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Domain Mapping of Product Service System Oriented on CNC Machine Tools

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Abstract: Product service system is the organic combination of product and services to adapt to the development needs of service-based society. The mapping between requirement domain, function domain, technology domain is an important approach for transferring customer requirements in the development process of product service system. Firstly, this paper determines the composition of requirement domain, function domain and technology domain, and constructs a model of mapping relationship and method between domains. Then, determining the weights of customer requirements based on RAHP (Rough Analytic Hierarchy Process), this paper constructs the requirement-function HoQ (House of Quality) and the function-technology HoQ based on the theory of Quality Function Deployment, completes the consistency test based on relevant analysis, and improves the quality target value of HoQ. Finally, this paper builds an integrated architecture of product service system based on relevance recognition between product modules and service modules. Taking ETC (Economic Turning Center) series CNC (Computer Numerical Control) machine tools as an example, the proposed method in this paper is verified.

Keywords: Product service system, Domain mapping, Quality function deployment, House of quality, CNC machine tools.

1. INTRODUCTION

With the rapid development of world economy, the consumption mode of human society has shifted from the industrial society consumption mode, mainly consisting of tangible products, into the service-based society consumption mode, mainly consisting of intangible services. Emphasizing personalization and service experience becomes the main characteristics of this social consumption mode. The proportion of service industry in national economy is growing, and plays more and more important role. The competition in manufacturing field becomes increasingly fierce, which forces manufacturing enterprises of tangible products to put more energy from the manufacturing of tangible products to the offering of intangible services.

The concept of product service system (PSS) first appeared in the middle 90's of the 20th century. At the beginning of the 21th century, United Nations Environment Program stated the important role of PSS in sustainable development. Then PSS became one of the widely studied issues in international academic and industry (Beuren el al., 2013; Meier el al., 2011; Aurich el al., 2006). The key idea of PSS is that what consumers need is not specific products but functions provided by product and services (Gessa-Perera et al., 2014). PSS meets consumer requirements through the integration of all resources, which plays an important role in improving social production and living standard, enterprise value-adding, environmental protection, etc.

The development of product service system is more complex, which includes many design phases that involve many design factors. In order to ensure the development of product service system running smoothly, it is needed to clarify the connection and check the rationality between design elements of all stages (Martin-Erro et al., 2015). The realization of domain mapping of product service system can well express the connection between requirement domain, function domain and technology domain, which is an important approach for transferring customer requirements in the development process of product service system.

CNC (Computer Numerical Control) machine tools are the key equipments of manufacturing industry and the carriers of advanced manufacturing technology. This paper takes ETC (Economic Turning Center) series CNC machine tools as an example, and studies the domain mapping of product service system. Firstly, this paper determines the composition of requirement domain, function domain and technology domain, and constructs a model of mapping relationship and method between domains. Then, determining the weights of customer requirement based on RAHP (Rough Analytic Hierarchy Process), this paper constructs the requirement-function HoQ (House of Quality) and function-technology HoQ based on the theory of Quality Function Deployment, completes the consistency test based on relevant analysis, and improves the quality target value of HoQ. Finally, this paper builds an integrated architecture of product service system based on relevance recognition between product modules and service modules.

2. LITERATURE REVIEW

Product service system is an organic combination of product, services and related support equipment, which brings services and product together through certain strategies. Product service system can meet the full range of customer requirements, improve the market competitiveness of products, and reduce the impact of consumption on environment. Studying the design process of product service system need clarify the design factors in each stage, reasonably express the relationship among design stages, then improve the design process constantly, finally finish the design of product service system. The main methods of product design include systematic design, axiomatic design, TRIZ (Theory of Inventive Problem Solving) theory and Quality Function Deployment (QFD) (Chen and Ko, 2010). In this paper, QFD method is used to study the design process of product service system.

As a customer requirements-centered design method, QFD has mainly three kinds of patterns accepted widely. Among them, four-stage ASI (American Supplier Institute) model corresponds to general product development process, which includes product planning, product design, process design and production plan. In the whole process of product development, customer requirements are gradually divided into design requirements, parts characteristics, process characteristics and production requirements (Yan-Jie LV et al., 2013). Hwaring proposed three-stage QFD mode of service design, which includes service planning, elements planning and production planning (Hwarng and Teo, 2000). Geng proposed a three-domain PSS conceptual design framework based on QFD (Geng et al., 2010). Zaim proposed a hybrid analytic network process (ANP)-weighted fuzzy methodology with the goal of synthesizing renowned capabilities of ANP and fuzzy logic to better rank technical characteristics of a product (or a service) while implementing QFD (Zaim et al., 2014).

Germani presented a method to define and evaluate a co-design platform dedicated to SMEs in mechanical product field and adopted QFD to manage correlation between process metrics, software functionalities and specific collaboration requirements (Germani et al., 2012). Bereketli proposed a multi aspect QFD for Environment to identify the improvement strategies by considering not only the end users' requirements but also the environmental stakeholders' ones and applied Fuzzy Analytic Hierarchy Process (FAHP) Extent Analysis approach to define the priorities of all stakeholders' requirements (Bereketli and Genevois, 2013; Turan, 2014). Zhai extended the fuzzy QFD methodology using rough set theory with the aim to facilitate decision making in the early stages of product development and combined fuzzy arithmetic operations with two novel concepts, which are rough number and rough boundary interval (Zhai et al., 2010).

In summary, QFD can not only guide the whole process of product design but also guide the whole process of service design. Related study provided useful reference to realize design process of product service system. QFD can be used in the design process of product service system.

3. DOMAIN MAPPING MODEL OF PRODUCT SERVICE SYSTEM

3.1 Domains for product service system design

The concept of domain is derived from axiomatic design. The theory of axiomatic design thinks that in design process the design problem can be divided into consumer domain, function domain, physical domain and process domain. Each domain includes multiple elements such as customer requirements, function requirements, design parameters and process variables. The domain is essentially a set of design elements for each design stage. According to design process, by transforming the parameters through the mapping between adjacent design stages, the design is completed.

This paper combines the concept and idea of domain in axiomatic design, and divides the design process of product service system into three stages including requirements acquisition, function decomposition and technology implementation, which respectively correspond to requirement domain, function domain and technology domain. The full process from obtaining customer requirements to meeting customer requirements is achieved by domain mapping, and the design of product service system is completed finally.

3.2 Domain mapping model of product service system

The requirement domain, function domain and technology domain are the basic elements of product service system design, which are not independent but gradually transform from the customer requirements to the characteristics of related technologies through domain mapping. In order to clearly express the mapping process, it is needed to describe the mapping relationship and method between them. Therefore the model of mapping relationship and the model of mapping method are established respectively.

