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Improvement And Application Of Comprehensive Weighted Allocated Method Based On Fault Rate And Design Character

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Abstract. In order to solve the problem of weighting factor in the maintenance comprehensive weighted allocation model based on failure rate and design characteristics. Firstly, the fuzzy comprehensive evaluation method is introduced. Secondly, the fuzzy judgment matrix is established by using the three-scale method and the weight is obtained. Then the binary fuzzy contrast is used to establish the relationship matrix of the influencing factors and the evaluation matrix is obtained. The weighting factor is calculated by the fuzzy transformation. When the failure rates vary widely, the allocation results will weak the design characteristics by relying on the failure rate. So the weighting factor should be modified to improve the rationality of the distribution result. Finally, take a machining center as an example to verify the maintenance distribution application.

Key words: machining center ; maintenance allocation ; fuzzy comprehensive evaluation ; weighting factor

1. Introduction

Maintainability allocation refers to the design phase. At that process, the quantitative requirements of product maintenance shall be assigned to each component of the product layer by layer from the top of the system according to certain rules^[1,2]. At present, the reliability level of domestic CNC machine tools has been greatly improved, but failures are inevitable. In order to improve the usability of products, maintenance research is needed. Maintenance design determines maintenance level. As an important part of design, maintenance allocation has been paid more and more attention^[3]. Therefore, it is necessary to study the maintenance distribution of domestic CNC machine tools.

Commonly used maintenance allocation methods include: equal distribution method, distribution method by failure rate, comprehensive weighted distribution method by failure rate and design characteristics, distribution method by using maintenance data of similar products, guaranteed availability, and weighted distribution method by considering unit complexity^[4]. The comprehensive weighted allocation method based on fault rate and design characteristics is more accurate than the allocation method based on fault rate. The application of this method can significantly improve the allocation accuracy when the failure detection, adjustable, accessible, replaceable and hazardous information of the product have been obtained. Therefore, this method is widely used in maintenance allocation.

The comprehensive weighted allocation method based on fault rate and design characteristics regards all the influencing factors are equally important. And the weighting factor comes from the statistical analysis of product structure type, which inevitably affects the accuracy of distribution. As a result, firstly, this paper introduces the theory of fuzzy comprehensive evaluation. Then the fuzzy judgment matrix is established by using the three-scale method and the weight is obtained^[5,6].



Secondly, the relation matrix of influencing factors is established by applying the binary fuzzy contrast and the evaluation matrix will be obtained. Finally, the weighted factor is calculated by fuzzy transformation. In the case that the allocation results depend too much on the fault rate, the design characteristics are weakened [7]. Therefore, modifying the weighting factor to improve the accuracy of maintenance allocation.

2. Fuzzy maintainability distribution principle

The traditional comprehensive weighted distribution method based on the failure rate and design characteristics is to transform the factors that affect the design characteristics, such as fault detection, adjustable, accessibility and replaceable, into the weighted factor, and the component failure rate is used for allocation. Maintainability weighting factors are generally obtained from statistical data [4]. The weighting factor is obtained under the assumption of equal weight, which inevitably leads to error. Therefore, based on the traditional maintenance weighted distribution method based on failure rate and design characteristics, this paper introduces the fuzzy comprehensive evaluation method and proposes an improved distribution model as follows:

$$T_{CT_i} = \frac{\theta_i \cdot \sum_{i=1}^n \bar{\lambda}_i}{\bar{\lambda}_i \cdot \sum_{i=1}^n \theta_i} T_{CT} \quad (1)$$

Where: T_{CT} is the average repair time of the whole product; T_{CT_i} is the mean time to restoration (MTTR) of component i ; $\bar{\lambda}_i$ is the average failure rate of component i ; n is the number of components; θ_i is the maintainability weighting factor of component i .

