Modular design research of computer numerical control machine tools oriented to customer requirements

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Abstract
In order to study the modular design of computer numerical control machine tools oriented to customer demands, the customer demand information model was established based on rough analytic hierarchy process and information entropy by analyzing and transforming customer demands. Based on the domain mapping method of axiomatic design and quality function deployment integration, the product function model and structure model of computer numerical control machine tools are established. Based on fuzzy clustering analysis, the module division of computer numerical control machine tools is studied, and the dynamic clustering diagram of computer numerical control machine tools is formed with MATLAB as the operating environment. Based on Technique for Order Preference by Similarity to Ideal Solution method, the scheme of computer numerical control machine tools module division is evaluated. Taking the horizontal computer numerical control machine tool products of Shenyang Machine Tool Group as an example, the module division is carried out. The example design and the result analysis prove that the module division system is very effective and fast.

Keywords
CNC machine tools, customer demands, modular design, inter-domain mapping, module division, program evaluation

Introduction
Computer numerical control (CNC) machine tools are the key basic equipment of equipment manufacturing industry. With the continuous improvement of industrialization level, people put forward higher and higher requirements on the diversification and personalization of CNC machine tool products. The cycle of replacement of CNC machine tools is also shorter and shorter. On the other hand, with the increasingly fierce market competition, enterprises are in urgent need of rapidly configuring CNC machine tools to meet the diverse needs of customers with lower cost and higher performance.¹ Modular design realizes the mass production and personalization of products with the cost of mass production through the reorganization of product structure design process, so as to find the best balance between product variety and cost performance.²,³

In the field of engineering, Simon⁴ and Alexander⁵ first proposed the idea of modular design, dividing the system into the least related components or modules can effectively reduce the complexity of the system. G Pahl et al.⁶ proposed the modular design method to map from the functional domain of a module to the structural domain, and realized the inter-domain...
mapping of the module based on the performance of
the module. On the basis of considering the whole
product, J Lao and S Wu.\textsuperscript{7} divided the system into
modules with the same or different functions according
to functions. W Hu\textsuperscript{8} transformed the general product
design tasks into modular design tasks. H Wang\textsuperscript{9}
proposed a modular product configuration method for
mass customization products. Most of the existing
research methods of modular design are directly map-
ping from functional domain to structural domain,
establishing product structure model, and then com-
pleting product modular design. Therefore, this article
brings forward modular design of CNC machine tools
for customer demands. Modular design is to decom-
pose products into different functional modules accord-
ing to certain rules. Then, according to the special
needs of each customer, select the appropriate func-
tional modules for combination and assembly to form
individual modular products, so as to achieve the goal
of providing customized products to customers in a
short time. Its significance has the following aspects:

1. Save design time and shorten supply cycle.
2. Improve product quality and reduce production cost.
3. It is convenient for product renewal and devel-
   opment of variant products.
4. It is beneficial to enhance the enterprises’ adapt-
   ability and reduce the cost of product replacement.
5. Easy to maintain, repair.

Therefore, it is necessary to divide modules accord-
ing to the customer demands. This article puts forward
modular design of CNC machine tools for customer
demands. It starts from the establishment of customer
demand information model. Using the mapping model
of integration of axiomatic design (AD) and quality
function deployment (QFD), it transforms customer
demands into product function model, and finally
establishes product structure model to meet customer
demands, so that product module division is more rea-
sonable and can meet customer demands.

The remainder of this article will proceed as follows:

**Modular design**

Customer demand information model is established to
provide customer demand domain. The model of AD
and QFD integration is used to solve the mapping of
product from customer demand domain to function
domain and function domain to structure domain. It
transforms customer demands into product function
model, and finally establishes product structure model
that meets customer demands. The fuzzy clustering of
transitive closure method is applied to classify modules,
and the results of module classification are evaluated
based on Technique for Order Preference by Similarity
to Ideal Solution (TOPSIS) method.

**Customer requirements information modeling**

**Customer requirements model construction.** The process
of customer demands acquisition mainly includes deter-
mining reasonable survey objects and survey methods
to conduct market survey and sort out customer
demands.\textsuperscript{10–12} According to the actual situation, adopt
appropriate survey method to accurately reflect the
customers’ demands.

The original customer demand information collected
through investigation often has various forms, which
need to be screened, summarized, and sorted out.
Affinity diagram\textsuperscript{13} (KJ method) was used to conduct
hierarchical analysis of customer demand information.
The main steps are as follows:

Step A. Organize the customer demands of each item
and write on each card.

Step B. Divide the same meaning cards into the same
group, keep only one card in each group, discard the
other cards in each group, and record their repetition
frequency.

Step C. Gather the cards with similar meaning to
divide them into different groups.

Step D. A word is used to describe the similar item,
which is a high-level customer demand item.

Step E. Gather the customer demand items obtained
in Step D according to the principle of similar mean-
ing and group them again.

Step F. Repeat Step D, use representative statements
to describe each group, and get a higher level of cus-
tomer requirements.

Step G. Repeat Steps C and D, and according to the
actual situation, continue to merge until a reasonable
hierarchical structure of customer needs is obtained.

Finally, the customer requirements tree model as
shown in Figure 1 is constructed.
Calculation of the importance of customer demands based on rough analytic hierarchy process and information entropy. The customer demand analysis is shown in Figure 2.

**Customer demand weight solution steps based on RAHP**

1. Construct AHP judgment matrix and conduct consistency test.

The hierarchy model of customer demands is built as shown in Figure 1. Make appropriate AHP\(^{15,16}\) questionnaire, solicit and invite customers to participate in AHP questionnaire survey, and construct customer demands judgment matrix, as shown in equation (1)

\[
A_i = \begin{bmatrix}
1 & a_{12} & \cdots & a_{1n} \\
\ddots & \ddots & \ddots & \ddots \\
a_{m1} & a_{m2} & \cdots & 1
\end{bmatrix}
\]

where \(i \in [1, m]\), \(m\) represents the total number of customers, \(n\) represents the number of categories of each level customer requirements, and \(A_i\) represents the AHP judgment matrix obtained from the evaluation of \(i\) customer.