(1) Model of mapping relationship between domains

The mapping relationship between domains mainly expresses the connection between domain elements, which including domain elements, mapping sequence and mapping relationship, etc.. This paper describes the mapping relationship between domain elements with the model as shown in Fig. 1.

As can be seen from Fig. 1, first it is the mapping process from requirement domain to function domain, then it is the mapping process from function domain to technology domain. Requirement domain is the set of product requirements and service requirements. Function domain is the set of service function characteristics and product function characteristics. Technology domain is the set of product modules and service modules. Although while expressing the domain elements of each domain, product elements are separated from service elements, there are not clear boundaries between product elements and service elements in same domain. There are intersections between product elements and service elements, which reflects the interaction of product and services. The mapping relationship between domain elements includes one-to-one, one-to-many, many-to-one, and so on.

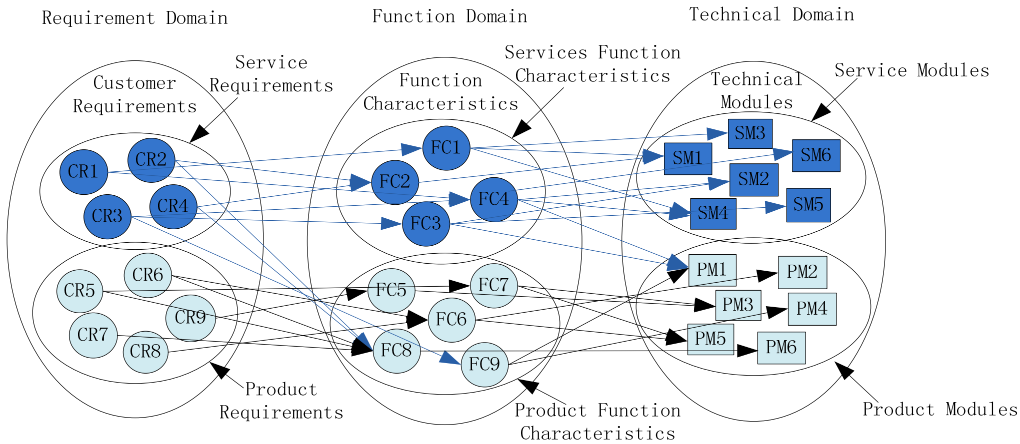


Fig. 1. Mapping relationship between domains of product service system.

(2) Model of mapping method between domains

The expression of mapping relationship between domains in Fig. 1 is just at the conceptual level, which does not show the mapping method between domains. So this paper determines the mapping method between domains of product service system based on QFD as shown in Fig. 2. QFD is both a kind of idea and a kind of method for product development and quality management. The core of QFD is the transmission and conversion of customer requirements, which is realized using a core tool named House of Quality (HoQ).

In Fig. 2, two-stage HoQ is used to express the mapping method between domains, of which the left is the first stage and the right is the second stage. The whole mapping process reflects the mapping method driven by customer requirements. The first stage of HoQ shows the relationship between customer requirements and product functions as well as service functions, and the relationship between product function characteristics and service function characteristics. Then the weights of customer requirements are passed to product function characteristics and service function characteristics, and the first delivery and distribution of customer requirements is finally realized. The second stage shows the relationship between product function characteristics as well as service function characteristics and product modules as well as service modules, and the relationship between product modules and service modules. The transfer of function weights to technical characteristic weights is realized finally.

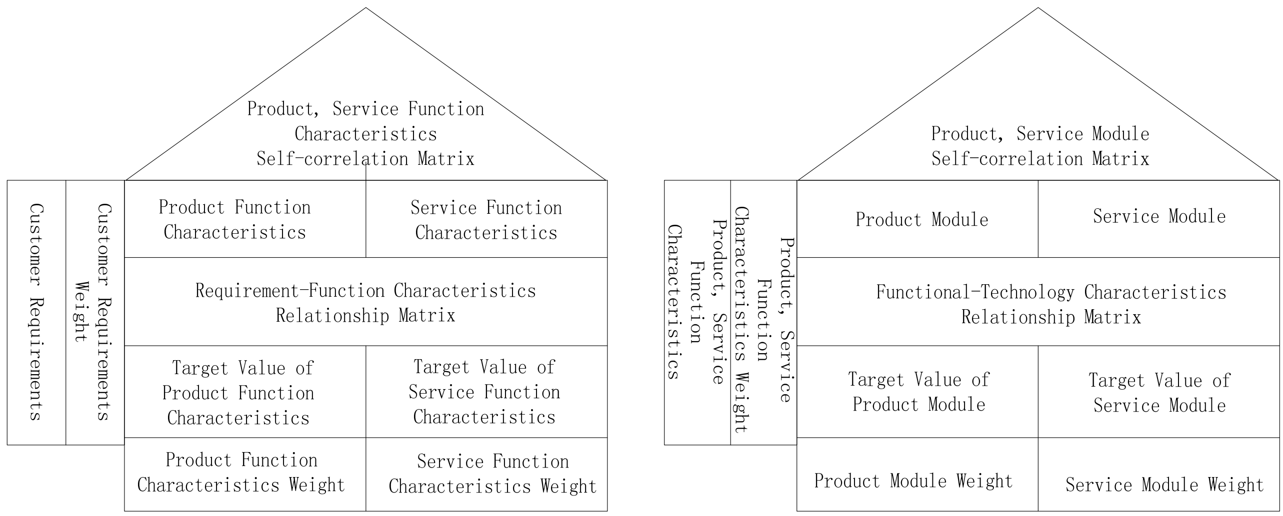


Fig. 2. HoQ-based mapping method between domains of product service system.

3.3 *Determination of the weights of customer requirements based on RAHP*

When using QFD to express the mapping relationship among requirement domain, function domain and technology domain, the importance of customer requirements should be first considered. The weights of customer requirements are important to analyze requirement-function HoQ and function-technology HoQ. AHP is a classical method to determine the weights of customer requirements. But the analysis results depend on the subjective judgment because of the lack of quantitative data. This paper combines AHP with rough sets theory, and introduces the idea of group decision-making to determine the weights of customer requirements, which is named as Rough Analytic Hierarchy Process (RAHP). This method not only inherits the characteristics of AHP that is good at treating complex hierarchy indicator structure, but also combines the advantages of rough set theory that does well in expressing fuzzy information and group decision-making.

Determine the weights of customer requirements based on RAHP as follows:

(1) Construct the customer requirements structure tree

Customer requirements structure tree is a structure to make customer requirements be hierarchical. The higher the level is, the fuzzier the requirements information is. The lower the level is, the clearer the requirements information is.