2.1 Determination of maintainability weighting factor based on fuzzy evaluation

The process of establishing a maintenance weighting factor evaluation model using fuzzy comprehensive evaluation includes: using the three-scale method to establish the fuzzy judgment matrix of the influencing factors; using the row normalization method to find the weight vector \mathbf{W} ; applying the binary fuzzy contrast to establish the relationship matrix of the influencing factors and obtaining the evaluation matrix \mathbf{R} ; getting the weight factor vector \mathbf{Q} by fuzzy transformation.

$$\mathbf{Q} = \mathbf{W} \circ \mathbf{R} = [w_1, w_2, \dots, w_m] \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix} = [\theta_1 : \theta_2 : \dots : \theta_n] \quad (2)$$

2.1.1 Determination of the weight of the maintenance influence factor \mathbf{W}

Due to various factors impact on the whole is more complex. A simple three-scale method is used to establish a fuzzy judgment matrix and obtain weights. The fuzzy consistency matrix obtained by the fuzzy judgment matrix satisfies the consistency condition, so no consistency test is needed [8,9].

The steps are as follows:

(1) establishing fuzzy judgment matrix by using three-scale method:

$$\mathbf{F} = (f_{ij})_{m \times m} = \begin{cases} 0 & \text{factor } i \text{ is poorer than factor } j \\ 0.5 & \text{factor } i \text{ is the same as factor } j \\ 1 & \text{factor } i \text{ is better than factor } j \end{cases}$$

Where: m is the number of influencing factors.

(2) Transform the fuzzy judgment matrix \mathbf{F} into a fuzzy consistency judgment matrix \mathbf{Q}

$$\mathbf{Q} = (q_{ij})_{m \times m}, \text{ where: } q_{ij} = \frac{q_i - q_j}{2m} + \frac{1}{2}; \quad q_i = \sum_{j=1}^m f_{ij}.$$

(3) Using the row normalization method to obtain the weight vector:

$$\tilde{W} = (w_1, w_2, \dots, w_m) \quad (3)$$

$$\text{Where: } w_i = l_i / \sum_{i=1}^m l_i = \frac{2l_i}{m(m-1)} \quad i = 1, 2, \dots, m; \quad l_i = \sum_{j=1}^m q_{ij} - \frac{1}{2} \quad ; \quad \sum_{i=1}^m l_i = m(m-1)/2.$$

2.1.2. Determination of the evaluation matrix \tilde{R}

Using the binary fuzzy comparison method to obtain the influencing factors B_i of maintenance distribution. The relationship matrix \tilde{V} is:

$$\tilde{V}_i = \begin{bmatrix} \mu_{11}(B_i) & \mu_{12}(B_i) & \dots & \mu_{1n}(B_i) \\ \mu_{21}(B_i) & \mu_{22}(B_i) & \dots & \mu_{2n}(B_i) \\ \vdots & \vdots & \dots & \vdots \\ \mu_{n1}(B_i) & \mu_{n2}(B_i) & \dots & \mu_{nn}(B_i) \end{bmatrix}_{n \times n} \quad (4)$$

Where: $\mu_{jk}(B_i) = \frac{\delta_j(B_i)}{\delta_j(B_i) + \delta_k(B_i)}$, $1 \leq i \leq m$, $1 \leq j \leq n$, $1 \leq k \leq n$; $\delta_j(B_i)$ is the average of the expert score values of component A for the influencing factor j .

Then the evaluation matrix \tilde{R} of the influencing factors is:

$$\tilde{R} = (r_{ij})_{m \times n} = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & \dots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix}_{m \times n} \quad (5)$$

$$\text{Where: } r_{ij} = \frac{\sum_{k=1}^n \mu_{jk}(B_i)}{n}.$$

Substituting the formulas (3) and (5) into the formula (2), the weigh factor is obtained.

2.2 Distribution result correction and verification

The status of failure rate and design characteristics are equally important when performing maintenance distribution. However, when the subsystem failure rates vary greatly (close to or greater than one order of magnitude), the distribution results will inevitably rely too much on the failure rate and weaken the design characteristics. Therefore, there is a need for maintainability redistribution of this machining center.

