ISSN 1330-3651(Print), ISSN 1848-6339 (Online)
UDC/UDK [658.512.012:519.25]:621.9-52

RESEARCH ON MODULE CONFIGURATION DESIGN BY CASE-BASED REASONING ORIENTED ON CNC MACHINE TOOL

Zhongqi Sheng, Lei Zhang, Hualong Xie, Pengjia Wang

Original scientific paper

CNC machine tool is a symbol of advanced manufacturing technology. The introduction of modular design into the design processes of CNC machine tool has important theoretical and practical value. Combining modular design with case-based reasoning (CBR), this paper puts forward one method of module configuration design. The key technologies including the transformation of customer requirements, the case retrieval and the case evaluation have been solved. This paper analysed the acquisition and transformation of customer requirements, and the mappings from the importance ratings of customer requirements to the importance ratings of product technical characteristics. The paper studied the technologies of CBR, and used the fuzzy similarity priority ratio and grey correlation analysis algorithm to realize the calculation of case priority and the case evaluation, and picked out the product case that best matches the customer requirements finally. CNC horizontal lathe is selected as an example to show the algorithm effectiveness.

Keywords: *case-based reasoning, CNC machine tool, configuration design, fuzzy similar preferable ratio, Grey correlation analysis, modular design*

Istraživanje projektiranja konfiguracije modula razmatranjem postojećih slučajeva usmjerenih na CNC alatne strojeve

Izvorni znanstveni članak

CNC alatni stroj je simbol razvijene proizvodne tehnologije. Uvođenje modularnog projekta u postupke projektiranja CNC alatnih strojeva ima važnu teoretsku i praktičnu vrijednost. Ovaj rad promiče metodu projektiranja konfiguracije modula kombiniranjem modularnog projektiranja i promišljanja zasnovanog na slučaju (case-based reasoning-CBR). Riješeni su ključni tehnološki postupci uključujući transformaciju zahtjeva kupca, pronalaženje sličnog slučaja i procjenu slučaja. U radu su analizirani primanje i transformacija zahtjeva kupaca i mapiranje prema procjenama važnosti zahtjeva kupaca do procjena važnosti tehničkih karakteristika proizvoda. Proučavane su tehnologije CBR-a i primijenjen je fuzzy omjer prioriteta sličnosti i algoritam Grey analize korelacije kako bi se odredio i procijenio slučaj koji ima prioritet te izabrao slučaj proizvoda koji konačno najbolje odgovara zahtjevima kupca. Izabrana je CNC horizontalna tokarilica kao primjer učinkovitosti algoritma.

Ključne riječi: *CNC alatni stroj, fuzzy omjer preferirane sličnosti, grey analiza korelacije, modularni projekt, projektiranje konfiguracije, promišljanje zasnovano na istraživanju postojećeg slučaja*

1 Introduction

CNC machine tool is one of the key equipment in manufacturing industry and a symbol of advanced manufacturing technology. With the further globalization of economic development, CNC machine tool industry is faced with rigorous challenges. As a result, the machine tool enterprises must improve the quality and performance of the products through advanced design methods. As one of the modern design methods and the production mode, modular design can quickly respond to the changes of uncertain markets, increase the quality of the products, shorten the period of product development, and benefit the upgrade of the products. The introduction of modular design method into the design and production processes of CNC machine tool has important theoretical and practical value.

The module configuration is the core process of modular design. This paper applies case-based reasoning technology to the module configuration design of CNC machine tool. The key technologies of configuration design of CNC machine tool, including the transformation of the customer requirements, the case retrieval and the case evaluation, have been properly solved and realized by using QFD, fuzzy similar preferable ratio and grey correlation analysis algorithm in this paper, which can improve the efficiency of product configuration design and make the machine tool enterprises have more market competitiveness.

2 Module configuration design

2.1 Literature review

Scholars have made enthusiastic exploration on basic theory and implementation methods of modular design, and the modular design technologies are continually applied to the design and manufacturing processes of various products [1]. Fujita studied the production cost of the modular products within entire lifecycle and applied 0-1 integer programming algorithm to solve the matching performance between the modules in module combination process [2].