(2) Build the judgment matrix of customer requirements

According to the customer requirements structure tree, the questionnaire oriented on AHP is designed, which allows customers to grade the requirements of every level, then builds the judgment matrix of customer requirements. If there is a target with n indicators and m customers participate in grading, m questionnaires can be obtained about the n indicators. The judgment matrix of customer requirements is shown in (1).

$$A_i = \begin{bmatrix} 1 & a_{12}^i & \cdots & a_{1n}^i \\ a_{21}^i & 1 & \cdots & a_{2n}^i \\ \vdots & \vdots & \cdots & \vdots \\ a_{n1}^i & a_{n2}^i & \cdots & 1 \end{bmatrix} \quad (1)$$

where, $i \in [1, m]$, A_i express the judgement matrix of the ith customer on the n indicators at certain level.

(3) Build the rough group decision-making matrix

If m judgement matrix for each target requirement at every level passes the consistency test, then all the views of customers are integrated into one matrix to construct the rough group decision-making matrix as shown in (2).

$$A^* = \begin{bmatrix} 1 & a_{12}^* & \cdots & a_{1n}^* \\ a_{21}^* & 1 & \cdots & a_{2n}^* \\ \vdots & \vdots & \cdots & \vdots \\ a_{n1}^* & a_{n2}^* & \cdots & 1 \end{bmatrix} \quad (2)$$

where, $a_{21}^* = \left\{a_{21}^1, a_{21}^2, \cdots, a_{21}^m\right\}$, and the other elements are in similar fashion.

(4) Calculate the fuzzy pairwise comparison matrix

While calculating the fuzzy pairwise comparison matrix, it is first needed to transform each element of rough group decision-making matrix into rough numbers. Taking a_{21}^* element of the group decision-making matrix as an example, the rough number corresponding to ith element in a_{21}^* is solved as

$$RN(a_{21}^i) = \left[\underline{Lim}\left(a_{21}^i\right), \overline{Lim}\left(a_{21}^i\right)\right]$$

where $i \in [1, m]$. In order to facilitate the expression, the rough numbers of the ith element is expressed as $RN(a_{21}^i) = \left[a_{21}^{i-}, a_{21}^{i+}\right]$, the rough number of a_{21}^* is

$$RN(a_{21}^*) = \left\{\left[a_{21}^{1-}, a_{21}^{1+}\right], \left[a_{21}^{2-}, a_{21}^{2+}\right], \cdots, \left[a_{21}^{m-}, a_{21}^{m+}\right]\right\}$$

After obtained the rough number of each element of rough group decision-making matrix, it is also needed to calculate the average rough interval of all elements. Average rough interval includes average rough lower limit and upper limit. If $RN_i=[L_i, U_i]$ and $RN_j=[L_j, U_j]$ are two rough numbers, L_i and L_j are their rough lower limit, U_i and U_j are their rough upper limit. $L_i, U_i, L_j, U_j \in \mathrm{R}^+$, and k is nonzero constant. Then some related algorithms are as follows,

$$RN_i + RN_j = \left[L_i, U_i\right] + \left[L_j, U_j\right] = \left[L_i + L_j, U_i + U_j\right] \quad (3)$$

$$RN_i - RN_j = \left[L_i, U_i\right] - \left[L_j, U_j\right] = \left[L_i - U_i, L_j - U_j\right] \quad (4)$$

$$RN_i \times RN_j = \left[L_i, U_i\right] \times \left[L_j, U_j\right] = \left[L_i \times U_i, L_j \times U_j\right] \quad (5)$$

$$k \times RN_i = k \times \left[L_i, U_i\right] = \left[kL_i, kU_i\right] \quad (6)$$

According to above algorithms, when getting the rough numbers of all elements, it can obtain the average rough interval corresponding to each element in rough group decision-making matrix. If the average rough interval is expressed as $RN(a_{21}) = [a_{21}^-, a_{21}^+]$, a_{21}^- and a_{21}^+ represent the average rough lower limit and upper limit respectively, so it can get the average rough lower limit and upper limit

$$a_{21}^- = \left(a_{21}^{1-} + a_{21}^{2-} + \cdots a_{21}^{m-}\right)/m \quad (7)$$

$$a_{21}^+ = \left(a_{21}^{1+} + a_{21}^{2+} + \cdots a_{21}^{m+}\right)/m \quad (8)$$

According to (7) and (8), it can get the average rough lower limit and upper limit of each element. The rough pairwise comparison matrix is composed of average rough interval as shown in (9).

$$A = \begin{bmatrix} [1,1] & \left[a_{12}^-, a_{12}^+\right] & \cdots & \left[a_{1n}^-, a_{1n}^+\right] \\ \left[a_{21}^-, a_{21}^+\right] & [1,1] & \cdots & \left[a_{2n}^-, a_{2n}^+\right] \\ \vdots & \vdots & \cdots & \vdots \\ \left[a_{n1}^-, a_{n1}^+\right] & \left[a_{n2}^-, a_{n2}^+\right] & \cdots & [1,1] \end{bmatrix} \quad (9)$$

(5) Compute the weights of customer requirements at each level

The rough pairwise comparison matrix is divided into rough lower matrix A^- and rough upper matrix A^+. The eigenvalues and eigenvectors are calculated respectively, and then normalized. Finally the average value of the weights for each indicator is calculated. The weights for n indicators at certain target layer are as follows

$$w^- = \left[\omega_1^-, \omega_2^-, \cdots, \omega_n^-\right]^T \quad (10)$$

$$w^+ = \left[\omega_1^+, \omega_2^+, \cdots, \omega_n^+\right]^T \quad (11)$$

$$f_j^- = \omega_j^- / \sum_{j=1}^{n} \omega_j^- \quad (12)$$

$$f_j^+ = \omega_j^+ / \sum_{j=1}^{n} \omega_j^+ \quad (13)$$

$$f_j = \frac{1}{2}\left(\left|f_j^-\right| + \left|f_j^+\right|\right) \quad (14)$$

where, $i \in [1, n]$, f_j^- represents the weight of jth indicator in rough lower limit matrix, f_j^+ represents the weight of jth indicator in rough upper limit matrix, and f_j represents the average rough weight of the jth indicator.

(6) Compute the final weights of customer requirements

For the indicators corresponding to each target at every level of hierarchical customer requirements tree, the step (1) - (5) are repeated to complete the calculation of average rough weights. Then the final weights of customer requirements are got by integrating the weights at each level of customer requirements structure tree. It is calculated by multiplying the weights of customer requirements corresponding to each layer with the weights of customer requirements corresponding to sub-level. Assume that customer requirements is divided into three levels, which is labelled as *T*, *M*, *CR* from top to bottom, then the weight calculation of the *i*th requirement at *CR* layer is as follows: if the *i*th indicator of *CR* layer belongs to the *j*th index at *M* layer, and the *j*th indicator at *M* layer belongs to the *k*th indicator at *T* layer, it can get

$$f_{CR_i}^* = f_{T_k} \times f_{M_j} \times f_{CR_i} \quad (15)$$

where, $f_{CR_i}^*$ is the final weight of the *i*th indicator at *CR* layer (bottom), f_{T_k} is average rough weight of the *k*th indicator at *T* layer (top), f_{M_j} is average rough weight of the *j*th indicator at *M* layer, and f_{M_j} is average rough weight of the *i*th indicator at *CR* layer (bottom).

