Research on importance evaluation of NC machine tool working loads based on AHP-fuzzy comprehensive evaluation method

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Abstract. The NC machine tool are subjected to a variety of working load during the actual machining process. The influence of different kinds of working loads on the NC machine tool’s reliability level are different. Therefore, this paper proposes an importance evaluation method of NC machine tool working loads based on analytic hierarchy process (AHP) -fuzzy comprehensive evaluation to judge the influence of different kinds of working loads on the reliability level. Firstly, the hierarchical structure of the importance evaluation of NC machine tool working loads is established, and then the structure of discrimination matrix and the consistency test of the matrix are determined. Secondly, the fuzzy membership R of the fuzzy subset is established, and then the weight vector M of the evaluation factor and the evaluation result vector S of the fuzzy comprehensive evaluation are determined to realize the quantitative analysis of the fuzzy object. Finally, the importance of calculating the machining center load is ranked as cutting force, feed rate, torque, tool changing frequency, temperature and noise in the example.

Keywords: AHP, fuzzy comprehensive evaluation, NC machine tool, working load, importance evaluation.

1. Introduction

The NC machine tool’s working load during the actual machining process have different influences on the NC machine tool’s reliability level. The influence of certain working loads on the NC machine tool’s reliability level is nonnegligible. The collection and storage of load data increases the difficulty of the work [1]. Therefore, it is of great significance to study the ability of different working loads to influence the NC machine tool’s reliability level.

Fang and Jawahir developed a methodology to give the quantitative assessments of the total machining performance in finish turning using the integrated fuzzy set models of machinability parameters [2]. Qian Wang applies the fuzzy comprehensive evaluation method to construct a comprehensive index and use the AHP and Delphi expert consultation method to determine weights of indicators. Furthermore, the comprehensive evaluation of nine core energy-saving technical measures
of tobacco industry is made [3]. Jun H established the model of a fuzzy comprehensive evaluation based on the AHP to quantitatively evaluate the seismic risk of the region with covers 3080.25 km² including hydraulic fracturing operation areas [4]. Zadeh proposed the fuzzy set theory to express the uncertainty of things [5]. Ramesh described an application of fuzzy rule-based modeling for the prediction of tool flank wear, surface roughness, and specific cutting pressure in the turning of titanium alloy. Based on the fuzzy set theory, the fuzzy comprehensive evaluation method can make a general evaluation of the objects affected by multiple factors [6]. It can be seen that AHP and fuzzy comprehensive evaluation methods are widely used.

Qingzhong Xu used fuzzy comprehensive evaluation method to evaluate the cutting performance of cemented carbide tools. The results indicate that cerments with the best comprehensive cutting performance are chosen as the optimum tool materials for the machining of high-strength steels. The analysis of tool wear proves the reliability and accuracy of fuzzy comprehensive evaluation method [7]. Ping Zhang evaluated the food effect of oilfield water by fuzzy comprehensive evaluation method. The results show that the method can accurately evaluate the effect of rapeseed water food [8]. With clear results and strong systematicness, the fuzzy comprehensive evaluation method can effectively solve various non-deterministic problems, which are fuzzy and difficult to quantify. The fuzzy comprehensive evaluation method can be used for tool selection [9]. Therefore, this paper uses the AHP-fuzzy comprehensive evaluation method to evaluate the influence of different working load on the reliability level of NC machine tools.

2. AHP-fuzzy comprehensive evaluation method

2.1. The establishment of AHP

2.1.1. Hierarchical structure. When applying AHP to analyze decision problems, the hierarchical structure is used to decompose complex problems into a set of multiple hierarchical elements, namely, target layer, criterion layer, and indicator layer. The hierarchical structure is shown in Fig.1.

![Hierarchical structure](image)

2.1.2. Structural discriminant matrix. The ratio of the degree of influence of the two different factors \( x_i \) and \( x_j \) on the target is taken by the discriminant matrix, and the comparison result of the \( n \) different factors can be represented by the discriminant matrix \( C=(a_{ij})_{n\times n} \). If the ratio of the influence degree of \( x_i \) and \( x_j \) on the target is \( a_{ij} \), then the ratio of the influence of \( x_j \) and \( x_i \) on the target should be \( a_{ji} \), where \( a_{ij}=1/a_{ji} \). The value of \( a_{ij} \) and \( a_{ji} \) is determined by the 1-9 scale method in Table 1 [10].

| \( a_{ij} \) | Definition                      |
|-----------|--------------------------------|
| 1         | \( x_i \) and \( x_j \) are equally important |
| 3         | \( x_i \) and \( x_j \) are slightly important |
| 5         | \( x_i \) and \( x_j \) are obviously important |
| 7         | \( x_i \) and \( x_j \) are very important |
| 9         | \( x_i \) and \( x_j \) are extremely important |
| 2, 4, 6, 8| Two adjacent comparison scale intermediate values |
2.1.3. Consistency test. In general, the consistency test is described by the consistency ratio indicator (C.R). C.R can be expressed by equation (1):

$$C.R = \frac{C.I}{R.I}$$  

Where C.I is the consistency test index, C.I= (λmax-n)/(n-1), λmax is the maximum eigenvalue of the discriminant matrix, and the randomness index (R.I) is shown in the Table 2.