Chakravary established the optimization model when the enterprise cannot determine what kind of modules they can provide. Based on the tradeoff between the profit maximization and the product diversification, the optimization problem of module combination was solved [3]. Guangda Gao put forward the concept of available modules, showed the discriminates of available modules, and introduced the algorithm of fuzzy similarity preference ratio to find the optimal modules [4].

Haijun Wang proposed a customer-driven configuration design for modular product, in which the customized customer demand was divided into two parts: the technical characteristic demand and the economic performance demand [5]. Xiaohu Li put forward the optimization configuration method for CNC machine tool based on the case-based reasoning and the rule-based reasoning [6].

On the whole, the existing methods of the product configuration design mainly include the template-based configuration method, the regularity model-based configuration method, the constraint model-based configuration method and the case-based reasoning configuration method. This paper adopted the case-based reasoning method to realize the module configuration design for CNC machine tool products.

2.2 Module configuration design by case-based reasoning

Case-based reasoning (CBR) is a similarity reasoning method, and its core idea is using past experience to solve new problems [7]. The usage of CBR in design field is realized by referring to previous product cases developed successfully and doing necessary modifications to generate the new products. This kind of similarity reasoning techniques is fit to traditional habit and thinking mode of the designers. The basic process of CBR is shown in Fig. 1.

The basic idea of module configuration design of the products by CBR can be described as follows. First, according to the customer requirements, the similar product case can be picked up from the case library. Then, some modules of the similar product case are modified, replaced, and created so as to realize the rapid configuration design of the products. On the basis of analyzing existing configuration design technologies and the characteristics of machine tool products, this paper proposes the module configuration design approach by case-based reasoning technology oriented to CNC machine tool products so as to realize the rapid configuration process of the products.

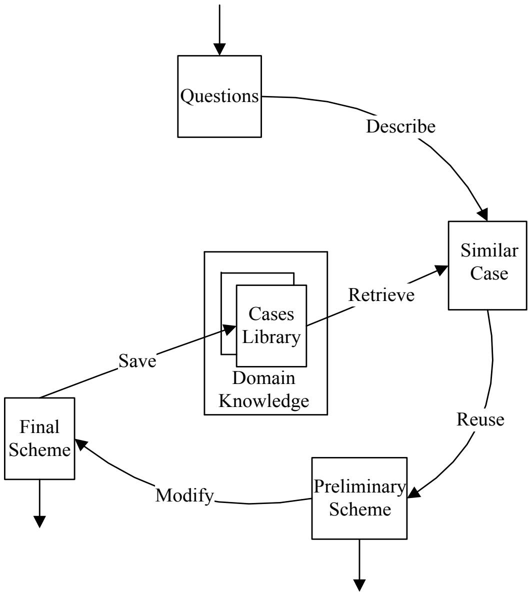

Figure 1 The basic process of CBR

The key technologies of module configuration design of CNC machine tool, including the transformation of the customer requirements, the case retrieval and the case evaluation, have been properly solved and realized by using QFD, fuzzy similar preferable ratio and grey correlation analysis algorithm.

3 Acquisition and transformation of the customer requirements

3.1 Obtaining the customer requirements and determining the requirement weight

It is the first step to obtain the customer requirements of the product while carrying out the module configuration design. Taking CNC horizontal lathe as an example, the customer requirement information can be considered from three aspects: main performance, reliability and maintainability. Fig. 2 shows the hierarchical chart of the customer requirements for CNC horizontal lathe.

In the investigation and analysis of the customer requirements on CNC horizontal lathe, each customer has different concern level on each requirement of the products. The weight is usually taken to express the concern level of the customer on the requirement. AHP is used in this paper to determine the weight of each requirement.

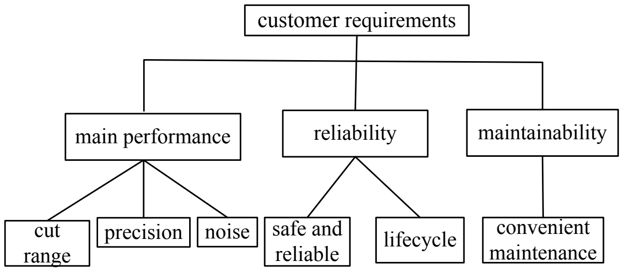

Figure 2 The hierarchy chart of the customer requirements on CNC horizontal lathe

For convenience, A is used to show the total customer requirements; B_1 main performance, B_2 reliability, B_3 maintainability; C_1 cut range, C_2 precision, C_3 noise, C_4 safe and reliable, C_5 lifecycle, and C_6 convenient maintenance. The comprehensive weight of C_1-C_6 in the third level can be calculated by using AHP. The results are shown in Tab. 1.