4. EXPRESSION OF DOMAIN MAPPING RELATIONSHIP OF PRODUCT SERVICE SYSTEM

Expression of mapping relationship among requirement domain, function domain and technology domain of product service system includes building HoQ, checking the consistency of HoQ, converting requirements weights and determining the target values of quality characteristics, etc..

4.1 Two-phase HoQ modeling

In order to clearly express the mapping relationship among requirement domain, function domain and technology domain, it is needed to carry out QFD analysis. Aiming at the design process of product service system, the two-stage mapping is applied in order to accomplish the transformation from the obtainment of customer requirements to the realization of customer requirements at last. Therefore this paper constructs two-stage HoQ to achieve the expression of domain mapping relationship of product service system. The two-stage HoQ includes the requirement-function HoQ and the function-technology HoQ.

(1) Build requirement-function HoQ

Requirement-function HoQ mainly completes the conversion from customer requirements to function requirements. After obtaining the requirement domain and function domain, the relationship matrix is constructed by analyzing the relationship between customer requirements and function characteristics, and the correlation matrix is constructed by analyzing the interaction between function characteristics. Then the first phase of HoQ is completed.

(2) Build function-technology HoQ

Function-technology HoQ is the second stage of domain mapping of product service system, of which the main role is to undertake the first stage of HoQ, and transforming function characteristics into corresponding technology characteristics. After obtaining function domain and technology domain, the relationship matrix is constructed by analyzing the relationship between function characteristics and technology characteristics, and the correlation matrix is constructed by analyzing the interaction among technology characteristics. Then the second phase of HoQ is completed.

4.2 HoQ analysis and planning

After constructing the two-stage HoQ, HoQ analysis is done by using related data. The HoQ analysis for domain mapping includes checking the consistency, determining the weights of quality characteristics, and determining the target value of quality characteristics.

1) HoQ consistency test

The HoQ consistency refers to the consistency between the self-correlation matrix of quality factors and the relational matrix of quality requirements with quality factors. This paper uses correlation analysis theory to check the HoQ consistency, and the basic process is as follows.

(1) The relationship matrix and the self-correlation matrix of requirement-function HoQ and function-technology HoQ are normalized. For the relationship matrix, 1 represents the strongest correlation, 0.7 represents strong correlation, 0.5 represents medium strong, 0.3 represents weak correlation. For the self-correlation matrix, 3 represents strong association, 1 represents weak association.

(2) Calculate the similarity coefficient. According to the related information about the relationship matrix and the self-correlation matrix in normalized HoQ, the similarity coefficient of relation strength in the relationship matrix column for quality characteristics QC_{j1} and QC_{j2} is calculated by (16)

$$s_{j_1 j_2} = 1 - \frac{\sum_{i=1}^{m} \left|r_{ij_1} - r_{ij_2}\right|}{k} \quad (16)$$

where, r_{ij1} represents the relation strength of *i*th quality requirements and the j_1th quality characteristics, r_{ij2}

represents the relation strength of ith quality requirements and the j_2th quality characteristics, k represents the number of quality requirements which have relationship with the j_1th or j_2th quality characteristics, n represents the number of relationship strength comparision. Among them, $0 \leqslant s_{j1j2} \leqslant 1$, $s_{j1j2}=0$ represents not similar completely, $s_{j1j2}=1$ represents exactly the same.

(3) Calculate the relation coefficient r_{cs} between the self-correlation strength c_{j1j2} and the similarity coefficient s_{j1j2} by (17)

$$r_{cs} = l_{cs} / \sqrt{l_{cc} \times l_{ss}} \tag{17}$$

where,

$$l_{cc} = \sum c_{j_1 j_2}^2 - \frac{1}{n}\left(\sum c_{j_1 j_2}\right)^2 \tag{18}$$

$$l_{ss} = \sum s_{j_1 j_2}^2 - \frac{1}{n}\left(\sum s_{j_1 j_2}\right)^2 \tag{19}$$

$$l_{cs} = \sum c_{j_1 j_2} s_{j_1 j_2} - \frac{1}{n}\left(\sum c_{j_1 j_2} . \sum s_{j_1 j_2}\right) \tag{20}$$

n is the number of quality characteristics pairs that have relationship in HoQ, c_{j1j2} represents the self-correlation strength of quality characteristics QC_{j1} and QC_{j2}, s_{j1j2} represents the similar coefficient of quality characteristics QC_{j1} and QC_{j2}. r_{cs} represents the relation strength of quality characteristics and the strength of similarity coefficient, $-1 \leqslant r_{cs} \leqslant 1$. When $r_{cs}=0$, there is no relation between the correlation strength and the similarity coefficient of quality characteristics. When $r_{cs}>0$, there is positive relation. When $r_{cs}<0$, there is negative relation.

(4) Hypothesis test

Make hypothesis test of the similarity coefficient r_{cs} between the correlation strength and the similarity coefficient by T test method as (21)

$$t = r_{cs}\sqrt{n-2} / \sqrt{1-r_{cs}^2} \sim t_{n-2} \tag{21}$$

If the hypothesis test of $r_{cs}=0$ is not passed, it indicates that there is positive relation between the correlation strength c_{j1j2} and the similarity coefficient s_{j1j2}, then the HoQ consistency test can get through. Otherwise, it indicates that there is inconsistency and HoQ should be modified.

2) Weight conversion of quality characteristics and target value determination

When the consistency test of requirement-function HoQ is passed, it indicates that the function characteristics in function domain are reasonable and meet all customer requirements, and function domain can be further mapped into technology domain. When the consistency test of function-technology HoQ is also passed, it indicates that the division granularity of service modules and product modules is consistent, and the elements of technology domain are able to meet the function requirements, which means that the specific technology measures of product service system can meet customer requirements. Next, the designers can make decisions on HoQ and determine the weight and target values of function characteristics and technology characteristics.

For requirement-function HoQ, the quality characteristics are composed of a series of function characteristics. For the description of function characteristics, the quantitative method and qualitative method are combined. The target values of quality characteristics is determined by combining qualitative description with quantitative description. For qualitative description seven fuzzy variables are used: "VL (very low)", "L (low)", "ML (lower)", "M (medium)", "MH (higher)", "H (high)" and "VH (very high)". For quantitative description, specific value is used according to the property of functional characteristics.