According to the related ideas of AHP, consistency test must be carried out for the judgment matrix obtained from customer evaluation. Calculate the consistency ratio \(CR\) of the AHP judgment matrix. If \(CR < 0.1\), the judgment matrix does not need to be modified. Otherwise, it needs to be corrected.

2. Construct rough group decision matrix

\[
A^* = \begin{bmatrix}
1 & a_{12} & \cdots & a_{1n} \\
a_{21} & 1 & \cdots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{m1} & a_{m2} & \cdots & 1
\end{bmatrix}
\]

where \(a_{ef}^* = \{a_{1f}^*, a_{2f}^*, \ldots, a_{nf}^*\}\).

3. Solve the rough pair comparison matrix

\[
A = \begin{bmatrix}
[1, 1] & [a_{12}^+, a_{12}^-] & \cdots & [a_{1n}^+, a_{1n}^-] \\
[a_{21}^-, a_{21}^+] & [1, 1] & \cdots & [a_{2n}^+, a_{2n}^-] \\
\vdots & \vdots & \ddots & \vdots \\
[a_{m1}^-, a_{m1}^+] & [a_{m2}^-, a_{m2}^+] & \cdots & [1, 1]
\end{bmatrix}
\]

where \([a_{ef}^-, a_{ef}^+]\)\(^{17}\) presents a rough number, caps and collars of which is \(a_{ef}^+\) and \(a_{ef}^-\).
4. Calculate the weight of customer demands at each level based on geometric average \( RN(qe) \)

\[
RN(qe) = \left[ \prod_{j=1}^{n} a_{ij} \right]^{1/n} \prod_{j=1}^{n} a_{ij}^{n}
\]

where \( n \) represents the number of categories of each level customer requirements.

5. Synthesize the basic importance of customer requirements.

The basic importance degree \( f_i \) of all customer demands can be obtained by multiplying the importance degree of customer requirements of each level and its corresponding sub-level.

**Evaluation of market competitiveness based on information entropy.** Assuming that, after market investigation and analysis, a product has \( m \) customer demands and \( n \) competing enterprises, the market competition evaluation matrix \( X \) can be formed

\[
X = (X_1, X_2, \ldots, X_n) = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}
\]

where \( x_i = \sum_{j=1}^{n} x_{ij} \) and \( p_{ij} = x_{ij}/x_i \) represents a possible distribution of customer requirements \( N_i \) across \( n \) enterprises

\[
E(N_i) = -\Phi_n \sum_{j=1}^{n} p_{ij} \ln(p_{ij}) = -\Phi_n \left( \frac{x_{ij}}{x_i} \right) \ln \left( \frac{x_{ij}}{x_i} \right)
\]

where \( E(N_i) \) is used to reflect relative competitive advantage, thus setting the priority of requirements. For normalization

\[
e_i = \frac{E(N_i)}{\sum_{i=1}^{m} E(N_i)}, i = 1, 2, \ldots, m
\]

According to the formula

\[
I_i = f_i \times e_i
\]

where \( f_i \) is the basic importance degree and \( e_i \) is market competitiveness assessment, and the final revised customer demands significance \( I_i \) is obtained.

**Domains of AD.** Domains are proposed in AD theory. According to the different design interaction content, AD divides the whole design process into four design activities, which are composed of four domains: Customer Domain, Functional Domain, Physical Domain, and Process Domain. Each field has its own corresponding elements, which are Customer Requirements (CRs), Functional Requirements (FRs), Design Parameters (DPs), and Process Variables (PVs). As shown in Figure 3, there is a certain mapping relationship between the design elements of the adjacent domain, and a mapping matrix is established to determine the relationship between them. The design process moves from the left domain to the right domain successively, and finally produces the product required by CRs.

**Hierarchy and inter-domain mapping.** Take the mapping of functional domain to physical domain as an example. The total functional requirements of the product are first determined, and then the overall design parameters are determined according to the total functional requirements. When the total functional requirements are met, the total function is decomposed according to the overall design parameters, and the corresponding sub-design parameters are determined according to the sub-functions. When the sub-functional requirements are met, the sub-functions of the next level are decomposed. And so on until all sub-functions are satisfied and no longer decomposed. After mapping, the hierarchical tree of function hierarchy and design parameters, as well as the relationship between design parameters and function requirements, is obtained. The mapping principle from functional domain to physical domain is shown in Figure 4, and the mapping process between other domains is similar.
Two axioms of design. There are two important axioms in AD: independence axiom and information axiom. The independent axioms in AD are used to study related problems. Independence axiom requires the independence of functional requirements, which is used to show the relationship between functional requirements and design parameters. When there are multiple functional requirements, the design results must meet each functional requirement without affecting each other.

The process of inter-domain mapping in AD can be expressed by matrix equation. For example, functional requirements in functional domain and design parameters in physical domain can be expressed as follows:

\[
\{FR\} = [A]\{DP\}
\]  

where \([A]\) is design matrix for the product, \(\{FR\}\) is function requirement vector, and \(\{DP\}\) is the design parameter vector. The design matrix \([A]\) can be expressed as

\[
A = \begin{bmatrix}
a_{11} & a_{12} & \ldots & a_{1n} \\
a_{21} & a_{22} & \ldots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{n1} & a_{n2} & \ldots & a_{nn}
\end{bmatrix}
\]  

where \(n\) is the number of functional decomposition and \(a_{ij} = \partial FR_i/\partial DP_j\). Equation (9) is expressed in differential form as

\[
\{\partial FR\} = [A]\{\partial DP\}
\]  

When some DPs change, some FRs will also change accordingly, so independent axioms cannot be satisfied in the mapping process. In order to satisfy the independent axioms, the design matrix must be diagonal or triangular. The forms are as follows:

1. The design matrix \([A]\) is diagonal

\[
A = \begin{bmatrix}
a_{11} & 0 & \ldots & 0 \\
0 & a_{22} & \ldots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \ldots & a_{nn}
\end{bmatrix}
\]  

This form is called uncoupled design, which is also the ideal design form.