Table 1 The comprehensive weights of the customer requirements on CNC horizontal lathe

Customer requirement	C_1	C_2	C_3	C_4	C_5	C_6
Requirements weight (w)	0,433	0,243	0,055	0,125	0,063	0,081

3.2 Transforming the customer requirements into the design requirements

For the module configuration design, it is necessary to transform the customer requirements that are fuzzy and qualitative into the design requirements that are accurate and quantitative. Quality function deployment (QFD) is a common method used to transform the customer requirements into specific technical requirements at the stage of product design, process planning and production planning [8, 9]. House of quality (HoQ) is the tool to realize QFD, which is used to transform the customer requirements into the main technical characteristics of the products and realize the mapping from the importance weight of the customer requirements to the importance weight of product technical characteristics.

In HoQ, the importance of the technical characteristics means the importance of implementing the technical characteristics. Here h_j is used to denote the importance of the item j of the technical characteristics, which also shows the contribution of the technical characteristics to meet the customer satisfaction level. In HoQ, h_j is calculated as Eq. (1):

$$h_j = \sum_{i=1}^{n} w_i r_{ij}, \; j = 1, 2, \cdots m . \tag{1}$$

In Eq. (1), w_i is the importance of item i of the customer requirements; r_{ij} is the relationship degree between the item i of the customer requirements and the item j of the technical characteristics.

		Weight	Maximum of cutting length	Maximum of cutting diameter	X-axis travel	Z-axis travel	Maximum of spindle speed	X-axis positioning accuracy	Z-axis positioning accuracy	Surface roughness	Maximum noise	Reliability	Lifecycle	Time-consuming of maintenance	Our company	Competitor companies
Main performance	Processing range	0,433	◎	◎	◎	◎	◎			△					5	3
	Accuracy	0,243						◎	◎	◎					4	2
	Noise	0,055					○				◎				2	3
Reliability	Safe and reliable	0,125	○	○							△	◎	○	△	5	4
	Life	0,063									△	○	◎	○	3	4
Maintenance	Maintenance -free	0,081											△	◎	4	2
Our company			4	4	5	5	4	4	4	3	3	4	3	4		
Competitor companies			3	3	4	4	4	3	3	2	4	3	5	2		
Target value			500 mm	320 mm	225 mm	630 mm	4000 rev/min	0,016 mm	0,025 mm	1,25 μm	70 db	99 %	15 years	8 hours		
Importance of the technical characteristics			2,54	2,54	2,17	2,17	2,33	1,22	1,22	1,65	0,463	0,814	0,771	0,719		

Note: ◎ is a strong correlation = 5; ○ is general correlation = 3; △ is weak correlation = 1; blank is irrelevant = 0

Figure 3 The HoQ of product planning stage for CNC horizontal lathe

3.3 The optimization decision-making model of HoQ at product planning stage

The established HoQ of product planning stage for CNC horizontal lathe is as shown in Fig. 3. Because there are fund and time constraints in the module configuration design for CNC horizontal lathe, not all technical characteristics that meet the customer requirements must be implemented. The resource input of the enterprise and the resource consumption of the technical characteristics in the module configuration design are also considered in this example. Therefore, it is necessary to establish the optimization decision-making model of HoQ of product planning stage for CNC horizontal lathe so that the key technical characteristics can be chosen under the limited resources constraints and the configuration of CNC horizontal lathe with maximized overall satisfaction of the customer can be obtained.