For function-technology HoQ, the quality characteristics are composed of product modules and service modules. The description of module target values includes qualitative method and quantitative method. The target value of product module is mainly described according to its attribute. There are two main types: the first is the attributes about function, geometric size, material and so on; the second is the attributes about object structure, assembly, interface, and so on. Service module is different from product module, of which the target value determination is connected with the factors that influence service value. Service value may be qualitative or quantitative. Qualitative factors include service quality and service mode. For qualitative description, fuzzy variable with seven grades is used to do it. For quantitative description the value is given according to actual situation.

5. CASE ANALYSIS

This paper takes the product service system design of ETC series CNC machine tools as an example. Based on QFD, the mapping from requirement domain to function domain and from function domain to technology domain are achieved successively, and the rationality and effectiveness of quality characteristics including function characteristics and technology characteristics are analyzed, which lays the foundation for configuration design of product service system.

5.1 Determination of requirement domain, function domain and technology domain

(1) Requirement domain

In product service system, the requirement domain is the set of all customer requirements. Requirement domain includes both technology requirements and service requirements. Selecting the customers of ETC series horizontal CNC machine tools to take customer survey, and combining previous customer requirements information of the enterprises, the requirements information about products and services of ETC series horizontal CNC machine tools is collected, which is divided into three levels by KJ method as shown in Fig. 3.

(2) Function domain

In product service system, function domain is the set of product functions and service functions obtained by converting function requirements, which can cover the customer needs. Overall product function is decomposed into a series of product functions, which form the product function structure tree. Overall service function is decomposed into a series of service functions, which form the service function structure tree. All product functions and service functions are the corresponding transformation results of customer requirements. For ETC series CNC machine tools, fifteen functions are obtained including cutting function, feed function Z, feed function X, positioning and supporting function, control function, safety protection function, detection function, intelligent monitoring function, man-machine interactive function, distribution function, financial function, training function, operation function and recovery processing functions through the functional decomposition and the function combination of service with related physical function.

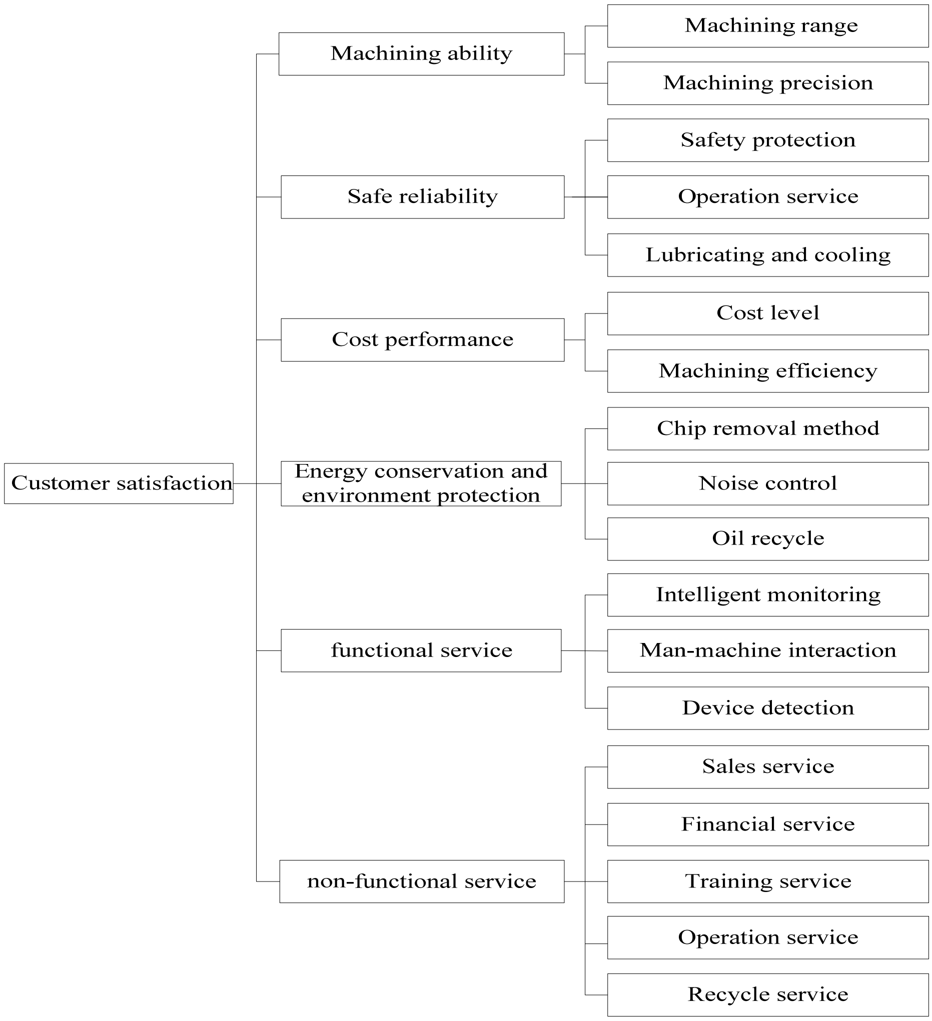


Fig. 3. Hierarchy structure tree of customer requirements for CNC machine tools.

(3) Technology domain

In product service system, the customer requirements should be converted into executable product elements eventually, which are product and services. Either product or services is composed of corresponding modules. Technology domain is the set of product modules and service modules. Technology domain is the result of modularization of product and services. By the product modularization on CNC machine tools, seven product modules are got finally, which are cutting module, hydraulic module, X feed module, protection module, control module, Z feed module and positioning supporting module. By the service modularization on CNC machine tools, six service modules are got, which are sales service module, monitoring service module, programming service module, repair service module, spare parts service module and recycling service module.

5.2 Determination of requirements weights of CNC machine tools based on RAHP

For the hierarchy structure tree of customer requirements shown in Fig. 3, this paper applies RAHP to calculate the indicator weights for all levels. Due to limited space, this paper just gives the solving process of customer requirements weights at the intermediate layer.

(1) Construct judgment matrix with customer involvement

In this paper, four customers are selected to join the requirements weight judgment. Taking six indicators at the intermediate layer as the example, four kinds of judgment are obtained, by which four judgment matrix are constructed as follows.

$$A_{11}=\begin{bmatrix}1&6&5&8&6&6\\1/6&1&1/4&5&1&1\\1/5&4&1&6&3&3\\1/8&1/5&1/6&1&1/4&1/4\\1/6&1&1/3&4&1&1\\1/6&1&1/3&4&1&1\end{bmatrix}\quad A_{12}=\begin{bmatrix}1&5&4&7&5&5\\1/5&1&1/3&5&2&2\\1/4&3&1&6&5&5\\1/7&1/5&1/6&1&1/3&1/3\\1/5&1/2&1/5&3&1&2\\1/5&1/2&1/5&3&1/2&1\end{bmatrix}$$

$$A_{13}=\begin{bmatrix}1&6&5&7&5&6\\1/6&1&1&7&3&4\\1/5&1&1&5&5&6\\1/7&1/7&1/5&1&1/4&1/3\\1/5&1/3&1/5&4&1&1\\1/6&1/4&1/6&3&1&1\end{bmatrix}\quad A_{14}=\begin{bmatrix}1&7&5&9&5&6\\1/7&1&1&5&3&4\\1/5&1&1&5&3&4\\1/9&1/5&1/5&1&1/4&1/5\\1/5&1/3&1/3&4&1&1/2\\1/6&1/4&1/4&5&2&1\end{bmatrix}$$

Carry out the consistency test for these four matrix, the results are shown in Table 1. According to Table 1, the four judgment matrix pass the consistency test.