The modified comprehensive weighting factor is β' [10]:

$$\beta'_i = \frac{\theta_i}{\theta} + \log_{\alpha} \frac{\bar{\lambda}_i}{\bar{\lambda}} \quad (6)$$

Where: $\bar{\lambda} = \frac{1}{n} \sum_{i=1}^n \bar{\lambda}_i$; the value of α is shown in Table 1.

Table 1. α standard table.

ξ (Ratio of maximum to minimum failure rate)	α
$1 \leq \xi < 10$	0.01
$10 \leq \xi < 100$	0.001
$100 \leq \xi < 1000$	0.0001
$1000 \leq \xi < 10000$	0.000001

Then, the restoration time that each subsystem should be assigned is:

$$T'_{CT_i} = \beta'_i T_{CT} \quad (7)$$

Bring the allocated maintenance time of each subsystem which is calculated by the above formula into the following formula:

$$T'_{CT} = \frac{\sum_{i=1}^n (\lambda_i \cdot T'_{CT_i})}{\sum_{i=1}^n \lambda_i} \quad (8)$$

If T'_{CT} is less than the maintenance allocation indicator T_{CT} , the adjusted distribution is considered to accord the requirements.

3. Case Analysis

This paper takes a domestic CNC machining center as an example, considers the user demand and the actual maintenance ability, and sets the maintainability index of the whole machine as $T_{CT} = 18h$. According to the functional and structural characteristics of machining center, the machining center can be divided into the following subsystems: spindle system (A_1), cooling system (A_2), electrical system (A_3), Tool magazine system (A_4), hydraulic system (A_5), pneumatic system (A_6), feeding system (A_7), lubrication system (A_8), numerical control system (A_9), auxiliary device (A_{10}), workbench (A_{11}).

According to the fault data collected and the method provided in reference [11], the average failure rate of each subsystem of the machining center is as shown in Table 2.

Table 2 Average failure rate of subsystem

Subsystem	λ_i	Subsystem	λ_i	Subsystem	λ_i
A_1	0.0009232	A_5	0.0001159	A_9	0.0006722
A_2	0.0006787	A_6	0.0001776	A_{10}	0.0004103
A_3	0.0002961	A_7	0.0006587	A_{11}	0.0002542
A_4	0.0006982	A_8	0.0004197		

In order to improve the maintenance level of the product, the subsystem with higher failure rate gives more stringent maintenance requirements, which means that lower *MTTR* is allocated to the system. On the other hand, it refers to the difficulty of product maintenance. Theoretically, the harder the product is to be repaired, higher *MTTR* should be allocated.

Combined with the maintenance characteristics of the machining center, the factors influencing maintenance allocation of the machining center are as follows: fault detection methods (B_1), replaceability (B_2), accessibility (B_3), adjustable (B_4) and perniciousness (B_5).

(1) Fault detection methods. Fault detection method in machining center can be divided into automatic, semi-automatic and manual detection. The higher *MTTR* is allocated to the subsystem which is not easy to detect the fault.

(2) Replaceability. Parts replacement in machining center can be divided into plug and pull, buckle, screw and welding. Typically, higher *MTTR* is allocated in the subsystem where the components are less likely to be replaced.

(3) Accessibility. The accessibility of machining center includes two aspects: whether the parts have cover and whether the cover can be removed quickly. In general, the higher *MTTR* is allocated in the subsystem where the cover is difficult to remove.

(4) Adjustable. Adjustment of machining center generally refers to whether adjustment is required after the replacement of new parts. Higher *MTTR* is allocated to more complex subsystems.

(5) Perniciousness. In order not to affect product quality, the more pernicious parts are, the faster the subsystem needs to be repaired after failure, so low *MTTR* is allocated to this subsystem.