The following assumption is set first when the enterprise of CNC horizontal lathe conducts the module configuration design. The total cost that the enterprise invests is C. The total time that the design takes cannot exceed T. There are m technical characteristics that meet the customer requirements. The cost interval estimate of the j^{th} technical characteristics to be configured is $[c_j^L, c_j^U]$, where $c_j^L \le c_j^U$. The time interval estimate of the j^{th} technical characteristics to be configured is $[t_j^L, t_j^U]$, where $t_j^L \le t_j^U$. P_j is used to denote the level of customer satisfaction with the j^{th} technical characteristics designed and calculated as Eq. (2):

$$p_j = \frac{h_j}{\sum_{j=1}^{m} h_j}, \; j = 1, 2, \cdots, m . \tag{2}$$

In Eq. (2), h_j is the importance of the j^{th} technical characteristic as given in Section 3.2.

Set n_j=1 if the j^{th} technical characteristics should be designed; or n_j=0 if the j^{th} technical characteristics need not be designed. Use M to denote the maximum of the overall customer satisfaction. The optimization decision-making model of HoQ of the product planning stage for CNC horizontal lathe is established as Eq. (3):

$$M = \max \sum_{j=1}^{m} p_j n_j ,$$

$$s.t. \begin{cases} \sum_{j=1}^{m} [c_j^L, c_j^U] n_j \leq C \\ \sum_{j=1}^{m} [t_j^L, t_j^U] n_j \leq T \\ n_j = 0,1 \end{cases} . \tag{3}$$

Solving the model, the combination of the technical characteristics that can maximize the customer satisfaction in limited C and T constraints can be determined, which in turn can determine the focus of the module configuration design then. As an example, under the constraints of existing resources and time, 6 technical characteristics, which are TC_1-maximum cutting diameter (mm), TC_2-maximum rotating diameter (mm), TC_3-X-axis stroke (mm), TC_4-Z-axis stroke (mm), TC_5-maximum spindle speed (rev/min), and TC_8-surface roughness of work-pieces (μm), should meet the corresponding technical requirements preferentially in the process of modular configuration design.

4 Case retrieval of modular product

The case retrieval of modular product is the similarity matching between the customer required product and the modular product cases. The common case retrieval methods include the nearest neighbour method, the inductive indexing method and the knowledge guidance method. In this paper, the fuzzy analogy preferred ratio is used for the case retrieval.

4.1 The principle of fuzzy analogy preferred ratio

The fuzzy similarity priority ratio method is based on the comparison between a pair of samples and a fixed sample. By determining which sample is more similar with the fixed sample, the most similar one in the samples can be found out.

Suppose that there is a set of samples labelled by $X=\{x_1, x_2, \ldots, x_n\}$, a pair of samples labelled by x_i, x_j are compared with a fixed sample labelled by x_k ($i, j=1, 2, \ldots, n$; $i, j \neq k$). Suppose that r_{ij} is the superior degree for the comparative results between x_i, x_j with a fixed sample x_k, $r_{ij} \in [0.5,1]$ means that x_i is more preferential than x_j, and $r_{ij} \in [0, 0.5]$ means that x_i is less preferential than x_j. The superior degree r_{ij} should satisfy Eq. (4):

$$\begin{cases} r_{ii} = 1 \\ r_{ij} \in [0,1] \qquad (i \neq j). \\ r_{ij} + r_{ji} = 1 \end{cases} \tag{4}$$

Eq. (4) shows that when x_i is compared with x_i, there is no priority. That is to say they are equivalent and remember it as r_{ii}=1. Each one has its own good points when x_i is compared with x_j, so add the two priorities together, the answer is 1, that is $r_{ij}+r_{ji}=1$. If x_i has more priority than x_j, and x_j does not have any priority to x_i, remember them as r_{ij}=1, r_{ji}=0. When both of them have the same priority, remember it as $r_{ij}=r_{ji}$=0,5.

The matrix $R=(r_{ij})_{n \times n}$ which meets the Eq. (4) is called the fuzzy analogy preferred ratio matrix. The absolute distance or Hamming distance can be used to define r_{ij} as Eq. (5):

$$r_{ij} = \frac{d_{kj}}{d_{ki} + d_{kj}} , \tag{5}$$

where, $d_{ki} = \left| x_k - x_i \right|$, $d_{kj} = \left| x_k - x_j \right|$.

After establishing the fuzzy analogy preferred ratio matrix, the lower bound of all non-diagonal elements in the matrix is chosen. Then the row in which the maximum of the lower bound lies is found out, which is corresponding to the first superior object. By repeating the above practice to the new matrix in which the row and the column that correspond to the first superior object have been deleted, the sequence of the sample set can be obtained.