Table 1. Consistency test results of judgment matrix.

Judgment matrix No.	CR value	Consistency test result
A_{11}	0.0556	CR<0.1, Pass consistency test
A_{12}	0.0673	CR<0.1, Pass consistency test
A_{13}	0.0965	CR<0.1, Pass consistency test
A_{14}	0.0954	CR<0.1, Pass consistency test

(2) Construct rough group decision-making matrix

Combined with four customer judgment matrix, group decision-making matrix is constructed as follows.

$$A_1^*=\begin{bmatrix}(1,1,1,1)&(6,5,6,7)&(5,4,5,5)&(8,7,7,9)&(6,5,5,5)&(6,5,6,6)\\(1/6,1/5,1/6,1/7)&(1,1,1,1)&(1/4,1/3,1,1)&(5,5,7,5)&(1,2,3,3)&(1,2,4,4)\\(1/5,1/4,1/5,1/5)&(4,3,1,1)&(1,1,1,1)&(6,6,5,5)&(3,5,5,3)&(3,5,6,4)\\(1/8,1/7,1/7,1/9)&(1/5,1/5,1/7,1/5)&(1/6,1/6,1/5,1/5)&(1,1,1,1)&(1/4,1/3,1/4,1/4)&(1/4,1/3,1/3,1/5)\\(1/6,1/5,1,5,1/5)&(1,1/2,1/3,1/3)&(1/3,1/5,1/5,1/3)&(4,3,4,4)&(1,1,1,1)&(1,2,1,1/2)\\(1/6,1/5,1/6,1/6)&(1,1/2,1/4,1/4)&(1/3,1/5/1/6,1/4)&(4,3,3,5)&(1,1/2,1,2)&(1,1,1,1)\end{bmatrix}$$

(3) Solve rough pairwise comparison matrix

Based on the existing rough group decision-making matrix, the rough number of each element in A_1^* is calculated. Taking a_{12}^*=(6, 5, 6, 7) of A_1^* as an example, the rough number of each element is calculated.

When sorting the elements of a_{12}^*=(6, 5, 6, 7) from small to large, the order is got as 5, 6, 6, 7. Then calculate the upper limit and lower limit for these elements. The calculation process is as follows:

$$\underline{Lim}(5)=5/1=5$$

$$\overline{Lim}(5)=(5+6+6+7)/4=6$$

Then it is got that the rough number of element 5 is $RN(5)=\left[\underline{Lim}(5),\overline{Lim}(5)\right]=\left[a_{12}^{1-},a_{12}^{1+}\right]=[5,6]$. By the same process, the rough numbers of other elements are calculated and the results are $RN(6)$ =[5.67, 6.33], $RN(7)$ =[6,7]. The rough number of a_{12}^* is $RN(a_{12}^*)$={[5.67, 6.33], [5, 6], [5.67, 6.33], [6, 7]}. Then calculate the average roughness limit by (7) and (8):

$$a_{12}^-=(a_{12}^{1-}+a_{12}^{2-}+a_{12}^{3-}+a_{12}^{4-})/4=(5.67+5+5.67+6.33)/4=5.59$$

$$a_{12}^+=(a_{12}^{1+}+a_{12}^{2+}+a_{12}^{3+}+a_{12}^{4+})/4=(6.33+6+6.33+7)/4=6.42$$

So the corresponding average roughness interval is $RN(a_{12})=[a_{12}^-,\ a_{12}^+]$=[5.59, 6.42]. According to above method, the average rough interval of each element in rough group decision-making matrix can be obtained. Finally the rough pairwise comparison matrix A_1 corresponding to A_1^* is got as follows.

$$A_1=\begin{bmatrix}[1,1]&[5.59,6.42]&[4.56,4.94]&[7.27,8.25]&[5.06,5.44]&[5.56,5.94]\\ [0.16,0.18]&[1,1]&[0.46,0.86]&[5.13,5.88]&[1.75,2.73]&[2.00,3.52]\\ [0.20,0.22]&[1.38,3.00]&[1,1]&[5.25,5.75]&[3.50,4.50]&[3.75,5.25]\\ [0.12,0.14]&[0.16,0.20]&[0.18,0.19]&[1,1]&[0.26,0.29]&[0.25,0.31]\\ [0.19,0.20]&[0.40,0.71]&[0.24,0.30]&[3.56,3.93]&[1,1]&[0.82,1.45]\\ [0.17,0.19]&[0.33,0.56]&[0.20,0.28]&[3.27,4.25]&[0.82,1.45]&[1,1]\end{bmatrix}$$

(4) Solve the indicator weight based on rough pairwise comparison matrix

The rough pairwise comparison matrix is split into rough lower matrix and rough upper matrix. Calculate the biggest eigenvalue and the corresponding eigenvectors respectively according to the (12)-(15), and normalize the eigenvectors. Then the weights of rough lower limit and rough upper limit of six indicators at this level are obtained. In order to reduce the manual calculation, MATLAB is used to solve and normalize the eigenvectors. The results are as follows.

$$\left[f_1^-,f_2^-,f_3^-,f_4^-,f_5^-,f_6^-\right]=[0.5156,0.1210,0.1922,0.0310,0.0732,0.0670]$$

$$\left[f_1^+,f_2^+,f_3^+,f_4^+,f_5^+,f_6^+\right]=[0.4719,0.1388,0.2168,0.0279,0.0737,0.0710]$$

$$[f_1,f_2,f_3,f_4,f_5,f_6]=[0.4937,0.1299,0.2045,0.0295,0.0735,0.0690]$$

By RAHP, the weights of the indicators at other levels are calculated successively, and the rough average weights are obtained. Then synthesize the indicator weights and get final target weight. The results are as shown in Table 2.

Table 2. Customer requirements weights.

