into interval from 0 to 1 using Eq. (1)
4:     **end for**
5: **end for**
6: **for** i =1 **to** number of CRs
7:     **if** the i th of CRs is belong to A group
8:         V_A is calculated by Eq. (2)
9:     **else if** the i th of CRs is belong to M group
10:        V_M is calculated by Eq. (3)
11:    **end if**
12: **end for**
13: **for** j =1 **to** number of characters in IPA model
14:    NP $\leftarrow$ 0
15:    **for** i=1 **to** number of CRs
16:        $z \leftarrow (x - \mu)/\sigma$
17:        p is calculate by z using a Z-table in the reference[18]
18:        **if** p<0.05
19:            NP $\leftarrow$ NP +1
20:        **end if**
21:    **end for**
22:    **if** NP> (30% × number of CRs)
23:        data for describing CRs will be determined separately in Table 2
24:    **end if**
25: **end for**

3.4 the data

Based on data in Table 2, matrix X is formed to represent n CRs. Each CR has t ($t = k + h + m$) attributes from influence characters in Kano and IPA models. Attributes show the number of characters for each CR, and the matrix is shown in Eq. (5).

$$X = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1t} \\ x_{21} & x_{22} & \cdots & x_{2t} \\ \vdots & \vdots & \cdots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nt} \end{bmatrix} \quad (5)$$

According to the graph theory in spectral clustering [31], an undirected weight similarity graph $G = (V, E)$ is defined for comparing similarity of CRs. A CR also is defined as a vertex V in G, $V = \{v_1, v_2, \cdots, v_n\}$. x_{nt} represents a character of one CR. For each CR, the character includes t factors: $v_i = \{x_{i1}, x_{i2}, \cdots, x_{it}\} (i = 1, 2, \cdots, n)$. Two vertices are connected by edge E. Length of the edge is shown by similarity w_{ij} between vertices v_i and v_j. Thus, the clustering problem is transformed into a graph partitioning problem of G.

The graph Laplace matrix L is defined in Eq. (6), where L is symmetric and positive semi-definite.

$$L = D - W \quad (6)$$

The similarity matrix W is calculated as follows.

$$W = (w_{ij}) \quad (7)$$

By combining Kano and IPA models, a similarity matrix W of the spectral clustering algorithm is formed using Eq. (8) where parameters c, d, and f are used to represent the proportion of Kano and IPA models. As the importance of Kano and IPA models is considered same, the value of c for the Kano model is 0.5. Values of d and f in the IPA model are equal to 0.25, respectively.

$$w_{ij} = c \cdot w_s(v_i, v_j) + d \cdot w_d(v_i, v_j) + f \cdot w_e(v_i, v_j) \quad (8)$$

In Eq. (9), w_s is the distance of categorical attributes of CRs based on k characters in the Kano model. K is the number of CRs in Eq. (10). Where, v_i^k and v_j^k shows the k dimension for the Kano model in Table 2.

$$w_s(v_i, v_j) = \begin{cases} \exp\left(-\dfrac{\|v_i^k - v_j^k\|^2}{2\sigma_s^2}\right) & i \neq j \\ 0 & i = j \end{cases} \quad (i, j = 1, \ldots, n.) \quad (9)$$

$$\sigma_s = \frac{1}{K}\left(\frac{\sum \|v_i^k - v_j^k\|^2}{\mathrm{Max}\left(\|v_i^k - v_j^k\|^2\right)}\right) \quad (i, j = 1, \ldots, n.) \quad (10)$$

Equation (11) is formed for the distance w_d in numerical attributes of CRs based on h characters for importance degrees in the IPA model. K is the number of CRs in Eq. (12). Where, v_i^h and v_j^h shows the h dimension for ID in Table 2.

$$w_d(v_i, v_j) = \begin{cases} \exp\left(-\dfrac{\|v_i^h - v_j^h\|^2}{2\sigma_d^2}\right) & i \neq j \\ 0 & i = j \end{cases} \quad (i, j = 1, \ldots, n.) \quad (11)$$

$$\sigma_d = \frac{1}{K}\left(\frac{\sum \|v_i^h - v_j^h\|^2}{\mathrm{Max}\left(\|v_i^h - v_j^h\|^2\right)}\right) \quad (i, j = 1, \ldots, n.) \quad (12)$$

Equation (13) is formed for the distance w_e in numerical attributes of CRs based on m characters for satisfaction degree in the IPA model. K is the number of CRs in Eq. (14). Where, v_i^m and v_j^m show the m dimension for SD in Table 2.

$$w_e(v_i, v_j) = \begin{cases} \exp\left(-\dfrac{\|v_i^m - v_j^m\|^2}{2\sigma_e^2}\right) & i \neq j \\ 0 & i = j \end{cases} \quad (i, j = 1, \ldots, n.) \quad (13)$$

Table 3 IR determination based on clusters results

Clusters	Category in Kano	Category in IPA	IR of CRs
1. Very high IR	M1	Concentrate on	5
	M2	Concentrate on	
	A3	Concentrate on	
2. High IR	A2	Concentrate on	4
	O	Concentrate on	
	M2	Keep up good work	
	A2	Keep up good work	
3. Middle IR	M3	Keep up good work	3
	M3	Concentrate on	
	M1	Keep up good work	
	A3	Keep up good work	
	O	Keep up good work	
	M (M1, M2, M3)	Low priority	
4. Low IR	O	Low priority	2
	A (A1, A2, A3)	Low priority	
	M (M1, M2, M3)	Possible overkill	
	O	Possible overkill	
5. Very low IR	A (A1, A2, A3)	Possible overkill	1
	I	Anyone in IPA model	
	R	Anyone in IPA model	