The method discussed above concerns single-factor fuzzy analogy preferred ratio. If X contains multiple factors, it is necessary to deal with each factor separately and make the fuzzy comprehensive evaluation. There are two commonly used methods for the fuzzy comprehensive evaluation.

(1) Total score method, in which the evaluation criterion is the sum of the sequence numbers of m factors. The evaluation criterion is shown as Eq. (6):

$$S = \sum_{i=1}^{m} S_i . \tag{6}$$

(2) The weighted average method, in which based on the importance of each factor, certain weight p_i is attached. The evaluation criterion is shown as Eq. (7):

$$S = \sum_{i=1}^{m} p_i S_i , \tag{7}$$

where, $\sum_{i=1}^{m} p_i = 1$.

In the two methods, the smaller the value of S is, the more similar the sample is to the fixed sample.

4.2 The case retrieval of CNC horizontal lathe products

According to the above customer requirements of CNC horizontal lathe, the corresponding technical requirements are obtained after the transformation of HoQ. From the decision-making of HoQ, it can be known that under the constraints of existing resources and time, it is necessary to let the six technical characteristics, which are TC_1, TC_2, TC_3, TC_4, TC_5 and TC_8, meet the corresponding technical requirements in the process of module configuration design preferentially. The parameter values of the customer requirements are listed in Tab. 2, and the product cases of CNC horizontal lathe are listed in Tab. 3.

Table 2 The parameter values of the customer requirements

Parameter	TC_1	TC_2	TC_3	TC_4	TC_5	TC_8
Value	500	320	225	630	4000	1,25

Table 3 The product cases of CNC horizontal lathe

No.	Model	TC_1	TC_2	TC_3	TC_4	TC_5	TC_8
HT1	HTC3250	500	320	165	630	4000	1,60
HT2	HTC2050	500	260	150	600	3000	0,80
HT3	HTC2558m	580	250	225	610	4000	1,25
HT4	HTC2550m	500	250	230	635	4500	0,80
HT5	HTC3255	550	320	208	600	3150	1,25
HT6	HTC4554	540	450	275	520	3400	1,60

Next, the fuzzy analogy preferred ratio method is used to retrieve the similar case from the product cases of CNC horizontal lathe. Two cases are selected from the product cases to form a pair of cases in sequence. The fuzzy analogy preferred ratio matrices R_1, R_2, R_3, R_4, R_5, R_6 about TC_1, TC_2, TC_3, TC_4, TC_5, TC_8 are calculated respectively by Eq. (5) and Eq. (6). Sorting all the fuzzy analogy preferred ratio matrices to get the fuzzy preference relations, as shown in Tab. 4, the designers can get the similar sequence numbers finally.

Table 4 The similarity sequence number of technical characteristics

No.	Model	TC_1	TC_2	TC_3	TC_4	TC_5	TC_8
HT1	HTC3250	1	1	5	1	1	3
HT2	HTC2050	1	2	6	4	5	3
HT3	HTC2558m	4	3	1	3	1	1
HT4	HTC2550m	1	3	2	2	2	2
HT5	HTC3255	3	1	3	4	4	1
HT6	HTC4554	2	4	4	5	3	2

Because different technical characteristics have different influence on the selected case, the weighted average method is adopted to apply the fuzzy comprehensive evaluation. By HoQ of product planning stage for CNC horizontal lathe above, the degrees of importance of technical characteristics TC_1, TC_2, TC_3, TC_4, TC_5, TC_8 are h_1=2,54, h_2=2,54, h_3=2,17, h_4=2,17, h_5=2,33, h_8=1,65, respectively. Normalizing all the degrees of importance, the relative weight of each technical characteristic is calculated. The results of relative weights are as follows: p_1=0,190, p_2=0,190, p_3=0,162, p_4=0,162, p_5=0,173, p_8=0,123. By Eq. (8), the results of S for the six product cases are: S_1=1,771, S_2=3,424, S_3=2,274, S_4=2,123, S_5=2,709, S_6=3,363, respectively.

After the total similar sequence number of S is sorted, the similar sequence of every product case in the product cases database can be obtained.