Three scale method was used to compare the influence of the above five factors on the overall maintenance distribution. Then, according to the expert guidance results, the fuzzy judgment matrix of influencing factors is obtained as follows:

$$\mathbf{F} = \begin{pmatrix} 0.5 & 0.5 & 0 & 1 & 1 \\ 0.5 & 0.5 & 0 & 1 & 1 \\ 1 & 1 & 0.5 & 1 & 1 \\ 0 & 0 & 0 & 0.5 & 1 \\ 0 & 0 & 0 & 0 & 0.5 \end{pmatrix}$$

Transform the fuzzy judgment matrix into the fuzzy consistency matrix:

$$\mathbf{Q} = \begin{pmatrix} 0.5 & 0.5 & 0.35 & 0.65 & 0.75 \\ 0.5 & 0.5 & 0.35 & 0.65 & 0.75 \\ 0.65 & 0.65 & 0.5 & 0.8 & 0.9 \\ 0.35 & 0.35 & 0.2 & 0.5 & 0.6 \\ 0.25 & 0.25 & 0.1 & 0.4 & 0.5 \end{pmatrix}$$

By using formulas (3), the weight is calculated as:

$$\mathbf{W} = (0.225, 0.225, 0.3, 0.15, 0.1)$$

Because of the complexity of the sub-system of machining center, it is difficult to accurately evaluate the level of factors affecting maintenance. Therefore, the experts compared the importance of the different subsystems by using binary fuzzy comparison under different maintainability factors, and the score is shown in table 3.

Table 3 Score values of subsystem under each factor

Subsystem	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆	A ₇	A ₈	A ₉	A ₁₀	A ₁₁
Fault detection methods(B ₁)	7.3	5.1	4.7	5.3	5.9	5.9	6.6	5.1	3.5	4.1	3.3
Replaceability(B ₂)	4.3	3	4.5	3.5	3.5	3.7	5.5	2.5	2	2.5	3.3
Accessibility(B ₃)	6.6	3.3	4.6	4.5	3.8	4.1	6.2	4.6	3.2	4.1	2.5
Adjustable(B ₄)	3.2	1.8	1.7	3.5	1.8	2	4.5	1.8	1.1	1.2	1.6
Perniciousness(B ₅)	0.8	5.3	7.4	2.5	7.6	8.9	5.8	6.9	5.7	9.2	8.3

According to formula (4), five binary fuzzy contrast relation matrices \mathbf{V}_i are calculated. Due to space reasons, only \mathbf{V}_1 is listed here.

$$\mathbf{V}_1 = \begin{pmatrix} 0.5000 & 0.5887 & 0.6083 & 0.5794 & 0.5530 & 0.5530 & 0.5252 & 0.5887 & 0.6759 & 0.6404 & 0.6887 \\ 0.4113 & 0.5000 & 0.5204 & 0.4904 & 0.4636 & 0.4636 & 0.4359 & 0.5000 & 0.5930 & 0.5543 & 0.6071 \\ 0.3917 & 0.4796 & 0.5000 & 0.4700 & 0.4434 & 0.4434 & 0.4159 & 0.4796 & 0.5732 & 0.5341 & 0.5875 \\ 0.4206 & 0.5096 & 0.5300 & 0.5000 & 0.4732 & 0.4732 & 0.4454 & 0.5096 & 0.6023 & 0.5638 & 0.6163 \\ 0.4470 & 0.5364 & 0.5566 & 0.5268 & 0.5000 & 0.5000 & 0.4720 & 0.5364 & 0.6277 & 0.5900 & 0.6413 \\ 0.4470 & 0.5364 & 0.5566 & 0.5268 & 0.5000 & 0.5000 & 0.4720 & 0.5364 & 0.6277 & 0.5900 & 0.6413 \\ 0.4748 & 0.5641 & 0.5841 & 0.5546 & 0.5280 & 0.5280 & 0.5000 & 0.5641 & 0.6535 & 0.6168 & 0.6667 \\ 0.4113 & 0.5000 & 0.5204 & 0.4904 & 0.4636 & 0.4636 & 0.4359 & 0.5000 & 0.5930 & 0.5543 & 0.6071 \\ 0.3241 & 0.4070 & 0.4268 & 0.3977 & 0.3723 & 0.3723 & 0.3465 & 0.4070 & 0.5000 & 0.4605 & 0.5147 \\ 0.3596 & 0.4457 & 0.4659 & 0.4362 & 0.4100 & 0.4100 & 0.3832 & 0.4457 & 0.5395 & 0.5000 & 0.5541 \\ 0.3113 & 0.3929 & 0.4125 & 0.3837 & 0.3587 & 0.3587 & 0.3333 & 0.3929 & 0.4853 & 0.4459 & 0.5000 \end{pmatrix}$$