$$\sigma_e = \frac{1}{K}\left(\frac{\sum \|v_i^m - v_j^m\|^2}{\mathrm{Max}\left(\|v_i^m - v_j^m\|^2\right)}\right) \quad (i, j = 1, \ldots, n.) \quad (14)$$
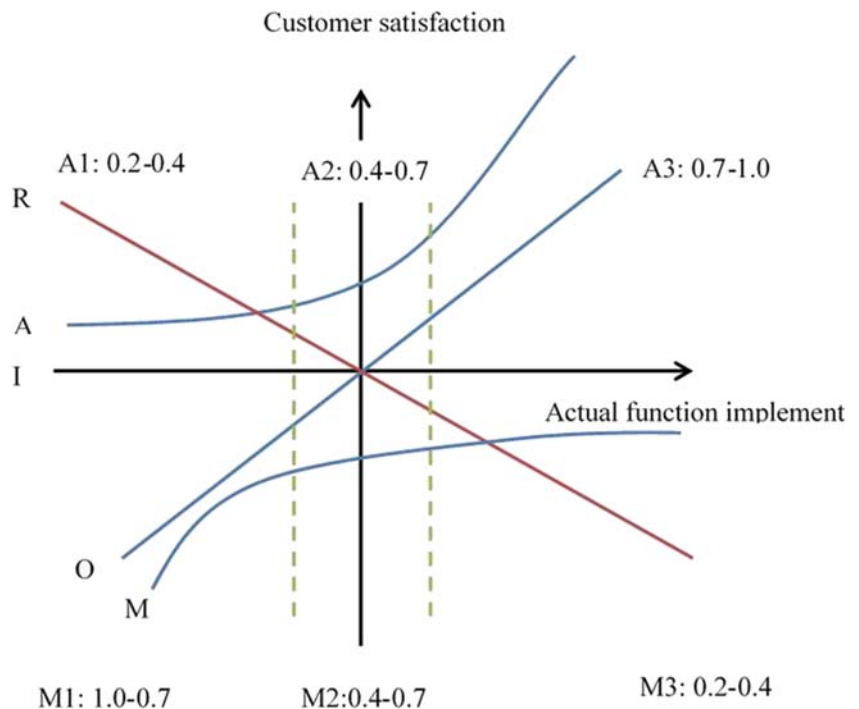

Fig. 2 An improved Kano model

A1: 0.2-0.4   A2: 0.4-0.7   A3: 0.7-1.0

Customer satisfaction

Actual function implement

M1: 1.0-0.7   M2: 0.4-0.7   M3: 0.2-0.4

Table 4 CRs of upper limb rehabilitation devices

No.	CRs	No.	CRs
CR.1	Smooth start and stop	CR.16	Reasonable price
CR.2.	Stable movement	CR.17	Interesting exercise
CR.3	Accurate position	CR.18	Suitable exercise difficult level
CR.4	Automatic rehabilitation data record	CR.19	Adjustable wrist structure
CR.5	Automatic detection for incorrect use	CR.20	Adjustable elbow structure
CR.6	Automatic control in operation	CR.21	Adjustable shoulder structure
CR.7	Clinical feedback	CR.22	Adjustable chair
CR.8	Movement feedback	CR.23	Light weight
CR.9	Exercise tracking	CR.24	Displacement restriction for safety
CR10	Easy operation	CR.25	Velocity restriction for safety
CR.11	Portability	CR.26	Angle restriction for safety
CR.12	Low maintenance cost	CR.27	Easy to store
CR.13	Adaptable to different users	CR.28	Easy maintenance
CR.14	Durability	CR.29	Fault detection for maintenance
CR15	Quiet		

Table 5 Questionnaires for upper limb rehabilitation devices

	Questions	Result or selection
1. Personal information	1.1 Age	Write your answer
	1.2 Injured duration/time	Write your answer
	1.3 Expected cost for device	Write your answer
	1.4 Exercise location	a. Home b. Hospital
	1.5 Injured level	a. Light b. Serious
	1.6 Gender	a. Male b. Female
2. Questions based on Kano model	2.1 If the rehabilitation device has CRn (n=1~29), how do you feel?	a. I like it that way
		b. It must be that way
		c. I am neutral
		d. I can live with it that way
		e. I dislike it that way
	2.2 If the rehabilitation device does not have CRn (n=1~29), how do you feel?	a. I like it that way
		b. It must be that way
		c. I am neutral
		d. I can live with it that way
		e. I dislike it that way
3. Questions based on IPA model	3.1 What's your opinion for the importance of CRn (n=1~29)?	a. very importance (5 marks)
		b. importance (4 marks)
		c. normal (3 marks)
		d. unimportance (2 marks)
		e. very unimportance (1 mark)
	3.2 What's your opinion for the performance of CRn (n=1~29)?	a. very satisfaction (5 marks)
		b. satisfaction (4 marks)
		c. normal (3 marks)
		d. dissatisfaction (2 marks)
		e. very dissatisfaction (1 mark)

A diagonal matrix D is formed in Eq. (15). The element d_{ii} in matrix D is shown in Eq. (16).

$$D = \begin{bmatrix} d_{11} & 0 & \cdots & 0 \\ 0 & d_{22} & \cdots & 0 \\ \cdots & \cdots & d_{ii} & \cdots \\ 0 & 0 & \cdots & d_{nn} \end{bmatrix} \tag{15}$$

$$d_{ii} = \sum_{i=1}^{n} w_{ij} \tag{16}$$

3.5 Clustering by the *K*-mean method in a feature space

A scale of 1 to 5 is used with 5 representing the highest level of importance for IR of CRs. More levels can increase the model complexity to affect the IR accuracy of CRs. Therefore, 5 clusters of CRs are used. Five levels from 1 to 5 are used to define IR of CRs based on 5 clusters obtained from the proposed method.

The eigenvectors of L matrix for the first 5 smallest eigenvalues are used to build a feature space. The number of clustering groups is defined as 5. The *K*-mean method is used to

cluster data into 5 clusters in the feature space because the number of clustering groups is fixed, and the spectral clustering method can avoid the effect of scales and data orders in the *K*-mean method.

3.6 Definition of IR of CRs using clustering results

Based on different actual function implementations, values of CRs in M and A groups for the Kano model are shown in Fig. 2. IRs of CRs in the 5 clusters are shown in Table 3.