5 Case evaluation of modular product

After the case retrieval, for the product case with the smallest total similar sequence number, the value of S only shows that the product case is more similar with the product that the customer requires, but it is not sure that the comprehensive performance of retrieved case is the best. So it is needed to evaluate the retrieved similar product case. This paper uses grey correlation analysis method to evaluate the retrieved similar cases to find out the best product case.

5.1 Evaluation model of grey correlation analysis

While applying the grey correlation analysis, it is necessary to appoint the reference sequence of number first, which is denoted as $\{x_0\}$ and $\{x_0\}=\{x_0(1), x_0(2),..., x_0(n)\}$. The sequences of number that are used to compare with the reference sequence of number are called contrast sequences of number, which are denoted as $\{x_1\},\{x_2\},\ldots,\{x_m\}$ and $\{x_1\}=\{x_1(1), x_1(2),\ldots, x_1(n)\},\ldots, \{x_m\}=\{x_m(1), x_m(2),\ldots, x_m(n)\}$. The judgment of the relational degree can be made through analysing the closeness degree between the reference sequence of number and the contrast sequences of number.

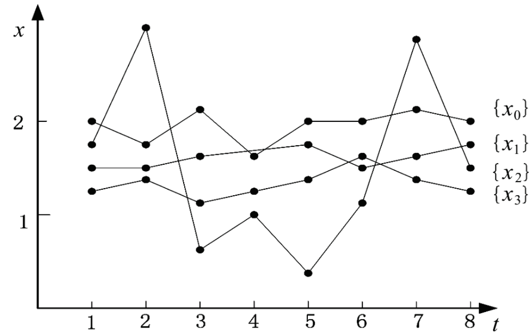

Figure 4 The geometric relations between the reference sequence of number $\{x_0\}$ and the contrast sequences of number $\{x_1\}$, $\{x_2\}$, $\{x_3\}$

As shown in Fig. 4, the contrast sequence of number and the reference sequence of number are expressed in the form of curve separately. And then, compare the geometrical shape of the contrast sequence curves $\{x_1\}$, $\{x_2\}$, $\{x_3\}$ with that of the reference sequence curve $\{x_0\}$ separately. The more similar the geometrical shape between the two curves is, the closer the variation trend is, and the greater the degree of correlation is, which means the higher similarity between the product case and the product that the customer requires.

(1) The correlation coefficient

Set $\{x_0\}=X_0(k)=\{x_0(1), x_0(2), ..., x_0(n)\}$ as the reference sequence of number and $\{x_i\}=X_i(k)=\{x_i(1), x_i(2),...,x_i(n)\}$ as the contrast sequence of number separately, where i=1, 2, …, m. Then the correlation coefficient between the reference sequence of number and the contrast sequence of number is calculated as Eq. (8):

$$\xi_i(k)=\frac{Min_iMin_k\left|X_0(k)-X_i(k)\right|+\rho\times Max_iMax_k\left|X_0(k)-X_i(k)\right|}{\left|X_0(k)-X_i(k)\right|+\rho\times Max_iMax_k\left|X_0(k)-X_i(k)\right|},\quad(8)$$

$$\Delta_i(k)=|X_0(k)-X_i(k)|,\quad(9)$$

$$\xi_i(k)=\frac{Min_iMin_k\Delta_i(k)+\rho\times Max_iMax_k\Delta_i(k)}{\Delta_i(k)+\rho\times Max_iMax_k\Delta_i(k)},\quad(10)$$

where ρ means resolution ratio, $\rho\in[0,1]$, and ρ=0,5 generally. $\Delta_i(k)$ is the absolute difference of the k^{th} index between X_0 and X_i. $Min_i Min_k \Delta_i(k)$ means the two-level minimum difference, in which $Min_k \Delta_i(k)$ is the one-level minimum difference and expresses the shortest distance between the points on X_i and the corresponding points on X_0. On the basis of $Min_k \Delta_i(k)$, $Min_i Min_k \Delta_i(k)$ can be got from all the curves, according to $i = 1, 2,\dots, m$. $Max_i Max_k \Delta_i(k)$ means the two-level maximum difference, which has the same meaning of the two-level minimum difference.