2. The design matrix \([A]\) is triangular

\[
A = \begin{bmatrix}
a_{11} & a_{12} & \ldots & a_{1n} \\
0 & a_{22} & \ldots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \ldots & a_{nn}
\end{bmatrix}
\]  

This form is called quasi coupled design, which also satisfies the independent axiom.

In addition, other design matrices do not satisfy the independent axioms and need to be decoupled. The mapping process relationships between other domains are similar.

The least amount of information in design is information axiom. The more complex the functional requirements are, the greater the information content is and the lower the probability of design success is. Therefore, it is necessary to make the design parameters meet the functional requirements as much as possible on the premise of satisfying the independent axioms, so that the design results will be better.

Inter-domain mapping. The AD process is shown in Figure 5. The implementation form of QFD is house of quality, as shown in Figure 6. By utilizing the complementarity of AD and QFD, based on the domain mapping method of AD and QFD integration, this article constructs the house of quality of customer demands and function demands, and the house of quality of function demands and design parameters. It establishes the mapping model, as shown in Figure 7. Product structure model is established to divide product modules.

The calculation transformation of the house of quality adopts the independent collocation method. On the premise of satisfying the independent axiom, using the house of quality, the relationship matrix between customer demands and functional demands is established. The correlation degree of them is 1, 3, 5, 7, 9. The larger the value is, the stronger the relationship between functional demands and customer demands is. If they are not related, the value is 0. According to the independent axiom, each functional demand is independent from each other, so it is not necessary to establish the autocorrelation matrix of functional demands.

Suppose \(CIR_i\) is the importance of the \(i\) customer demand, \(R_{ij}\) is the value of the correlation degree between the \(i\) customer demand and the \(j\) functional
demand, and $TIR_j$ is the importance of the $j$ functional demand. Thus, equation (14) is as follows

$$TIR_j = \sum_{i=1}^{n} CIR_i R_{ij}$$

(14)

If the $j$ functional engineering measure is closely related to multiple customer demands, and these customer demands are more important, then the weight of functional requirements is more important. Similarly, the transformation calculation from the weight of functional requirements to the importance of design parameters can also be obtained by using this equation.

**Product module division**

**Principle of product module division.** The principle of module division has the same commonality:

- The functions of each module are independent from each other and the structure of each module is complete.
- Each module interface is convenient for loading and unloading.
- Weak coupling between modules, and strong coupling among parts in modules.
- Module partition granularity is moderate.
- Unit modules are typical and different product modules are universal.
- Module extensibility and so on.

There is a prerequisite for product module division, that is, there should be some correlation between product components. According to the above listed module classification principles and combined with the actual situation of the product, the relevant elements that need to be considered under the classification principles are determined. The relationship model of product parts and components is established.

**Construction of product parts relation model.** The parts relation model is constructed, including parts correlation analysis and parts synthesis relation matrix. When analyzing the correlation of parts, it is necessary to comprehensively consider the relevant factors that have interactive effects on parts. In this article, functional, geometric, design, and information-related and physical-related elements among components are considered as the judgment basis for module division. And the component relationship model is established. Finally, the AHP is used to calculate the importance of the relevant elements, and the component synthesis matrix is established.

1. Component correlation analysis.
According to the strength of the correlation of parts, it is divided into four strength levels: strong, medium, weak, and none. The quantification method is shown in Table 1.

Starting from the principle of module division, and according to the definition of component correlation, the article analyzes and describes the five related elements of components, including functional correlation, geometric correlation, design correlation, information correlation, and physical correlation.

By analyzing the function correlation of parts, the function relation matrix of parts can be established. If the product is divided into \( n \) parts by function, a \( n \times n \) functional relation matrix \( R_{\text{FUN}} \) can be established.

Obtain in turn: geometric correlation matrix \( R_{\text{GEO}} \), design correlation matrix \( R_{\text{DES}} \), information correlation matrix \( R_{\text{INF}} \), and physical correlation matrix \( R_{\text{PHY}} \).

Table 1. The strength of component correlation.

| Relationship strength | Assignment |
|-----------------------|------------|
| Strong                | 1          |
| Medium                | 0.6        |
| Weak                  | 0.3        |
| None                  | 0          |
2. Analysis of component comprehensive correlation matrix.

Finally, it is necessary to consider the influence of all related factors comprehensively. The AHP is applied to calculate the weight of each relevant element, and then the component comprehensive correlation matrix $R_{SYN}$ is obtained by the weighted average. The size of each element in the comprehensive relation matrix is shown in equation (15)

$$R_{SYN}^{ij} = w_f R_{FUN}^{ij} + w_g R_{GEO}^{ij} + w_d R_{DES}^{ij} + w_m R_{INF}^{ij} + w_p R_{PHY}^{ij}$$

(15)

where $w_f$, $w_g$, $w_d$, $w_m$, and $w_p$ are the relative weights among the five related elements, including functional correlation, geometric correlation, design correlation, information correlation, and physical correlation, $1 \leq i, j \leq n$.

**Product module division based on fuzzy clustering algorithm.** The product module division is studied by fuzzy clustering analysis with transitive closure method.