IR determination rules are proposed in Table 3. IRs are divided into 5 levels including very high, high, middle, low, and very low. For ensuring that all CRs can be matched within 5 levels, rules are defined as follows. Based on clusters in Table 3, if over 50% of CRs in each cluster are included in the same level, IR for all CRs will be clustered in this level. If the percentage of CRs in any level is lower than 50%, the clustering is not successful because the value of CRs in these clusters cannot be defined based on the clusters in Table 3. The raw data of CRs will be clustered again until finding a solution.

Algorithm 2 is developed to determine IR of CRs for the process described in Sections 3.4–3.6 as follows.

Algorithm 2 Determining IR of CRs

1: **input** Number of character in Kano model k; Number of character in ID h; Number of character in SD m; Attribute of CRs t ($t=k+h+m$); Number of CRs n

2: **for** $i =1$ **to** n

3:     **for** $j=1$ **to** t

4:         Forming matrix X

5:     **end for**

6: **end for**

7: **for** $i=1$ **to** n

8:     **for** $j=1$ **to** n

9:         $w_s(v_i, v_j)$ is calculated by Eqs. (9) and (10)

10:         $w_d(v_i, v_j)$ is calculated by Eqs. (11) and (12)

11:         $w_e(v_i, v_j)$ is calculated by Eqs. (13) and (14)

12:         $w_{ij} \leftarrow c \cdot w_s(v_i, v_j) + d \cdot w_d(v_i, v_j) + f \cdot w_e(v_i, v_j)$

13:     **end for**

14: **end for**

15: **for** $i=1$ **to** n

16:     $d_{ii} = \sum_{i=1}^{n} w_{ij}$

17: **end for**

18: Laplace matrix $L \leftarrow D - W$

19: CRs are clustered into 5 clusters using Laplace matrix

20: IR of CRs in each cluster is defined using Table 2

Table 6 CRs based on the IPA-Kano model

CRs	Kano model				IPA model							
	1. Serious injured patients	2. Light injured patients	3. Patients used at home	4. Patients used in hospital	5. ID for serious injured	6. ID for light injured	7. ID for used at home	8. ID for used in hospital	9. SD for used at home	10. SD for used in hospital	11. SD for serious injured	12. SD for light injured
CR.1	M	M	M	M	4.8	4.5	4.6	4.7	2.5	2.8	2.6	2.9
CR.2.	M	O	M	M	4.9	4.6	4.7	4.6	3.9	4.2	4.1	4.1
CR.3	M	M	M	M	4.8	4.4	4.6	4.6	4.1	4.5	4.3	4.5
CR.4	A	O	A	A	4.1	2.9	4.6	2.6	2.6	2.7	2.3	2.6
CR.5	O	A	A	A	3.7	2.5	4.5	2.8	1.9	4.2	4.1	4.2
CR.6	M	M	M	M	4.9	4.9	4.8	4.8	4.5	4.6	4.5	4.6
CR.7	O	O	A	O	2.3	1.8	1.9	2.1	3.3	3.5	3.6	3.6
CR.8	A	A	A	A	4.3	4.4	4.3	4.3	2.5	2.6	2.6	3.6
CR.9	A	A	O	A	1.3	1.4	1.5	1.3	4.2	4.3	4.3	4.2
CR.10	A	O	O	O	2.4	2.8	2.6	2.7	4.6	4.6	4.5	4.6
CR.11	O	O	O	O	2.1	4.2	4.7	2.3	1.8	3.9	2.9	3.3
CR.12	O	O	O	O	4.5	4.6	4.5	4.5	4.2	4.3	4.2	4.2
CR.13	O	O	O	I	2.6	4.2	4.5	2.6	1.4	3.3	3.3	3.2
CR.14	M	M	M	M	4.3	4.6	4.5	4.5	2.4	2.5	2.4	2.5
CR.15	O	O	M	O	1.7	2.2	2.3	1.9	4.3	4.1	4.3	4.2
CR.16	M	M	M	O	4.3	4.0	4.3	2.9	4.2	4.1	4.2	4.2
CR.17	O	A	A	A	1.3	1.5	1.8	1.7	2.1	2.6	2.3	2.5
CR.18	M	M	M	M	4.2	4.0	4.1	4.1	4.2	4.3	4.3	4.3
CR.19	M	O	M	M	4.2	4.3	4.2	4.3	2.5	3.1	2.8	2.9
CR.20	M	O	M	M	4.3	4.1	4.2	4.2	4.2	4.5	4.5	4.3
CR.21	M	O	M	M	4.5	4.4	4.5	4.5	1.7	2.2	1.9	1.8
CR.22	M	O	M	M	1.6	2.1	1.8	1.9	4.2	4.3	4.3	4.3
CR.23	A	A	A	O	2.1	1.7	1.9	2.2	1.2	1.5	1.6	1.7
CR.24	M	M	M	M	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.6
CR.25	M	M	M	M	4.9	4.9	4.8	4.8	4.6	4.5	4.5	4.6
CR.26	M	M	M	M	4.8	4.8	4.9	4.9	4.3	4.6	4.5	4.6
CR.27	I	I	O	I	2.3	2.5	2.4	2.3	4.1	4.2	4.2	4.3
CR.28	A	O	A	A	4.3	4.1	4.3	4.6	2.7	2.9	3.1	2.8
CR.29	A	A	M	A	2.8	2.9	3.1	2.7	3.2	3.1	2.9	3.1

The result for IR of CRs will be used in the QFD method by manufacturing industry to provide useful product functions for improving customer satisfactions and remove unnecessary functions to reduce the manufacturing cost.

4 Case study

Two case studies are conducted using the proposed method to decide IR of CRs in the design of an upper limb rehabilitation device and a feed drive system of the CNC lathe.