Weight at T_k level	Weight at CR_{ki} level	Final weight f_{CRi}^*
0.4937	0.5593	0.2761
	0.4407	0.2176
0.1299	0.4044	0.0525
	0.3929	0.0510
	0.2027	0.0263
0.2045	0.6840	0.1399
	0.3160	0.0646
0.0295	0.5082	0.0150
	0.2210	0.0065
	0.2709	0.0080
0.0735	0.7009	0.0515
	0.1488	0.0109
	0.1502	0.0110
0.0690	0.2999	0.0207
	0.0949	0.0065
	0.2572	0.0177
	0.2271	0.0157
	0.1210	0.0083

5.3 *Building of requirement-function HoQ and function-technology HoQ*

(1) Build requirement-function HoQ

First 18 customer requirements are determined including processing range, accuracy, sales service and recycling services according to the hierarchy structure tree of customer requirements as shown in Fig. 3. The weights of 18 customer requirements are calculated based on RAHP. Then according to 15 function characteristics including cutting function, feed function Z and recovery processing functions, the requirement-function matrix is constructed, in which the strength is divided into "strongest (1)", "strong (0.7)", "medium (0.5)", "weak (0.3)", "none(0)" expressed by “◎”, “○”, “□”, “△”and “blank” respectively. Finally the self-correlation matrix of function characteristics is construct, in which the interaction feature is divided into "strong positive (3)", "weak positive (1)", "none(0)", "weak negative (-1)", "strong negative (-3)" expressed by the symbol “●”, “▲”, “blank”, “△” and “○” respectively. The requirement-function HoQ is built as shown in Fig. 4.

(2) Build function-technology HoQ

The function characteristics of the first stage HoQ is used as the input of the second stage HoQ. The service modules and product modules construct the technology domain, which includes 13 technology characteristics including cutting module, hydraulic module, spare parts module and recovery module. Finally the correlation matrix of function-technology and self-correlation matrix are determined.

5.4 *Consistency test of two-stage HoQ*

First, check the consistency of the requirement-function HoQ as follows.

(1) The relation matrix and self-correlation matrix of requirement-function HoQ are normalized, and the requirement-function relation matrix and the self-correlation matrix of requirement-function HoQ are obtained.

(2) Calculate the similarity coefficient of function characteristics pair. The similarity coefficients of function characteristics pair are obtained as shown in Table 3.

Table 3. Similarity coefficient of function characteristics pairs.

	FC1	FC2	FC3	FC4	FC5	FC6	…	FC11	FC12	FC13	FC14	FC15
FC1		0.82	0.82	0.82	0.30	0.36	…	0.00	0.00	0.00	0.00	0.00
FC2			1.00	1.00	0.32	0.43	…	0.00	0.00	0.00	0.00	0.00
FC3				1.00	0.32	0.43	…	0.00	0.00	0.00	0.00	0.00
FC4					0.32	0.43	…	0.00	0.00	0.00	0.00	0.00
FC5						0.00	…	0.00	0.00	0.00	0.04	0.00
…							…	…	…	…	…	…
FC12										0.23	0.26	0.00
FC13											0.52	0.00
FC14												0.26
FC15												

(3) Calculate the relation coefficient. Calculate the relation coefficient between function characteristics and similarity coefficient and get the results as follows: l_{cc}=27.9, l_{ss}=8.2854, l_{cs}=8.2854, r_{cs}=8.2854.

(4) Hypothesis test

According to the self-correlation of requirement-function HoQ, there are n=40 pairs of function characteristics that have relationship. Then t=2.9122 is got through calculating. Hypothesis test is carried out on the correlation coefficient. When the confidence is 0.05 and r_{cs} is 0, t_{n-2}=t_{38}=2.0244. Because of t=2.9122>t_{38}=2.0244, the assumption is invalid, which indicates that there is relationship between the self-correlation and the similarity coefficient of function characteristics. Then it indicates that the consistency of requirement-function HoQ passes test.

Next, check the consistency of function-technology HoQ as follows.

(1) The relation matrix and self-correlation matrix of function-technology HoQ are normalized, then the function-technology relation matrix and the self-correlation matrix of technical characteristics are got.

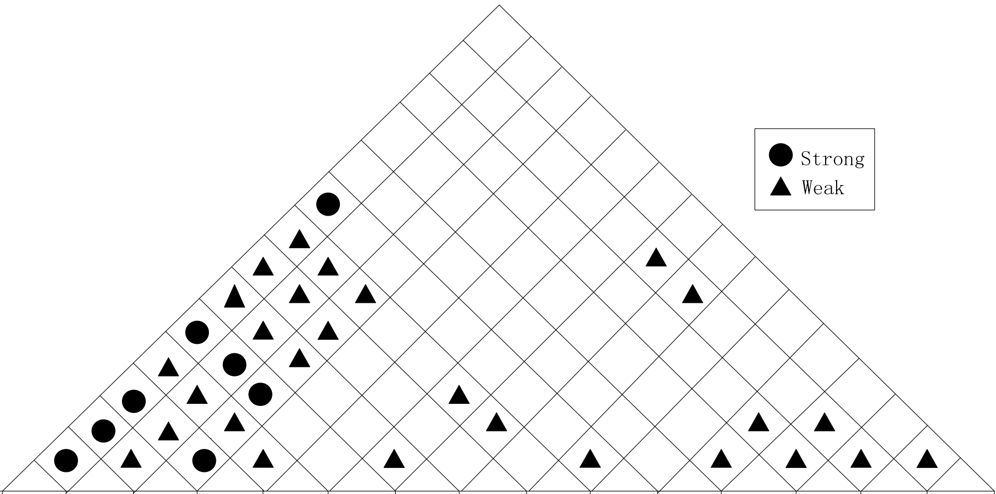
(2) Calculate the similarity coefficient of technical characteristics pairs. The result is shown in Table 4.

Table 4. Similarity coefficients of technology characteristics pairs.

	PM1	PM2	PM3	PM4	PM5	PM6	PM7	SM1	SM2	SM3	SM4	SM5	SM6
PM1		0.75	0.74	0.65	0.79	0.74	0.74	0.00	0.59	0.64	0.59	0.71	0.64
PM2			0.00	0.00	0.72	0.00	0.00	0.00	0.00	0.00	0.46	0.74	0.67
PM3				0.00	0.62	0.00	0.00	0.00	0.00	0.00	0.36	0.65	0.57
PM4					0.46	0.52	0.52	0.00	0.00	0.00	0.00	0.60	0.62
PM5						0.62	0.62	0.00	0.52	0.00	0.38	0.57	0.48
PM6							0.00	0.00	0.52	0.00	0.36	0.65	0.57
PM7								0.00	0.52	0.00	0.36	0.65	0.57
SM1									0.00	0.00	0.00	0.00	0.00
SM2										0.00	0.00	0.00	0.00
SM3											0.00	0.00	0.00
SM4												0.00	0.00
SM5													0.00
SM6													

(3) Calculate the relation coefficient between the technical characteristics and similarity coefficient. The calculation result is l_{cc}=31.2632, l_{ss}=0.4985, l_{cs}=1.9967, r_{cs}=0.5058.