According to formula (5), the evaluation matrix \mathbf{R} of influencing factors is obtained:

$$\mathbf{R} = \begin{pmatrix} 0.5910 & 0.5036 & 0.4835 & 0.5131 & 0.5395 & 0.5395 & 0.5668 & 0.5036 & 0.4117 & 0.4500 & 0.3977 \\ 0.5609 & 0.4729 & 0.5718 & 0.5107 & 0.5107 & 0.5243 & 0.6192 & 0.4996 & 0.3760 & 0.4286 & 0.4962 \\ 0.6111 & 0.4430 & 0.5243 & 0.5189 & 0.4774 & 0.4960 & 0.5964 & 0.5036 & 0.4355 & 0.4960 & 0.3770 \\ 0.6109 & 0.4749 & 0.4612 & 0.6311 & 0.4749 & 0.5001 & 0.6853 & 0.4990 & 0.3602 & 0.3798 & 0.4468 \\ 0.1514 & 0.4908 & 0.5673 & 0.3286 & 0.5733 & 0.6089 & 0.5114 & 0.5513 & 0.5075 & 0.6163 & 0.5933 \end{pmatrix}$$

According to formula (2), the fuzzy evaluation result \mathbf{B} of maintainability weighted factor is obtained:

$$\mathbf{B} = \{0.5493, 0.4729, 0.5206, 0.5136, 0.5081, 0.5241, 0.4387, 0.5068, 0.4127, 0.4651, 0.4406\}$$

Considering the problem that the distribution results depend too much on the fault rate and weaken the design characteristics when the failure rates vary greatly, the weighted factor is corrected. According to the value standard table of table 1 and the failure rate data of table 2, let $\alpha = 0.01$. By formula (6), the modified comprehensive weighting factor can be obtained as follows:

$$\beta'_i = \{0.9877, 0.8976, 1.1758, 0.9749, 1.3536, 1.2938, 0.8337, 1.0715, 0.7758, 0.9908, 1.0444\}$$

According to formula (7), the revised maintenance time distribution of each subsystem should be calculated as:

$$T'_{ci} = \{17.78, 16.16, 21.16, 17.55, 24.37, 23.29, 15.01, 19.29, 13.96, 17.83, 18.80\}$$

According to formula (8), the average repair time of the whole machine T'_{CT} is calculated. If $T'_{CT}=17.40h \leq 18h$, the adjusted distribution results are considered to meet the requirements.

Referring to the above results, higher *MTTR* should be allocated for electrical system, hydraulic system and pneumatic system, while lower *MTTR* should be allocated for numerical control system and feeding system, which is basically consistent with the actual situation. It can be seen that this method has good practicability.

4. Conclusion

- (1) For the problem that weight cannot be calculated under the data of influencing factors. Fuzzy mathematics tri-scale method is introduced to establish the fuzzy judgment matrix of factors influencing maintenance allocation and to solve the weight. The method can effectively reduce the difficulty of decision-making and the subjective error of evaluation of influencing factors by different experts.
- (2) Based on the comprehensive weighting method of fault rate and design characteristics, a fuzzy comprehensive evaluation method combining quantitative analysis and qualitative analysis is introduced. Fuzzy mathematics is applied to quantify the weight of each influencing factor and each subsystem, which gives full play to the role of the expert and reduces the judgment error caused by subjective judgment.
- (3) Considering that while the distribution results are too dependent on the failure rate due to the failure rate varies greatly, the design characteristics will be weakened. So the weighted factor is corrected to make the maintenance allocation decision more reasonable. Providing a scientific and reasonable method for the maintenance allocation of products.

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