Table 2. The R.I of orders n in different discriminant matrix.

| n | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|---|---|----|----|----|----|----|----|----|----|
| R.I | 0  | 0  | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

Generally, if C.R<0.1, the discriminant matrix is a consistency matrix, otherwise the judgment matrix needs to be reset.

2.2. Fuzzy comprehensive evaluation method

The fuzzy comprehensive evaluation analysis method takes the fuzzy object and the concept of reflecting the fuzzy object as the fuzzy set, and then the appropriate fuzzy membership function is established, and the fuzzy object is quantitatively analyzed through the correlation operation and transformation of the fuzzy set theory [11]. The main steps of the fuzzy comprehensive evaluation analysis method are as follows.

Step 1: The set U of the evaluation index u of the p fuzzy comprehensive evaluation objects is determined, U= {u1, u2,..., up}.

Step 2: The importance level and value set are determined in the Table 3.

| Level | 1  | 2  | 3  | ... | n-1 | n |
|---|---|----|----|-----|-----|---|
| Value | n  | n-1 | n-2 | ... | 2   | 1 |

Step 3: After determining the fuzzy subset corresponding to the important level, each factor ui of the selected evaluation object is quantized, and then the membership degree matrix R of the fuzzy subset of the evaluated object is obtained in equation (2).

$$R = \begin{bmatrix}
    r_{11} & r_{12} & \cdots & r_{1m} \\
    r_{21} & r_{22} & \cdots & r_{2m} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{p1} & r_{p2} & \cdots & r_{pm}
\end{bmatrix}_{p,m}$$  

Where the i-th row and the j-th column element rij in the fuzzy membership matrix R represent the membership degree of the evaluated object from the factor ui to the vj level fuzzy subset.

Step 4: The weight vector M of the evaluation factor are determined. The weight vector M= [a1, a2, ..., ap], Σai=1, and the element ai is the membership degree of the factor ui to the fuzzy subset.

Step 5: The evaluation result vector S of the fuzzy comprehensive evaluation is equal to the product of the weight vector M of the evaluation factor and the fuzzy membership matrix R, S=M*R.

3. Case analysis

The case analysis of the machining center to evaluate the importance of different working loads. In order to construct the hierarchical structure, firstly, the reliability level of the machining center (A1) is
determined as the target layer of AHP. Secondly, based on the cumulative damage theory, the NC machine tool working load is mainly applied to the spindle system and feed system. The on-site statistical analysis shows that the ATC system is also the key subsystem with high failure rate of the machining center, so the spindle system, the feed system and the ATC system are selected as the criteria layer of AHP. Finally, the cutting force (C1), torque (C2), noise (C3), feed speed (C4), temperature (C5), tool change (C6) six kinds of NC machine tool working loads are determined as the indicator layer of AHP. The hierarchical structure of machining center is shown in the Fig.2.

![Figure 2. The hierarchical structure of Machining center.](image)

The discriminant matrix of A1, B1, B2, and B3 is constructed by Table 2, the discriminant matrix of A1, B1, B2, and B3 is shown in the Table 4-7.

**Table 4. The discriminant matrix of A1**

|     | B1  | B2  | B3  |
|-----|-----|-----|-----|
| B1  | 1   | 2   | 3   |
| B2  | 0.5 | 1   | 2   |
| B3  | 0.3333 | 0.5 | 1   |

**Table 5. The discriminant matrix of B1**

|     | C1   | C2   | C3   | C4   | C5   | C6   |
|-----|------|------|------|------|------|------|
| C1  | 1    | 3    | 8    | 5    | 7    | 5    |
| C2  | 0.3333 | 1    | 9    | 4    | 6    | 4    |
| C3  | 0.125 | 0.1111 | 1     | 0.1666 | 0.5  | 0.25 |
| C4  | 0.2  | 0.25 | 6    | 1    | 6    | 4    |
| C5  | 0.1429 | 0.1666 | 2     | 0.1666 | 1    | 2    |
| C6  | 0.2  | 0.125 | 4    | 0.25 | 0.5  | 1    |

**Table 6. The discriminant matrix of B2**

|     | C1   | C2   | C3   | C4   | C5   | C6   |
|-----|------|------|------|------|------|------|
| C1  | 1    | 2    | 9    | 0.25 | 7    | 8    |
| C2  | 0.5  | 1    | 8    | 0.25 | 6    | 7    |
| C3  | 0.1111 | 0.125 | 1     | 0.1111 | 0.5  | 1    |
| C4  | 4    | 4    | 9    | 1    | 8    | 7    |
| C5  | 0.1429 | 0.1666 | 2     | 0.125 | 1    | 2    |
| C6  | 0.125 | 0.1429 | 1     | 0.1429 | 0.5  | 1    |
Table 7. The discriminant matrix of B3

| B3 | C1 | C2 | C3 | C4 | C5 | C6 |
|----|----|----|----|----|----|----|
| C1 | 1  | 1  | 0.5| 1  | 0.2| 0.1111 |
| C2 | 1  | 1  | 0.5| 1  | 0.2| 0.1111 |
| C3 | 2  | 2  | 1  | 2  | 0.5| 0.25 |
| C4 | 1  | 1  | 0.5| 1  | 0.2| 0.1429 |
| C5 | 5  | 5  | 2  | 5  | 1  | 0.25 |
| C6 | 9  | 9  | 4  | 7  | 4  | 1    |