4.1 Case study of rehabilitation devices

As upper limb rehabilitation devices are used to recover patients' injured joints, design of a rehabilitation device needs to meet CRs for different patients. Existing rehabilitation devices in the market have problems of product function, structure, size, adaptability, portability, and price. They cannot meet different patient requirements [29]. These problems are caused by the low IR accuracy of CRs in the product design stage. We propose the IR determination method to reduce the dependence of experience and to define IR of CRs accurately.

Based on collected customer needs for upper limb rehabilitation devices [32], 29 CRs are initialized as shown in Table 4.

A questionnaire to collect user personal data, data for Kano, and IPA models is designed using 29 CRs for customers' survey as shown in Table 5. Factors of personal information in questionnaires are selected based on potential factors that may cause conflict attitudes for different patients. A total of 262 patients with the upper limb injury were surveyed using online questionnaires and paper questionnaires in hospitals. A total of 215 questionnaires with completed information are used as raw data in the case study.

Data for the IPA model are normalized using Eq. (1). Data for the Kano model are transferred into numerical attributes based on Eqs. (2) and (3). Values of CRs in groups O, I, and R are defined with a stable value according to the proposed method. The value of O is assigned as 0.6, I as 0.2, and R as 0.1. All the classification results of M and A in the Kano model are transferred into numerical results using Eqs. (2) and (3).

A hypothesis test for the consistency of customer comments was conducted using Eq. (4) and Z-table in the AVOVA method. The results show different comments for CRs classification in the Kano model from patients with different injured levels and using devices in different places. Patients with different injured levels and in different places using devices have also different comments for importance degrees of CRs and satisfactory degrees of CRs in the IPA model. Characters of each CR with 12 parameters are shown in Table 6.

The spectral clustering method divides the similarity of CRs into 5 clusters. Based on data in Table 4, matrix X is formed to represent 29 CRs with 12 attributes using Eq. (5). Laplace matrix L is formed by a diagonal matrix D and similarity matrix W using Eq. (6).

Similarity matrix W is defined based on the similarity of 29 CRs using Eqs. (7) and (8). The distance of 4 categorical attributes of 29 CRs in the Kano model is decided by Eq. (9). The distance of 4 numerical attributes of 29 CRs for the

Table 7 Comparison for 3 existing methods and the proposed method

CRs	Kano model	IPA model	Existing combined IPA and Kano	Proposed IR method
CR.1	M (5)	Concentrate on (5)	Fatal (5)	Very high IR (5)
CR.2.	M (5)	Keep good work (4)	Survival (3)	Middle IR (3)
CR.3	M (5)	Keep good work (4)	Survival (3)	Middle IR (3)
CR.4	A (3)	Low priority (3)	Chronic disease (2)	Very high IR (5)
CR.5	A (3)	Possible overkill (2)	Fitness (1)	Very low IR (1)
CR.6	M (5)	Keep good work (4)	Survival (3)	High IR (4)
CR.7	O (4)	Low priority (3)	Chronic disease (2)	Very low IR (1)
CR.8	A (3)	Concentrate on (5)	Defenseless (1)	Very high IR (5)
CR.9	A(3)	Possible overkill (2)	Fitness (1)	Low IR (2)
CR.10	O (4)	Possible overkill (2)	Fitness (1)	Very low IR (1)
CR.11	O (4)	Low priority (3)	Defenseless (1)	High IR (4)
CR.12	O (4)	Keep good work (4)	Major weapon (4)	Middle IR (3)
CR.13	O (4)	Low priority (3)	Chronic disease (2)	High IR (4)
CR.14	M (5)	Concentrate on (5)	Fatal (5)	High IR (4)
CR.15	O (4)	Possible overkill (2)	Fitness (1)	Very low IR (1)
CR.16	M (5)	Keep good work (4)	Survival (3)	High IR (4)
CR.17	A (3)	Low priority (3)	Chronic disease (2)	Very low IR (1)
CR.18	M (5)	Keep good work (4)	Survival (3)	Middle IR (3)
CR.19	M (5)	Concentrate on (5)	Fatal (5)	High IR (4)
CR.20	M (5)	Keep good work (4)	Survival (3)	Middle IR (3)
CR.21	M (5)	Concentrate on (5)	Fatal (5)	High IR (4)
CR.22	M (5)	Possible overkill (2)	Fitness (1)	Low IR (2)
CR.23	A (3)	Low priority (3)	Chronic disease (2)	Low IR (2)
CR.24	M (5)	Keep good work (4)	Survival (3)	Middle IR (3)
CR.25	M (5)	Keep good work (4)	Survival (3)	Middle IR (3)
CR.26	M (5)	Keep good work (4)	Survival (3)	Middle IR (3)
CR.27	I (2)	Possible overkill (2)	Fitness (1)	Very low IR (1)
CR.28	A (3)	Concentrate on (5)	Defenseless (1)	Very high IR (5)
CR.29	A (3)	Low priority (3)	Chronic disease (2)	Very high IR (5)

importance degree in the IPA model is calculated using Eq. (11). The distance of 4 numerical attributes of 29 CRs in the Kano model is decided by Eq. (13). Based on the result of similarity matrix W, a diagonal matrix D is formed using Eqs. (15) and (16).

According to the feature space built by the first 5 smallest eigenvalues, the K-mean method is used to cluster data in the feature space into 5 clusters. Using the IR determination rules in Table 2, results of 5 clusters are defined as follows.

$$P_1 = \{CR_2, CR_3, CR_{12}, CR_{18}, CR_{20}, CR_{24}, CR_{25}, CR_{26}\} \tag{17}$$

$$P_2 = \{CR_9, CR_{22}, CR_{23}\} \tag{18}$$

$$P_3 = \{CR_5, CR_7, CR_{15}, CR_{17}, CR_{27}\} \tag{19}$$

$$P_4 = \{CR_1, CR_4, CR_8, CR_{10}, CR_{28}, CR_{29}\} \tag{20}$$

$$P_5 = \{CR_6, CR_{11}, CR_{13}, CR_{14}, CR_{16}, CR_{19}, CR_{21},\} \tag{21}$$

IRs of CRs in each group are determined using the proposed rules in Table 2. Values for IRs of CRs in each cluster are shown in Eq. (22).

$$\{P_1, P_2, P_3, P_4, P_5\} = \{3, 2, 1, 5, 4\} \tag{22}$$

The result can then be used in the QFD method for guiding manufacturing companies to determine the function and structure of the upper limb rehabilitation device.