1. Transitive closure.

Products-integrated relationship matrix is obtained by components correlation analysis, which only satisfy reflexivity and symmetry and does not meet the transitivity. In the transitive closure method of fuzzy clustering analysis, the product fuzzy similarity matrix (component synthesis correlation matrix) obtained by correlation analysis is constructed into a transitive fuzzy equivalence matrix, which is transitive closure $t(R).$\(^{23}\)

The transitive closure of fuzzy similarity matrix is obtained by the flat method. For the fuzzy similarity matrix on the field $F$, the reflexivity and symmetry are satisfied. When there is a minimum positive integer $k$, such that $R^{2k} = R^k$, $t(R) = R^k$.

2. Fuzzy clustering based on $\lambda$ intercept array.

In the transitive closure $t(R) = [t_{ij}]_{n \times n}$, where $0 \leq t_{ij} \leq 1$, $\lambda$ represents some value of $t_{ij}$ that is $R_{\lambda} = [\lambda_{ij}]_{n \times n}$, as shown in equation (16)

$$\lambda_{ij} = \begin{cases} 1 & t_{ij} \geq \lambda \\ 0 & t_{ij} < \lambda \end{cases} \quad (16)$$

where $R_{\lambda}$ is the $\lambda$ intercept array of $t(R)$. When module division is carried out, only the product parts whose sub-matrix elements are all 1, which is composed of corresponding row and column vectors, can be classified into a class. Depending on the different level of confidence $\lambda \in [0, 1]$, different partition results can be obtained to form a dynamic cluster diagram.$^{24}$

Program evaluation of module division based on TOPSIS method. The product module division scheme is evaluated and decided based on TOPSIS. Module partition scheme evaluation is a typical multi-attribute decision-making process, determining the priority of multiple options through the relationship between multiple attributes and multiple options, so as to select the most required options. As far as this article is concerned, the attribute is the evaluation criterion of the module partition scheme, and the option is the multiple module partition schemes. The attributes of evaluation criteria fall into two categories:

- The first category is properties that require investment. The smaller the value, the better.
- The other is the output attribute, where the higher the value, the better.

Suppose the number of module division scheme is $n$, which constitute scheme set $H = \{H_1, H_2, \ldots, H_n\}$. Evaluation criterion of the scheme to be decided is $m$, which constitute criterion set $Z = \{Z_1, Z_2, \ldots, Z_k, Z_{k+1}, Z_{k+2}, \ldots, Z_m\}$. The $Z_1, Z_2, \ldots, Z_k$ is attribute of input, and $Z_{k+1}, Z_{k+2}, \ldots, Z_m$ is output attribute. If the correlation value of scheme $H_i$ under the criterion $Z_j$ is $x_{ij}$, where $1 \leq i \leq n, 1 \leq j \leq m$, then the following decision matrix $X_{m \times n}$ can be obtained

$$X = \begin{bmatrix} \mathbf{H}_1 & \mathbf{H}_2 & \cdots & \mathbf{H}_n \\ Z_1 & x_{11} & \cdots & x_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_k & x_{k1} & \cdots & x_{kn} \\ Z_{k+1} & x_{k+1,1} & \cdots & x_{k+1,n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_m & x_{m1} & \cdots & x_{mn} \end{bmatrix}$$

(17)

The application principle of TOPSIS method in evaluating module division scheme is to make the final module division option as close as possible to the most ideal module division scheme $H^+$ and as far as possible from the least ideal module division scheme $H_-$. The general steps of the program evaluation of module division based on TOPSIS method$^{25}$ are as follows:

1. After normalization, the importance of each evaluation criterion calculated by AHP is $\omega = (\omega_1, \omega_2, \ldots, \omega_m)$.
2. Normalization processing

$$Z'_j = \frac{Z_j}{\|Z\|} = \left(\frac{x_{j1}}{\|Z\|}, \frac{x_{j2}}{\|Z\|}, \ldots, \frac{x_{jm}}{\|Z\|}\right) = \left(x'_{j1}, \ldots, x'_{jm}\right) (j = 1, \ldots, m)$$

(18)

where $\|Z\| = (x_{j1}^2 + \cdots + x_{jm}^2)^{1/2}, j = 1, \ldots, m$. 

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\(^{23}\) Ref: Principles of Fuzzy Set Theory and Application, 2019

\(^{24}\) Ref: Cluster Analysis, 2013

\(^{25}\) Ref: TOPSIS Method, 2010
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\[ H_i^* = (x_{i1}, \ldots, x_{in}) = \left( \frac{x_{ij}}{Z_i}, \ldots, \frac{x_{ijn}}{Z_{im}} \right) (i = 1, \ldots, n) \]  

(19)

\[ H^*_+ = (x_{i1}^+, \ldots, x_{in}^+) = \left( \frac{x_{i1}^+}{Z_i}, \ldots, \frac{x_{in}^+}{Z_{im}} \right) (i = 1, \ldots, n) \]  

(20)

\[ H^*_- = (x_{i1}^-, \ldots, x_{in}^-) = \left( \frac{x_{i1}^-}{Z_i}, \ldots, \frac{x_{in}^-}{Z_{im}} \right) (i = 1, \ldots, n) \]  

(21)

3. Calculate the Euclidean distance

\[ d(H_i, H_{i+}) = \left\{ \sum_j \left[ \omega_j (x_{ij}^+ - x_{ij}^-)^2 \right] \right\}^{\frac{1}{2}} = \]  

\[ \left\{ \sum_j \left[ \frac{\omega_j (x_{ij}^+ - x_{ij}^-)^2}{Z_j} \right] \right\}^{\frac{1}{2}} (i = 1, \ldots, n) \]  

(22)

\[ d(H_i, H_{i-}) = \left\{ \sum_j \left[ \omega_j (x_{ij}^- - x_{ij}^+)^2 \right] \right\}^{\frac{1}{2}} = \]  

\[ \left\{ \sum_j \left[ \frac{\omega_j (x_{ij}^- - x_{ij}^+)^2}{Z_j} \right] \right\}^{\frac{1}{2}} (i = 1, \ldots, n) \]  

(23)

where \( j = 1, \ldots, m \).