Firstly, the maximum eigenvalues of the respective discriminant matrices are respectively obtained as 3.0092, 6.5613, 6.4076, and 6.0910, and the consistency test indicators of the discriminant matrix are respectively 0.0046, 0.1122, 0.0815, and 0.0182. Finally, the consistency ratio can be obtained according to the formula. The index CR is 0.0079, 0.090, 0.066, 0.0147. All C.R values are less than 0.1, so all discriminant matrices can pass the consistency test.

The A1 discriminant matrix is added row by row, and the normalization process is performed to obtain the weight vector $K = [0.5294 \ 0.3088 \ 0.1618]$. Similarly, the weight vector $K_1$ of the discriminant matrix B1 is $[0.3473 \ 0.2914 \ 0.0257 \ 0.2090 \ 0.0656 \ 0.0610]$, the discriminant matrix B2 is $[0.2893 \ 0.2415 \ 0.0302 \ 0.3503 \ 0.0577 \ 0.0309]$, and the weight vector $K_3$ of the discriminant matrix B3 is $[0.0533 \ 0.0533 \ 0.1084 \ 0.0538 \ 0.2554 \ 0.4758]$. The calculated weight vector of the evaluation factor M is $[0.2621 \ 0.1885 \ 0.0288 \ 0.2329 \ 0.1217 \ 0.1659]$ T in Table 8.

Table 8. The weight of evaluation indicator

| Weight | B1 Level | B2 Level | B3 Level | Total weight | Total value | M   |
|--------|----------|----------|----------|--------------|-------------|-----|
| C1     | 0.3473   | 0.2893   | 0.533    | 0.6899       | 13          | 0.2621 |
| C2     | 0.2914   | 0.2415   | 0.0533   | 0.5862       | 11          | 0.1885 |
| C3     | 0.0257   | 0.0302   | 0.1084   | 0.1643       | 6           | 0.0288 |
| C4     | 0.2090   | 0.3503   | 0.0538   | 0.6131       | 13          | 0.2329 |
| C5     | 0.0656   | 0.0577   | 0.2554   | 0.3787       | 11          | 0.1217 |
| C6     | 0.0610   | 0.0309   | 0.4758   | 0.5677       | 10          | 0.1659 |

Note: The product of the total weight value and the total value is normalized to obtain M.

The fuzzy membership matrix R can be expressed as follows.

$$R = \begin{pmatrix}
0.3473 & 0.2893 & 0.0533 \\
0.2914 & 0.2415 & 0.0533 \\
0.0257 & 0.0302 & 0.1084 \\
0.2090 & 0.3503 & 0.0538 \\
0.0656 & 0.0577 & 0.0255 \\
0.0610 & 0.0309 & 0.4758
\end{pmatrix}$$

The evaluation result vector S of the fuzzy comprehensive evaluation can be expressed as follows:

$$S = M \ast R = \begin{pmatrix}
0.0910 & 0.0758 & 0.0139 \\
0.0549 & 0.0455 & 0.0010 \\
0.0007 & 0.0009 & 0.0031 \\
0.0487 & 0.0816 & 0.0125 \\
0.0080 & 0.0070 & 0.0031 \\
0.0101 & 0.0051 & 0.0789
\end{pmatrix}$$
The values of each row of $S$ are added, and the evaluation result vectors of cutting force, torque, noise, feed rate, temperature, and tool change times are respectively $S_1=0.1807$, $S_2=0.1014$, $S_3=0.0047$, $S_4=0.1428$, $S_5=0.0181$, $S_6=0.0941$. It can be judged that the importance of machining center’s working load is ranked as cutting force, feed speed, torque, tool change, temperature and noise.

4. Conclusion

In this paper, an importance evaluation method based on AHP-fuzzy comprehensive evaluation of NC machine tool’s working load is proposed to judge the influence of different working load on the NC machine tool’s reliability level. Firstly, the hierarchical structure of the importance evaluation of NC machine tool working load is established and then the structure of discrimination matrix and the consistency test of the matrix are determined. Secondly, the fuzzy membership degree $R$ of the fuzzy subset of the evaluation factor is established. Finally, the weight vector $M$ of the evaluation factor and the evaluation result vector $S$ of the fuzzy comprehensive evaluation are determined to realize the quantitative analysis of the fuzzy object.

In the example, it can be obtained that the working load with great influence on the spindle system is cutting force and torque, and the working load with great influence on the feeding system is the feed speed and cutting force, and the working load with great influence on the ATC system is the tool change and temperature. By comparing the evaluation result vectors for each working load, the importance of the machining center load is ranked as cutting force, feed speed, torque, tool change, temperature and noise.

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