4.2 Solutions and discussion of the rehabilitation device

For verifying advantages of the proposed method, three existing IR methods including the Kano model, IPA model, and existing combined IPA-Kano model are compared with the proposed method in the case study for design of an upper limb rehabilitation device. IRs of CRs for these methods are shown in Table 7.

Based on different IRs of CRs in Table 7, the structure and functions of four rehabilitation devices are designed using QFD and benchmarking methods. As the different IRs of CRs, different IRs of function requirements (FRs) can be defined for four rehabilitation devices using house of quality in the QFD method. The design priority is determined by IRs of FRs. Based on different design priorities, the best components of rehabilitation devices are selected from benchmark products.

Different structures and functions of four rehabilitation devices are shown in Fig. 3 and Table 8. There are 29 CRs in total. 3D models of four devices show the performance of functions related to 19 CRs including CR.1, CR.2, CR.3, CR.6, CR.9, CR.10, CR.11, CR.12, CR.13, CR.14, CR.19, CR.20, CR.21, CR.22, CR.23, CR.24, CR.25, CR.26, and CR.28 in Fig. 3. The product functions related to other 10 CRs are defined and compared by the description in Table 8.

According to the 3D models, the size and weight of the four rehabilitation devices are calculated. D_1 is a 6-DOF

Fig. 3 3D models of four rehabilitation devices

D$_1$: Designed by Kano model

D2: Designed by IPA model

D$_3$: Designed by existing IPA-Kano model

D$_4$: Designed by proposed method
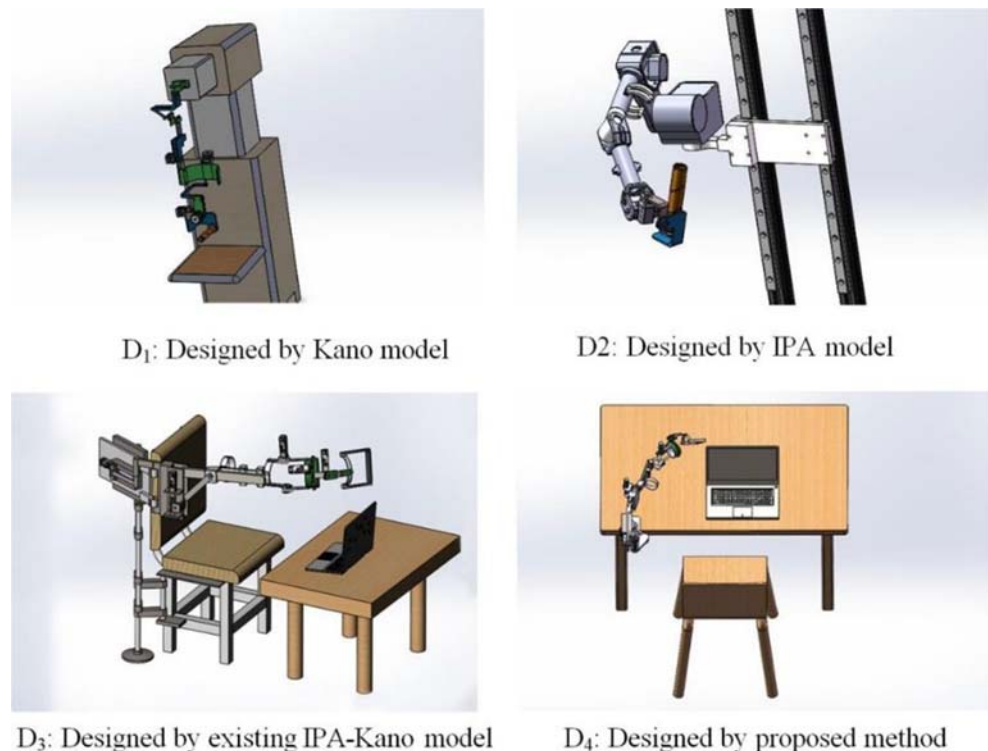
rehabilitation device designed based on IR from the Kano model. The size is $3.5 \times 2.2 \times 1.5$ m^3. The weight is about 110 kg. D_2 is a 7-DOF rehabilitation device designed based on IR from the IPA model. The size is $1.8 \times 1.7 \times 1.4$ m^3. The weight is about 160 kg. D_3 is a 5-DOF rehabilitation device designed based on IR from the existing combined IPA-Kano method. The size is $1.6 \times 1.2 \times 0.9$ m^3. The weight is about 70 kg. D_4 is a 5-DOF rehabilitation device designed based on IR using the proposed IPA-Kano method. The size is $1.4 \times 0.5 \times 0.3$ m^3. The weight is about 35 kg.

The product functions related to other 10 CRs are defined and compared by the description in Table 8. These functions are defined based on IRs of FRs and benchmarking. As functions related to CR.4, CR.5, CR.7, CR.8, CR.17, CR.18, and CR.29 are independent, these functions are defined by IRs of CRs directly. The function related to CR.15 is influenced by the noise of selected motors and rehabilitation device operations. The function related to CR.16 is decided by the cost of raw materials from material suppliers and cost of manufacturing based on the ISO metric standard [33]. The function for CR.27 is provided to meet easy storage of the product.

After determining the structure details and functions of four rehabilitation devices, an analytic hierarchy process (AHP) is used to compare the function implementation for each CR.

AHP is developed to derive ratio scales from pairwise comparisons. The AHP method is applied for 29 times to compare performances of four rehabilitation devices in the case study for meeting the 29 CRs. Based on the design solution of 29 CRs, relationships between values of w_j and 29 CRs in the design of four upper limb rehabilitation devices are compared in Fig. 4. w_j shows the performance of rehabilitation devices.