4. Calculate how close the alternatives are to the best

\[ \rho(H_i, H_{i+}) = \frac{d(H_i, H_{i+})}{d(H_i, H_{i+}) + d(H_i, H_{i-})} (i = 1, \ldots, n) \]  

(24)

The higher the value of \( \rho(H_i, H_{i+}) \), the closer the scheme is to the optimal scheme to determine the optimal module partition scheme.

**Application example**

Taking horizontal CNC lathe products of Shenyang Machine Tool Group (SYM) as an example, the customer demand information collected was summarized and sorted by KJ method, and customer demands were divided into three levels. The hierarchical structure model of customer demand of this horizontal CNC lathe was established, as shown in Figure 8. With the successive development of requirements, the information is more and more specific and detailed, which can guide the functional decomposition of the next step. In this paper, the third level customer demands will be as the horizontal CNC lathe demand domain.

Calculate the importance of customer demand of CNC machine tools based on RAHP and information entropy. Take the second level of customer needs as an example and build AHP judgment matrix, and the evaluation scale and its meaning are shown in Table 2.

\[
\begin{bmatrix}
1 & 3 & 9 & 7 & 5 & 9 \\
1/3 & 1 & 4 & 5 & 3 & 6 \\
1/9 & 1/4 & 1 & 4 & 2 & 5 \\
1/7 & 1/5 & 1/4 & 1 & 2 & 3 \\
1/5 & 1/3 & 1/2 & 1/2 & 1 & 3 \\
1/9 & 1/6 & 1/5 & 1/3 & 1/3 & 1 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
1 & 4 & 5 & 6 & 7 & 9 \\
1/4 & 1 & 5 & 3 & 2 & 7 \\
1/5 & 1/8 & 1 & 1 & 1/3 & 1/2 \\
1/6 & 1/8 & 2 & 1 & 1/4 & 1 \\
1/7 & 1/7 & 4 & 2 & 1 & 3 \\
1/9 & 1/8 & 1 & 3 & 1/2 & 1 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
1 & 3 & 5 & 7 & 6 & 8 \\
1/3 & 1 & 1 & 7 & 3 & 4 \\
1/5 & 1 & 1 & 5 & 5 & 6 \\
1/7 & 1/7 & 1/5 & 1 & 1/4 & 1/3 \\
1/6 & 1/3 & 1/5 & 4 & 1 & 1 \\
1/8 & 1/4 & 1/6 & 3 & 1 & 1 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
1 & 4 & 5 & 9 & 5 & 9 \\
1/4 & 1 & 1 & 5 & 3 & 4 \\
1/5 & 1 & 1 & 5 & 3 & 4 \\
1/9 & 1/5 & 1/5 & 1 & 1/4 & 1/5 \\
1/5 & 1/3 & 1/3 & 4 & 1 & 1/2 \\
1/9 & 1/4 & 1/4 & 5 & 2 & 1 \\
\end{bmatrix}
\]
If the value of \( CR \) for the judgment matrix is less than 0.1, the judgment matrix does not need to be modified. Otherwise, it needs to be corrected. According to the consistency test formula proposed by professor E Sundin et al.,

\[
CR = CI/RI, \quad CI = (l_{\text{max}} - n)/(n - 1).
\]

\( RI \) stands for random consistency index, and the values of which are shown in Table 3. \( l_{\text{max}} \) is the maximum eigenvalue of the judgment matrix. The judgment matrix passes the consistency test. By calculation, the weight of customer demand at the second level is multiplied by the weight of customer demand at the corresponding third level to obtain the basic importance of the customer demands \( f_i \). Specific results are shown in Table 5.

A questionnaire survey was conducted on the horizontal CNC lathe and the two competing targets, and customers could score the corresponding customer needs according to 1, 2, 3, 4, and 5 respectively. The design of the questionnaire is shown in Table 4. All the survey results obtained through the market survey questionnaire were sorted out according to the corresponding customer demand to obtain the arithmetic average value of the customer demand scoring results. Finally, the evaluation matrix of market competition was constructed

\[
X = \begin{bmatrix} 4.4 & 4.5 & 5 \\ 4 & 4.25 & 4.5 \\ 4 & 4.2 & 5 \\ 4 & 4.6 & 4.2 \\ 4.2 & 4.75 & 4.5 \\ 3.5 & 3.8 & 4 \\ 4 & 3.9 & 4.8 \\ 4.5 & 4.5 & 4.6 \\ 3.5 & 3.4 & 3.5 \\ 4 & 3.8 & 4 \\ 3.8 & 4.5 & 4.6 \\ 4.2 & 4 & 4.4 \\ 4 & 4.5 & 4.2 \\ 4.8 & 3 & 3 \\ 4.5 & 4 & 4.25 \end{bmatrix}
\]

Based on the principle of information entropy, equations (5) and (6), MATLAB software can be used to solve the relative importance of market competition of the horizontal CNC lathe based on information entropy. Based on information entropy, \( e_t \), the relative importance of customer demand market competition for horizontal CNC lathe is obtained. The calculation results are shown in Table 5.

According to the formula \( I_i = f_i \times e_t \), the calculation results are normalized, and the final importance of the customer requirements of horizontal CNC lathe is shown in Table 5.