According to the self-correlation of function-technology HoQ, there are n=38 pairs of function characteristics that have relationship. Then t=3.5178 is got through calculating. Hypothesis test is carried out on the relation coefficient. When the confidence is 0.05 and r_{cs} is 0, t_{n-2}=t_{36}=2.0281. Because of t=3.5178>t_{36}=2.0281, the assumption is invalid, which indicates that there is relationship between the self-correlation and the similarity coefficient of function characteristics. Then it indicates that the consistency of function-technology HoQ passes test.



Customer Requirements	Requirements weight	Cutting Function	Feed Function z	Feed Function x	Positioned Support	Support Function	Control Function	Security Protection	Detection Function	Intelligent Monitoring	Interactive Function	Sales Function	Financial Function	Training Function	Operation Function	Recycling
Machining Scope	0.2761	◎	▭	▭	▭	◎	○	△		△	△					
Machining accuracy	0.2176	◎	○	○	○	△	△	▭	○	▭						
Security Protection	0.0525						△	◎								
Service life	0.0510	◎	◎	◎	◎		△	▭			△					
Lubricating cooling	0.0263						○	◎		○						
Cost Levels	0.1399	○	○	○	○		◎			△		▭		△	△	△
Machining efficiency	0.0646	◎	○	○	○		△	△			△					
Chip Removal Way	0.0150					▭		◎								
Noise Control	0.0065	△	△	△	△					◎						
Oil Recycling	0.0080						◎	○		△						
Intelligent Monitoring	0.0515						○			◎	△					
Computer Interaction	0.0109						○	△		▭	◎					
Equipment Testing	0.0110								◎	○	△				○	
Sales Service	0.0207											◎	○	○	▭	
Financial Service	0.0065												◎			
Training Service	0.0177													◎	▭	
Operation Service	0.0157														◎	
Recycling Service	0.0083															◎
Function Target																
Function Weight		0.7092	0.4865	0.4865	0.4865	0.3489	0.5190	0.3393	0.1633	0.3204	0.1472	0.0960	0.0210	0.0742	0.0846	0.0503

◎ Strongest
○ Strong
▭ Medium
△ Weak

Fig. 4. Requirement-function HoQ.

5.5 Integrated expression of product modules and service modules

Service modules can be divided into function service modules and non-function service modules. Because the function module need realize its service function by means of some physical components, in product modules there must be corresponding modules to guarantee that this kind of service can be realized. If the function service module is separated from those product modules in the following configuration process of product service system, it not only increases the difficulty of module configuration, but also is not reasonable. So before product service system configuration, it is necessary to identify the function service modules and the corresponding product modules, and integrate them to form integrated product service modules, which can make the structure of product service module more reasonable, and the configuration design more concise and efficient.

Through the analysis of product modules and service modules, it is known that in service modules, programming service module and monitoring service module are function service modules, which need corresponding product modules to ensure the implementation of these services. The control and monitoring module in product modules is closely linked with the programming service module and monitoring service module. The hydraulic module also needs monitoring service, so in the function service modules the monitoring service module is closely related to hydraulic module. Therefore, hydraulic product module and monitoring service module are needed to realize integration, and control product module and monitoring service module as well as programming services module are needed to realize integration. The structure of integrated product service modules is shown in Fig. 5, in which PM represents product module, SM represents service module, and PS represents integrated product service module.

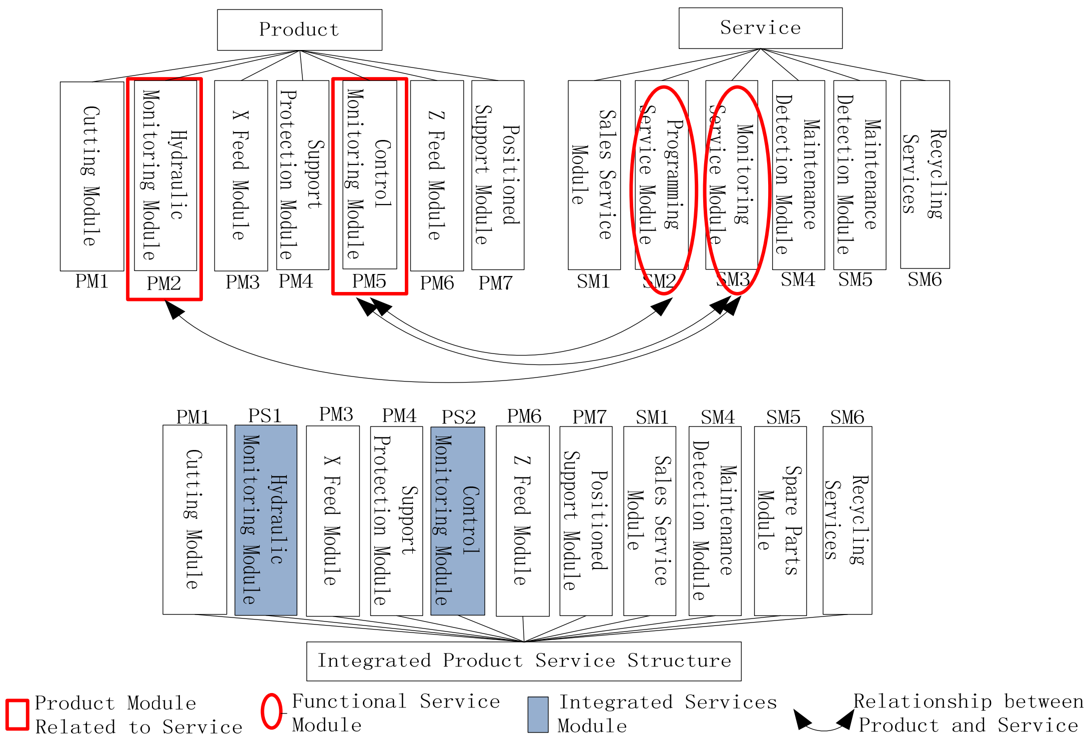


Fig. 5. The structure of integrated product service modules.

6. CONCLUSIONS

In order to adapt to the rapid development of service economy, manufacturing enterprises should not only provide products to customers, but also provide full range of services. Product service system design can combine products and services organically. This paper established the model of mapping relationship and mapping method between product service system domains, determined the weight of each element in requirement domain using RAHP, built the requirement-function HoQ and function-technology HoQ based on QFD, and checked the consistency of the two-stage HoQ according to correlation analysis theory. Finally related product modules and service modules were integrated in order to facilitate the following configuration design of product service system.

Taking ETC series CNC machine tool as an example, this paper verified the feasibility and universality of mapping method between product service system domains, and expressed mapping relations between product service system domains well. Through the effective integration of product modules and service modules, the complexity of elements in the product service system is reduced, which can better guide the following design process of product service system.

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