(2) The association degree

The association degree is defined as the value that intensively shows the correlation coefficient of various indicators for the contrast sequence of number. Generally, remember the association degree between the contrast sequence of number X_i and the reference sequence of number X_0 as $R(X_0, X_i)$, which is abbreviated as R_{i0}. The calculating formula of the association degree is shown as Eq. (11):

$$R_{i0} = \frac{1}{n}\sum_{k=1}^{n} \omega(k)\xi_i(k) . \tag{11}$$

5.2 The case evaluation of CNC horizontal lathe product

(1) The determination of the reference sequence of number

The selecting principle of the reference sequence of number is to select the optimum value for each index. For example, the maximum value is chosen as the optimal value for maximal milling length (TC_1). For the surface roughness of the workpiece, the minimum value is chosen as the optional value for surface roughness of work pieces (TC_8). According to this principle, the reference sequence of number can be obtained through the analysis of the data from the case database of CNC horizontal lathe. Finally, the reference sequence of number is $\{x_0\}=\{TC_1$ (mm), TC_2 (mm), TC_3 (mm), TC_4 (mm), TC_5 (mm), TC_8 (μm)$\}=\{580, 450, 275, 635, 4500, 0{,}8\}$.

(2) The determination of the contrast sequence of number

For the product cases of CNC horizontal lathe, it has been found that the S values of HT1 (HTC3250), HT3 (HTC2558m) and HT4 (HTC2550m) are smaller according to the calculation in Section 4. Therefore, the technical parameters of these three similar cases are selected as the contrast sequence of number, and the contrast sequences of number are:

$$\{x_1\} = \{500, 320, 165, 630, 4000, 1{,}6\},$$
$$\{x_2\} = \{580, 250, 225, 610, 4000, 1{,}25\},$$
$$\{x_3\} = \{500, 250, 230, 635, 4000, 0{,}8\}.$$

(3) The normalization processing of the index value

From the reference sequence of number and contrast sequences of number, it can be seen that for different index, there are differences in the order of magnitudes. In order to make each index have the same order of magnitudes, it is necessary to carry out the normalization processing. The approach used in this paper is linear normalized method. Eq. (12) is the normalized calculation formula for the index that chooses the maximum value as the optimal value, and Eq. (13) is the normalized calculation formula for the index that chooses the minimum value as the optimal value.

$$x'_{ik} = \frac{x_{ik}}{\max_i x_{ik}}, \tag{12}$$

$$x'_{ik} = \frac{\min_i x_{ik}}{x_{ik}}, \tag{13}$$

where, $\max_i x_{ik}$ and $\min_i x_{ik}$ denote the maximum value and the minimum value of the k^{th} index in the reference sequences of number and the contrast sequences of number, where $i = 0, 1, 2, 3$ and $k = 1, 2, \dots, 6$. After the normalization processing of the reference sequence of number and contrast sequences of number, the results are shown as follows:

$$\{x_0\} = \{1{,}0000; 1{,}0000; 1{,}0000; 1{,}0000; 1{,}0000; 1{,}0000\},$$
$$\{x_1\} = \{0{,}8621; 0{,}7111; 0{,}6000; 0{,}9921; 0{,}8889; 0{,}5000\},$$
$$\{x_2\} = \{1{,}0000; 0{,}5556; 0{,}8182; 0{,}9906; 0{,}8889; 0{,}6400\},$$
$$\{x_3\} = \{0{,}8621; 0{,}5556; 0{,}8364; 1{,}0000; 1{,}0000; 1{,}0000\}.$$

(4) The calculation of the correlation coefficient

The absolute difference $\Delta_i(k)$ (one-level difference) for each sequence of number is obtained by means of Eq. (9):

$$\Delta_1 = (0{,}1379; 0{,}2889; 0{,}4000; 0{,}0079; 0{,}1111; 0{,}5000),$$
$$\Delta_2 = (0; 0{,}4440; 0{,}1818; 0{,}0384; 0{,}1111; 0{,}3600),$$
$$\Delta_3 = (0{,}1379; 0{,}4444; 0{,}1636; 0; 0; 0).$$

According to the absolute difference for each sequence of number, the two-level maximum difference can be obtained as 0,5000, and the two-level minimum difference is 0.