QFD house of quality transforms customer requirements into functional requirements with independent axioms in AD to ensure the independence of functional requirements in horizontal CNC lathe. After analysis, the horizontal CNC lathe has eight basic functional requirements, respectively: cutting function, feeding function, support function, control function, detection function, protection function, intelligent monitoring function, and human–machine interaction function. Since the basic functional requirements satisfy the independence axiom, the autocorrelation matrix of functional requirements is omitted. By using the

![Figure 8. Hierarchy model of customer requirements for horizontal CNC lathes.](image-url)
independent collocation method, the importance of customer demand of horizontal CNC lathe is converted to the importance of each function requirement of horizontal CNC lathe. And then the obtained weight of function requirement is normalized to gain the relative weight of function requirement. The configuration table of quality room of customer demands and function requirements of horizontal CNC lathe is shown in Table 6 to realize the mapping of customer domain to function domain.

After the basic functions of horizontal CNC lathe are determined, the function decomposition and design parameter selection of horizontal CNC lathe are carried out by using the mapping in AD until the function carrier is produced. The basic functions of horizontal CNC lathe are these: $FR_1$ is cutting function, $FR_2$ is feeding function, $FR_3$ is support function, $FR_4$ is control function, $FR_5$ is detection function, $FR_6$ is protection function, $FR_7$ is intelligent monitoring function, and $FR_8$ is human–machine interaction function. According to the axiom of independence of AD, when determining the functional demands of horizontal CNC lathe, each functional demand is independent of any other functional demand. In order to maintain the independence

### Table 2. Scale meaning.

| Scale | Meaning                                                                 |
|-------|-------------------------------------------------------------------------|
| 1     | When two elements are compared, they are equally good and bad           |
| 3     | Compared with the two elements, the former is slightly superior to the latter |
| 5     | Compared with the two elements, the former is superior to the latter    |
| 7     | Compared with the two elements, the former is more superior to the latter |
| 9     | Compared with the two elements, the former is extremely superior to the latter |
| 2, 4, 6, 8 | The intermediate value of the above adjacent judgment              |
|       | Index a is compared with index b. If index a is less important than the latter, the inverse of the above value is taken |

| n    | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|------|---|---|---|---|---|---|---|---|---|----|----|
| RI   | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.51 |

RI: random consistency index.

### Table 4. Market competitiveness evaluation questionnaire of horizontal CNC lathe customer demand based on information entropy.

According to various customer requirements, the enterprise and the competition targets are compared, and the corresponding customer needs are scored. The scoring criteria are as follows: very dissatisfied (1 point), dissatisfied (2 points), satisfied (3 points), relatively satisfied (4 points), and very satisfied (5 points).

| Customer requirements (CR) | The enterprise | Competition target 1 | Competition target 2 |
|---------------------------|----------------|----------------------|----------------------|
| Working accuracy          |                |                      |                      |
| Processing range          |                |                      |                      |
| Safety protection         |                |                      |                      |
| Service life              |                |                      |                      |
| Lubrication cooling       |                |                      |                      |
| Intelligent control       |                |                      |                      |
| Man–machine interaction   |                |                      |                      |
| Device detection          |                |                      |                      |
| Chip removal way          |                |                      |                      |
| Noise control             |                |                      |                      |
| The oil recovery          |                |                      |                      |
| Price level               |                |                      |                      |
| Processing efficiency     |                |                      |                      |
| Easy maintenance          |                |                      |                      |
| Credible quality          |                |                      |                      |

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of functional demands, the corresponding design parameters are $DP_1$ is cutting system, $DP_2$ is feeding system, $DP_3$ is support system, $DP_4$ is control system, $DP_5$ is detection system, $DP_6$ is protection system, $DP_7$ is intelligent monitoring system, and $DP_8$ is human–machine interaction system. The specific mapping of the functional and physical domain is shown below.

1. Take the decomposition of cutting function $FR_1$ as an example.

In order to meet the functional requirements of design parameters $DP_1$, the cutting function ($FR_1$) can be decomposed, as shown in Table 7. The design matrix equation is shown in equation (25)

$$
\begin{bmatrix}
FR_{11} \\
FR_{12} \\
FR_{13} \\
FR_{14} \\
FR_{15}
\end{bmatrix} =
\begin{bmatrix}
X & 0 & 0 & 0 & 0 \\
0 & X & 0 & 0 & 0 \\
0 & 0 & X & 0 & 0 \\
0 & X & 0 & X & 0 \\
0 & 0 & 0 & 0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{11} \\
DP_{12} \\
DP_{13} \\
DP_{14} \\
DP_{15}
\end{bmatrix}
$$ (25)
For the calculated transitive closure, $\lambda$ intercept different values, and get different module partition results. According to the module division method of intercept array and the MATLAB tool, when $\lambda$ change from 1 to 0, the fuzzy dynamic clustering diagram is obtained, as shown in Figure 11.

According to Figure 11, 22 different modules can be divided according to different values, $\lambda$. Because the granularity of module partition is related to whether the module partition is reasonable and effective, the number of classification cannot be too much or too little. Generally speaking, $\epsilon_{\text{max}} = 2 \ln (n)$. In combination with the actual situation, in this article, $5 \leq c \leq 12$. A few possible modules are screened out, as shown in Table 10.

According to the design characteristics of horizontal CNC lathe and customer demands, the evaluation criteria for the product module division of CNC lathe are as follows:

1. Module system cost, including design cost, manufacturing and assembly cost, management cost, and so on.
2. Interchangeability of modules.
3. Product function, accuracy, and strength.
4. Simplicity of module interface.
5. The number of module classification is reasonable.
6. Expansibility of module system.