The average value of w_j shows the performance of the four rehabilitation devices as follows.

$$\{D_1, D_2, D_3, D_4\} = \{0.188, 0.234, 0.261, 0.317\} \qquad (23)$$

In the design of rehabilitation devices based on IR from the Kano model [10], the 6-DOF rehabilitation device only focuses on the basic requirement. Because there are 14 must-be requirements with 5 marks. Functions related to basic requirements have a good performance. However, all the attractive functions such as the movement feedback automatic, rehabilitation data record, and easy maintenance are not considered, which reduces competitiveness of the product.

In the device designed based on IR from the IPA model [13], the IR determination only focuses on two factors of the current important degree and satisfaction degree. Functions

Table 8 Comparisons of the 3 existing methods and proposed method

| 1. D_1 designed by Kano model		2. D_2 designed by IPA model	
CR.4	None	CR.4	Automatic record for displacement and force for patients' arm by sensors.
CR.5	None	CR.5	None
CR.7	Rehabilitation level evaluation	CR.7	Rehabilitation level evaluation
CR.8	None	CR.8	Force sensor with closed loop control
CR.15	Operation noise is about 45 dB	CR.15	Operation noise is about 40 dB
CR.16	$7000–$8000	CR.16	$15,000–$16,000
CR.17	3 different movement gestures	CR.17	15 different movement gestures
CR.18	5 different levels for all patients	CR.18	10 different levels for all patients
CR.27	Store space $2.1 \times 2.1 \times 2.3$ m^3	CR.27	Store space $2.5 \times 2.5 \times 2.6$ m^3
CR.29	None	CR.29	Indicator light for component maintenance
3. D_3 designed by existing Kano-IPA method		**4. D_4 designed by proposed method**	
CR.4	Automatic record only for displacement	CR.4	Automatic record for displacement and force for patients by sensors and screen
CR.5	None	CR.5	None
CR.7	Rehabilitation level evaluation	CR.7	Rehabilitation level evaluation
CR.8	Vision and sound feedback	CR.8	Vision and sound and force feedback
CR.15	Operation noise is about 35 dB	CR.15	Operation noise is about 30 dB
CR.16	$4000–$5000	CR.16	$3000–$4000
CR.17	10 gestures and virtual games	CR.17	15 gestures and virtual games
CR.18	5 different levels for all patients	CR.18	8 different levels for all patients
CR.27	Store space $1.5 \times 1.5 \times 1.6$ m^3	CR.27	Store space $1.5 \times 1.5 \times 1.3$ m^3
CR.29	Indicator light for component maintenance	CR.29	Indicator light for component maintenance and sensor for position error detection
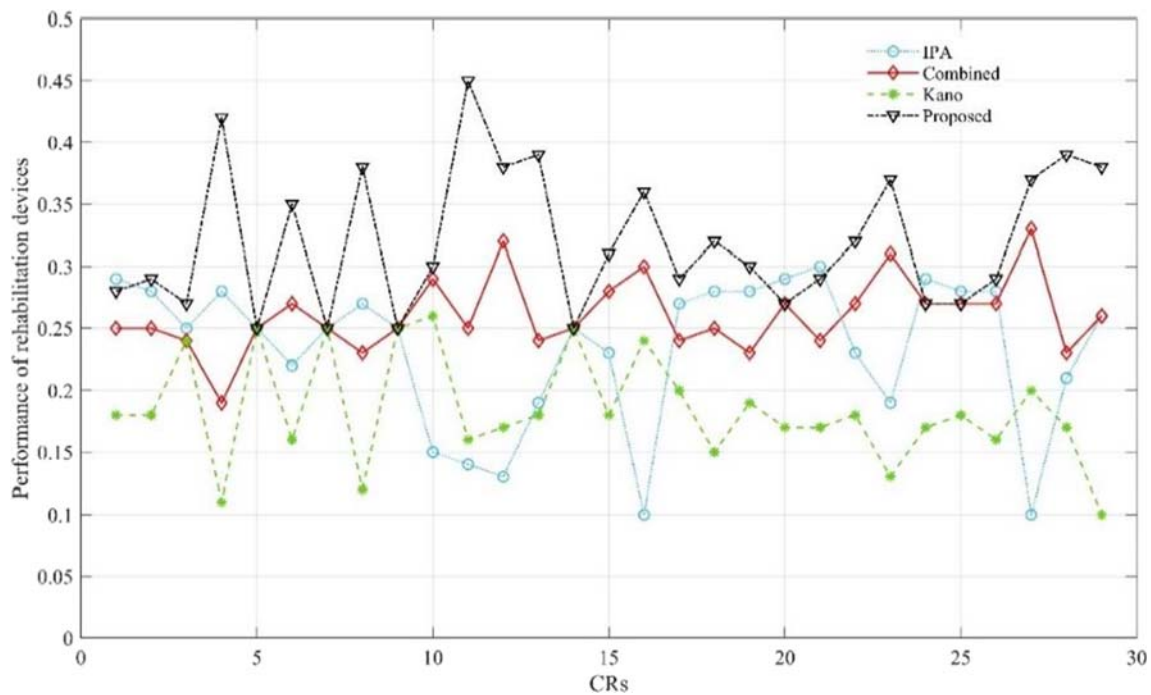
Fig. 4 Relationships between performances of rehabilitation devices and 29 CRs

that are important and not satisfied can get a highest priority. However, some improvements of functions are difficult and costly, which causes many problems for the final design of the device. For example, functions for meeting CR.1 and CR.8 are improved based on the high IR for CR.1 and CR.8. However, the weight, size, and portability for the device are affected seriously because of the function improvement for fully meeting CR.1 and CR.8. Therefore, the design based on IR from the IPA model cannot consider all the important factors to design the device.