Take the results of two-level maximum difference and two-level minimum difference into Eq. (10), and set ρ=0,5, then the correlation coefficient is calculated as:

$$\xi_i(k) = \frac{Min_i Min_k \Delta_i(k) + \rho \times Max_i Max_k \Delta_i(k)}{\Delta_i(k) + \rho \times Max_i Max_k \Delta_i(k)} =$$
$$= \frac{0 + 0{,}5 \times 0{,}5}{\Delta_i(k) + 0{,}5 \times 0{,}5} = \frac{0{,}25}{\Delta_i(k) + 0{,}25}.$$

Take the values of $\Delta_i(k)$ into the above formula, then the results are:

$$\xi_1 = (0{,}6444; 0{,}4639; 0{,}3846; 0{,}9695; 0{,}6923; 0{,}3333),$$
$$\xi_2 = (1{,}000; 0{,}3600; 0{,}5789; 0{,}8639; 0{,}6923; 0{,}4098),$$
$$\xi_3 = (0{,}6444; 0{,}3600; 0{,}6044; 1{,}000; 1{,}000; 1{,}000).$$

(5) The calculation of the relational grades

The weights for evaluating the index are the same as those for retrieving the cases, which is denoted as w_k = (0,190; 0,190; 0,162; 0,162; 0,173; 0,123). Take the weights and the correlation coefficient into Eq. (11), the results of the relational grades are: R_1 = 0,0844, R_2 = 0,0946, R_3 = 0,1067.

According to the calculations in Section 4 and this section, it can be found that for the product case that has the smallest similar sequence value *S*, the relational grade is not always the highest. So it is necessary to balance the two aspects in order to select the product case that best matches the customer requirements. Through considering the two aspects, *S* values and the relational grades, HTC2550m is chosen as the product case that best matches the customer requirements.

5.3 Case modification of modular product

In order to satisfy the design requirements, it is necessary to modify some parts of the similar case, and this process is known as case modification. In the process of case modification, first, the designer needs to find the differences between the case and the new design requirements, and then modify the parts that do not meet the requirements.

At present, there are many ways to realize the case modification. The method of frame-based product case transformation can be used to realize them. The process can be described as follows: first the most similar product case is conducted as the frame; then the modules that do not match the attribute values of the new design requirements can be retrieved from the modules library by using the same principle and approach introduced above about modular product case. If there exist the modules that match the attribute values in the modules library, these modules are used to replace. If not, it is necessary to modify the modules which do not match, or create new modules.

6 Conclusions

CNC machine tool is one of the basic equipment of manufacturing industry and a symbol of advanced manufacturing technology. The introduction of modular design method into the design and production processes of CNC machine tool has an important theoretical and practical value. Combining the modular design technology with the case-based reasoning technology, this paper proposed one method of module configuration design for CNC machine tool. The key technologies including the transformation of customer requirements, the case retrieval and the case evaluation have been properly solved in the process of module configuration design. This paper discussed the acquisition and transformation of the customer requirements during the process of module configuration, and the mappings from the importance ratings of the customer requirements to the importance ratings of product technical characteristics by using QFD. The paper studied the technologies of CBR, and used the fuzzy similarity priority ratio and grey correlation analysis algorithm respectively to realize the calculation of case priority and the case evaluation and picked out the product case that best matches the customer requirements finally.

Acknowledgement

This work is supported by the Fundamental Research Funds for the Central Universities (N120403003), the Natural Science Fund of Liaoning Province (2013020052) and the Research Funds of State "Twelve Five" Support Program (2012BAF12B08).

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Authors' addresses

Zhongqi Sheng
School of Mechanical Engineering & Automation,
Northeastern University, Shenyang
110819, P. R. China
E-mail: zhqsheng@mail.neu.edu.cn

Lei Zhang
School of Mechanical Engineering & Automation,
Northeastern University, Shenyang
110819, P. R. China
E-mail: 18502408218@163.com

Hualong Xie
School of Mechanical Engineering & Automation,
Northeastern University, Shenyang
110819, P. R. China
E-mail: hlxie@mail.neu.edu.cn

Pengjia Wang
School of Mechanical Engineering & Automation,
Northeastern University, Shenyang
110819, P. R. China
E-mail: dongxiewpj876@163.com