In these six evaluation criteria, module system cost and module interface simplicity are input attributes, which are denoted as $Z_1, Z_2$. The rationality of module classification number, module interchangeability, product function, and module system expansibility are output attributes, which are denoted as $Z_3, Z_4, Z_5, Z_6$. AHP is used to determine the weight of evaluation criteria for product module division scheme. The final weights obtained are as follows: $\omega_1 = 0.34, \omega_2 = 0.11, \omega_3 = 0.06, \omega_4 = 0.16, \omega_5 = 0.26$, and $\omega_6 = 0.07$.

According to the application principle of TOPSIS method, the relevant values of the six alternative module partition schemes under each evaluation criterion are determined, and the final constructed initial decision matrix is as follows

\[
X = \begin{bmatrix}
Z_1 & Z_2 & Z_3 & Z_4 & Z_5 & Z_6 \\
7 & 3 & 1 & 5 & 8 & 9 \\
0.2 & 0.25 & 0.3 & 0.5 & 0.7 & 0.9 \\
5 & 7 & 9 & 5 & 3 & 1 \\
6 & 8 & 10 & 8 & 7 & 5 \\
0.6 & 0.8 & 1 & 0.8 & 0.4 & 0.2 \\
7 & 9 & 8 & 6 & 5 & 3 
\end{bmatrix}
\]

According to the calculation procedure of TOPSIS method, the nearness degree of the optimal scheme is calculated
Figure 9. The function tree of horizontal CNC lathes.
Figure 10. The structure tree of horizontal CNC lathes.
Therefore, the corresponding scheme $H_3$ is closest to the most ideal scheme and is the optimal module partition scheme among the alternatives. The final product module division result is shown in Table 11.

**Conclusion**

- In this article, a product customer demands information analysis model is established, and a customer demands importance calculation method based on RAHP and information...
Table 10. The module partition plans of product.

| Package number | Threshold value $\lambda$ | Classification number $c$ | Results |
|----------------|---------------------------|---------------------------|---------|
| $H_1$          | 0.18                      | 5                         | \{DP_1, DP_2, DP_3, DP_4, DP_5, DP_6, DP_7\}, \{DP_8, DP_9, DP_{10}, DP_{11}, DP_{12}, DP_{13}, DP_{14}, DP_{15}\}, \{DP_{16}, DP_{17}, DP_{18}, DP_{19}, DP_{20}\}, \{DP_{21}, DP_{22}, DP_{23}, DP_{24}, DP_{25}, DP_{26}\}, \{DP_{27}, DP_{28}, DP_{29}, DP_{30}\}, \{DP_{31}, DP_{32}, DP_{33}, DP_{34}, DP_{35}, DP_{36}\}, \{DP_{37}, DP_{38}, DP_{39}, DP_{40}\} |
| $H_2$          | 0.36                      | 6                         | \{DP_1, DP_2, DP_3, DP_4, DP_5, DP_6, DP_7\}, \{DP_8, DP_9, DP_{10}, DP_{11}\}, \{DP_{12}, DP_{13}, DP_{14}, DP_{15}\}, \{DP_{16}, DP_{17}, DP_{18}, DP_{19}, DP_{20}\}, \{DP_{21}, DP_{22}, DP_{23}, DP_{24}, DP_{25}, DP_{26}\}, \{DP_{27}, DP_{28}, DP_{29}, DP_{30}, DP_{31}, DP_{32}, DP_{33}, DP_{34}, DP_{35}, DP_{36}, DP_{37}, DP_{38}, DP_{39}, DP_{40}\} |
| $H_3$          | 0.63                      | 7                         | \{DP_1, DP_2, DP_3, DP_4, DP_5, DP_6, DP_7\}, \{DP_8, DP_9, DP_{10}, DP_{11}\}, \{DP_{12}, DP_{13}, DP_{14}, DP_{15}\}, \{DP_{16}, DP_{17}, DP_{18}, DP_{19}, DP_{20}\}, \{DP_{21}, DP_{22}, DP_{23}, DP_{24}, DP_{25}, DP_{26}\}, \{DP_{27}, DP_{28}, DP_{29}, DP_{30}, DP_{31}, DP_{32}, DP_{33}, DP_{34}, DP_{35}, DP_{36}, DP_{37}, DP_{38}, DP_{39}, DP_{40}\} |
| $H_4$          | 0.66                      | 8                         | \{DP_1, DP_2, DP_3, DP_4, DP_5, DP_6, DP_7\}, \{DP_8, DP_9, DP_{10}, DP_{11}\}, \{DP_{12}, DP_{13}, DP_{14}, DP_{15}\}, \{DP_{16}, DP_{17}, DP_{18}, DP_{19}, DP_{20}\}, \{DP_{21}, DP_{22}, DP_{23}, DP_{24}, DP_{25}, DP_{26}\}, \{DP_{27}, DP_{28}, DP_{29}, DP_{30}, DP_{31}, DP_{32}, DP_{33}, DP_{34}, DP_{35}, DP_{36}, DP_{37}, DP_{38}, DP_{39}, DP_{40}\} |
| $H_5$          | 0.67                      | 11                        | \{DP_1, DP_2, DP_3, DP_4, DP_5, DP_6, DP_7\}, \{DP_8, DP_9, DP_{10}, DP_{11}\}, \{DP_{12}, DP_{13}, DP_{14}, DP_{15}\}, \{DP_{16}, DP_{17}, DP_{18}, DP_{19}, DP_{20}\}, \{DP_{21}, DP_{22}, DP_{23}, DP_{24}, DP_{25}, DP_{26}, DP_{27}, DP_{28}, DP_{29}, DP_{30}, DP_{31}, DP_{32}, DP_{33}, DP_{34}, DP_{35}, DP_{36}, DP_{37}, DP_{38}, DP_{39}, DP_{40}\} |
| $H_6$          | 0.68                      | 12                        | \{DP_1, DP_2, DP_3, DP_4, DP_5, DP_6, DP_7\}, \{DP_8, DP_9, DP_{10}, DP_{11}\}, \{DP_{12}, DP_{13}, DP_{14}, DP_{15}\}, \{DP_{16}, DP_{17}, DP_{18}, DP_{19}, DP_{20}\}, \{DP_{21}, DP_{22}, DP_{23}, DP_{24}, DP_{25}, DP_{26}, DP_{27}, DP_{28}, DP_{29}, DP_{30}, DP_{31}, DP_{32}, DP_{33}, DP_{34}, DP_{35}, DP_{36}, DP_{37}, DP_{38}, DP_{39}, DP_{40}\} |