In the device designed based on IR from the existing combined IPA-Kano method, the performance of the rehabilitation device is better than devices designed by the Kano and IPA models. The existing combined IPA-Kano method can balance more important factors including the relationship between function implement and customer satisfaction for CRs, current important degree, and satisfaction degree for CRs in the design [19]. However, the IR determination is not accurate for CRs if customers have conflict comments for the CRs. For example, CR.11 belongs to one-dimensional quality with a low important degree and low satisfaction degree. According to the raw data, most of serious injured patients believe that portability is not important for the rehabilitation device, because they cannot complete the rehabilitation exercise by themselves and they do not need to take the device with them. However, most of light injured patients believe that portability is very important for rehabilitation because they can change the position of rehabilitation when

using the device at home. As 60% of patients are serious injured based on the collected data, the average value shows that CR 13 adaptability is not important for patients. Because of the neglect of conflict comments from different customers, IR of CR.13 is not defined accurately.

In the device designed based on IRs using the proposed method, all the important factors are considered and balanced with IRs of CRs accurately. With the accurate IR, the existing design problems are improved with remaining the existing design advantages. For example, the portability is improved by installing the device on a table. Meanwhile, the existing advantages such as the stable movement, easy maintenance, and light weight are remained. Therefore, the performance of D_4 is better than other three devices in many aspects.

As the proposed method considers all the important factors to balance conflict comments of different customers, the overall function performance of D_4 is the best in the four devices. The D_4 design has the highest customer satisfaction with the lowest cost. Therefore, the proposed method has advantages to define IRs of CRs accurately compared with the existing IR methods.

4.3 Case study of a feed drive system in the CNC lathe

A case study of the feed drive system in the CNC lathe is conducted to further verify the proposed method in applications of industrial equipment. A total of 336 engineers and workers in different manufacturing factories were surveyed

Table 9 IR of CRs for the design of feed system in CNC lathe

CRs	Kano model	IPA model	Existing combined IPA and Kano	Proposed IR method
CR.1 High reliability	O (4)	Keep good work (4)	Major weapon (4)	High IR (4)
CR.2 Easy operation	M (5)	Keep good work (4)	Survival (3)	Middle IR (3)
CR.3 High precision	M (5)	Keep good work (4)	Survival (3)	Middle IR (3)
CR.4 Machine safety	M (5)	Keep good work (4)	Survival (3)	Middle IR (3)
CR.5 Operator safety	M (5)	Concentrate on (5)	Fatal (5)	Very high IR (5)
CR.6 Easy to install	I (2)	Possible overkill (2)	Fitness (1)	Very low IR (1)
CR.7 Automatic control	A (3)	Concentrate on (5)	Defenseless (1)	High IR (4)
CR.8 Surface roughness	O (4)	Keep good work (4)	Major weapon (4)	High IR (4)
CR.9 Low vibration	M (5)	Concentrate on (5)	Fatal (5)	Very high IR (5)
CR.10 High energy efficiency	O (4)	Keep good work (4)	Major weapon (4)	High IR (4)
CR.11 Movement feedback	M (5)	Concentrate on (5)	Fatal (5)	High IR (4)
CR.12 Easy for delivery	I (2)	Low priority (3)	Fitness (1)	Middle IR (3)
CR.13 Low maintenance cost	O (4)	Keep good work (4)	Major weapon (4)	High IR (4)
CR.14 Easy maintenance	M (5)	Concentrate on (5)	Fatal (5)	Very high IR (5)
CR.15 Quiet	O (4)	Keep good work (4)	Major weapon (4)	Very high IR (5)
CR.16 Cutting fault detection	A (3)	Concentrate on (5)	Defenseless (1)	Very high IR (5)
CR.17 Fast cooling	A (3)	Low priority (3)	Chronic disease (2)	Very low IR (1)
CR.18 Long machining range	O (4)	Keep good work (4)	Major weapon (4)	Middle IR (3)
CR.19 High feed depth	A (3)	Concentrate on (5)	Defenseless (1)	Very high IR (5)
CR.20 Automatic tool change	O (4)	Keep good work (4)	Major weapon (4)	Very high IR (5)
CR.10 Reasonable price	O (4)	Keep good work (4)	Major weapon (4)	High IR (4)
CR.22 Remote operation	I (2)	Possible overkill (2)	Fitness (1)	Very low IR (1)
CR.23 Durability	O (4)	Keep good work (4)	Major weapon (4)	Very high IR (5)

using online questionnaires and paper questionnaires with 23 CRs in the first column of Table 9. A total of 273 questionnaires with completed information are used as raw data in the case study.

By a hypothesis test using Eq. (1) to Eq. (4), results show different comments for CR classifications in the Kano model from customers in light and heavy industries. Customers with different frequencies and different places using the feed drive system also have different comments for importance degrees of CRs and satisfactory degrees of CRs in the IPA model. Based on the proposed method using Eq. (5) to Eq. (16), the result is shown in the last column of Table 9.

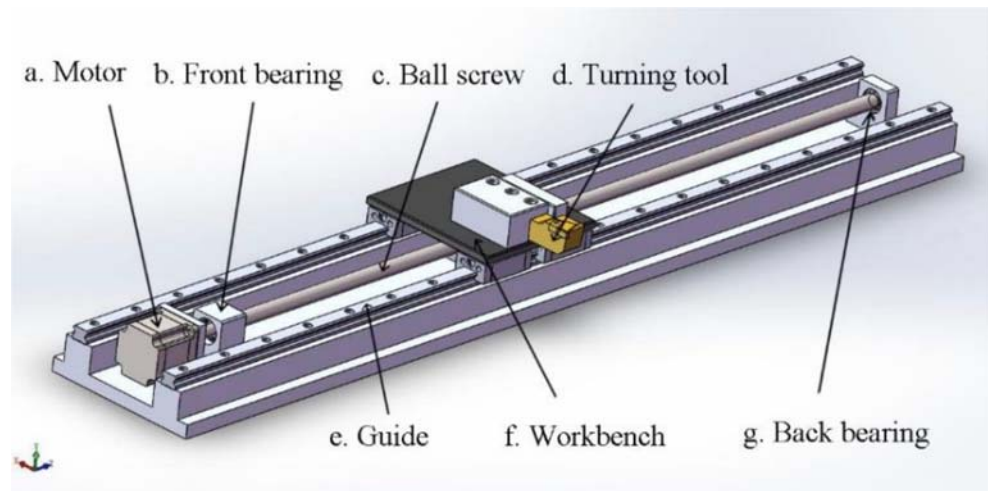**Fig. 5** Basic structure of the feed drive system