Table 11. Module partition results of horizontal CNC lathes.

| Module name                  | Components that make up a module |
|------------------------------|----------------------------------|
| Cutting module               | Chuck, spindle motor, magazine tool, tool changing manipulator, magazine tool base, drive system, the spindle box body |
| Z feed module                | Z motor, Z lead screw, the bed saddle, Z guide rail |
| X feed module                | X motor, X lead screw, the skateboard, X guide rail |
| Positioning support module   | The tailstock motor, the tailstock lead screw, the tailstock body, the tailstock guide rail, sleeve mandrel assembly |
| Support protection module    | Lathe bed, the anchor, overall protective cover, lead screw guard, chip removal device |
| Control and prosecution module| CNC system, electrical control device, grating ruler, fault detector, precision detection module, status monitoring module, temperature rise monitoring module, noise monitoring module, hygrothermograph, convenient programming module, remote diagnostic module |
| Hydraulic module             | Hydraulic device, lubrication device, cooling device, lubrication monitoring module |

CNC: computer numerical control.

Entropy market competition evaluation is proposed.

- Based on AD and QFD, the product structure model of horizontal CNC lathes was established, and the validity of the mapping model was verified.
- The comprehensive correlation matrix of product parts is established through the relevant elements among parts. Taking the horizontal CNC lathes as an example, the division scheme under different thresholds is obtained by the method based on transfer closure, and the dynamic clustering diagram is formed. The results show that the module partition based on this method is reasonable and provides a basis for the evaluation of the optimal partition scheme. This article puts forward the general evaluation criteria of the module division scheme of horizontal CNC lathes, evaluates six alternative schemes based on TOPSIS method, and finally determines the optimal module division result. The results show that the module partition scheme evaluation based on this method is reasonable and effective.

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References
1. China Machine Tool Industry Association Marketing Department. China machine tool market demand analysis of 2009. WMEM J 2009; 2: 87–93.
2. Jia Y. Modular design. 1st ed. Beijing, China: China Machine Press, 1993.
3. Zhuang J and Zhuang W. Automotive system integration and modular technology. 1st ed. Beijing, China: Beihang University Press, 1998.
4. Simon HA. The architecture of complexity. P Am Philos Soc 1962; 106: 467–482.
5. Alexander C. Notes on the synthesis of form. 1st ed. Cambridge, MA: Harvard University Press, 1964, pp.56–63.
6. Pahl G, Beitz W, Feldhusen J, et al. Engineering design—a systematic approach. 3rd ed. London: Springer-Verlag, 1996, pp.30–34.
7. Lao J and Wu S. Modularity and modern manufacturing techniques. Manuf Technol Mach Tool 1994; 9: 40–42.
8. Hu W. Research and practice of modular design and intelligent support system for machine tools. PhD Thesis, Huazhong University of Science and Technology, Wuhan, China, 1993.
9. Wang H, Sun Y, Wang J, et al. Product modular design method for mass customization. CIMS J 2004; 10(10): 1171–1176.
10. Kano N, Seraku N, Takahashi F, et al. Attractive quality and must-be quality. J Jpn Soc Qual Control 1984; 14: 39–48.
11. Fong D. Using the self-stated importance questionnaire to interpret Kano questionnaire results. Center Qual Manage 1996; 5: 21–24.
12. Lawrence B, Wiegers K and Ebert C. The top risk of requirements engineering. IEEE Software 2001; 18: 62–63.
13. Takai S and Ishii K. A use of subjective clustering to support affinity diagram results in customer needs analysis. Concurrent Eng 2010; 18: 101–109.
14. Wang XT and Xiong W. Rough AHP approach for determining the importance ratings of customer requirements in QFD. Comput Integr Manuf 2010; 16: 763–771.
15. Partovi FY and Corredoira RA. Quality function deployment for the good of soccer. Eur J Oper Res 2002; 137: 642–656.
16. Saaty TL. The analytic hierarchy process: planning, priority setting, resource allocation. New York: McGraw-Hill, 1980, pp.1–203.
17. Zhai LY, Khoo LP and Zhong ZW. A rough set enhanced fuzzy approach to quality function deployment. Int J Adv Manuf Tech 2008; 37: 613–624.
18. Suh NP. The principles of design. New York: Oxford University Press, 1990.
19. Sullivan LP. Quality function deployment. Qual Prog 1986; 19: 39–50.
20. Albano LD and Suh NP. Axiomatic design and concurrent engineering. Comput Aided Design 1994; 26: 499–504.
21. Suh NP. Designing-in of quality through axiomatic design. IEEE T Reliab 1995; 44: 256–264.
22. Wei X. Quality function deployment. Beijing, China: Chemical Industry Press, 2005.
23. Le K. Fuzzy relation compositions and pattern recognition. Inform Sciences 1996; 89: 107–130.
24. Yang MS and Shih HM. Cluster analysis based on fuzzy relations. Fuzzy Set Syst 2001; 120: 197–212.
25. Hwang CL and Yoon K. Multiple attribute decision making: methods and applications. New York: Springer-Verlag, 1981.
26. Sundin E, Lindahl M and Ijomah W. Product design for product/service systems: design experiences from Swedish industry. J Manuf Tech Manag 2009; 20: 723–753.