a. Motor   b. Front bearing   c. Ball screw   d. Turning tool

e. Guide   f. Workbench   g. Back bearing

Table 10 Structures and parameters of four feed drive systems

1. F_1 designed by Kano model		2. F_2 designed by IPA model	
a	Semi-closed-loop servo motor	a	Closed-loop servo motor
b	Cylindrical roller bearing	b	Two-way thrust angular contact bearings
c	Single nut ball screw with outside loop	c	Double nut ball screw with inner loop
d	Forming turning tool	d	Indexable turning tool
e	Double slide guide	e	Double slide guide
f	V-slot workbench	f	T-slot workbench
g	Cylindrical roller bearing	g	Two-way thrust angular contact bearings
3. F_3 designed by existing Kano-IPA method		4. F_4 designed by proposed method	
a	Closed-loop servo motor	a	Closed-loop servo motor
b	Angular contact bearing	b	Angular contact bearing
c	Single nut ball screw with outside loop	c	Single nut ball screw with outside loop
d	Forming turning tool	d	Indexable turning tool
e	Double slide guide	e	Double slide guide
f	T-slot workbench	f	T-slot workbench
g	Angular contact bearing	g	Angular contact bearing

Based on different IRs of CRs in the last column of Table 9, structures and functions of the feed drive system are proposed using QFD and benchmarking methods.

4.4 Solutions and discussion of the feed drive system

Design solutions are evaluated to compare three existing IR methods and the proposed method. The basic structure of a feed drive system in the CNC lathe is shown in Fig. 5.

For a feed drive system, most CRs are met by the selection of parts from a to g in Fig. 5. Therefore, the design mainly focuses on the selection of these parts. Based on different IRs of CRs in Table 9, design solutions of four feed drive systems are listed in Table 10.

For comparing four design solutions in Table 10, performance measures are evaluated as shown in Table 11. The cost is decided based on quotations from suppliers. Stiffness, positioning accuracy, and maximum feed depth are calculated based on parameters of selected components such as ball screw, bearing, and guide.

In the solution based on the Kano model, the design mainly focuses on CRs in the must-be group. Most of the attractive

requirements such as CR.7 and CR.17 are ignored. In the solution based on the IPA model, the design is mainly improvement for CRs that are important and not satisfied. However, CRs such as CR.9 and CR.15 in concenter on group of IPA model are difficult to improve. In addition, improvement of these CRs is also costly, which affects the final design seriously. In the design based on the existing combined IPA-Kano method, the IR determination is not accurate for CRs that have conflict comments from different customers, such as conflict comments of different customers for CR.19 from light and heavy industries. However, the maximum feed depth related to CR.19 is not enough for light industries such as furnishing and textile companies, which reduces the efficiency significantly.

Comparing with above three existing methods, the proposed method can provide a better performance on the design solution because comments from different customers for CRs are balanced accurately. For example, the design by the proposed method has a high accuracy of operations and the large feed rate by selecting a suitable ball screw. Therefore, the system can meet requirements for the high accuracy from heavy industries and large feed rate from light industries at

Table 11 Solutions of the feed drive systems

Technical parameters	F1 designed by Kano model	F_2 designed by IPA model	F_3 designed by existing combined IPA and Kano	F_4 designed by proposed IR method
Cost (USD)	4500	6000	3900	3700
Stiffness (N/um)	320	630	480	650
Positioning accuracy (mm)	± 0.020 mm	± 0.010 mm	± 0.015 mm	± 0.010 mm
Maximum feed depth (mm)	5.0 mm	7.0 mm	6.0 mm	9.0 mm
Material to be machines	Steel, aluminum	Steel, aluminum, alloy steel	Steel, aluminum	Steel, aluminum, alloy steel
Axis feedback	Semi-closed-loop	Close loop	Close loop	Close loop

the same time. Therefore, the design can satisfy more customers to improve competitiveness of the product.

In the two case studies, different IRs of CRs lead to different design solutions to best meet customer requirements. Therefore, the proposed IR determination method contributes the product development and finally improves product quality and customer satisfaction.

5 Conclusions and further work

This research proposed a new IR determination method to meet CRs in the QFD method. CRs were classified by a spectral clustering method based on categorical attributes in the Kano model and numerical attributes in the IPA model. A Laplacian matrix was designed to improve accuracy of the classification by considering the conflict comments from different customers. Results of the classification were used to define IR of CRs. The IR of CRs was used in QFD for manufacturing companies to define product function, structure, and manufacturing process.

For verifying advantages of the proposed method, four upper limb rehabilitation devices and four feed drive systems were designed based on IRs of CRs using three existing IR determination methods and the proposed method. Results show that the design of rehabilitation devices and feed drive systems based on IRs of CRs from the proposed method has the best function for completing the rehabilitation exercise or machining operations. Therefore, the proposed method can determine IRs of CRs accurately to improve competitiveness of both consumer and industrial products for manufacturing industries.

Main contributions of this paper are summarized as follows. (1) Efficiency of defining IR of CRs is improved by clustering CRs automatically using a spectral clustering method. (2) Accuracy of defining IR of CRs is improved by combining different comments of customers using a similarity matrix in the spectral clustering method. (3) Industry can improve customer satisfactions in the product design using the accurate IR of CRs decided by our proposed method.

The future work will consider other factors based on different stakeholders. The environment requirements can be combined with customer requirements to further improve the proposed IR determining method for guiding the product design and manufacturing. Data mining methods will be applied to improve understanding customers for customer classifications and changeable requirement predictions.

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