Research on Availability Function Deployment for Motorized Spindle based on User Requirement

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Abstract. Users are the basis for the survival and development of enterprises. Only by understanding user requirement can products have sufficient competitiveness. In this paper, the machining center motorized spindle is taken as the research object. Based on the user requirement, this paper takes the motorized spindle as the research object, and combines the failure performance characteristics to expand the availability function. This method can transform the requirement information into the availability improvement strategy of the motorized spindle weak links, which is an effective method to quickly improve the availability level of the machining center motorized spindle.

1. Introduction
As the key functional component of machining center, motorized spindle has the characteristics of high speed and high precision. Its availability largely restricts the availability level of the machining center. Availability means the ability of a product to be in an executable specified functional state under specified conditions and specified time or time interval. It is a comprehensive reflection of reliability and maintainability. Current availability studies are mostly single factor studies based on failure data, such as failure mode impact and criticality analysis[1-2], availability evaluation[3], impact analysis[4], etc. The ultimate goal of availability research is to improve and enhance availability. However, the above research has less analysis of user requirement, and the availability improvement strategy cannot quickly meet the user requirement. Based on this, this paper takes the machining center motorized spindle as the object, intends to study the availability function deployment, and determines the availability improvement strategy from the user requirement for product availability.

2. Phased research method of availability function deployment
Referring to the QFD method[5-6], this paper transforms the user requirement for availability into the design, manufacture, assembly, outsourcing, and other aspects of the production chain by constructing the availability house as shown in Figure 1.

2.1 Determining the Weight of Availability Requirement Index Based on Improved AHP Method
Constructing the user availability requirement index system and determining the index weight is the starting point and key of availability function deployment.

The AHP helps to reduce the human factors in the evaluation and make the determination of the weight of the availability index more scientific. But the scale value often cannot fully reflect the
relationship between the indexes. Therefore, this paper uses the improved AHP method to construct the availability requirement index weight.

2.1.1 The hierarchical structure of availability requirement index.

By analyzing the machine tool enterprise workflow, product, service characteristics, and market characteristics, the hierarchy of the availability index system is constructed, as shown in Fig. 2.

2.1.2 Determine the scoring criteria of AHP.

In order to determine the weight coefficient as reasonably as possible, this paper uses the improved ‘1-9 scale grading method’ of AHP to determine the relative importance of the evaluation index [7]. As shown in Table 1. The table reflects the scores of the relative importance of the two indexes. If the comparison score of the index \(i\) relative to the index \(j\) is \(a_{ij}\), then the comparison score of index \(j\) relative to the index \(i\) is \(a_{ji} = 1/a_{ij}\).

| Score | Meaning (the importance of one indicator relative to another) |
|-------|-------------------------------------------------------------|
| 5.5   | The two indexes are of equal importance.                    |
| 6:4   | The former index is slightly more important than the latter one. |
| 7:3   | The former index is obviously more important than the latter one. |
| 8:2   | The former index is mightily more important than the latter one. |
| 9:1   | The former index is extremely more important than the latter one. |
| 5.5:4.5, 6.5:3.5, 7.5:2.5, 8.5:1.5 | Intermediate score of the above adjacent judgment. |

2.1.3 Establish judgment matrix.

Assuming that there are \(n\) elements, \(n(n-1)/2\) pairs of comparisons are required. The value of the pairwise comparison is the improved 1-9 scale scoring scale. The results of the comparison of \(n\)
elements are placed in the upper triangle part of the judgment matrix, and the value of the lower triangle part is the reciprocal of the relative position value of the upper triangle.

According to Table 1, the judgment matrix for pairwise comparison can be constructed. Where \( a_{ij} > 0 \), \( a_{ij} = (a_{ji})^{-1}, \ a_{ii} = 1, \ i, j = 1, 2, \ldots, n \). In the same way, the judgment matrix \( R_0 \) and \( M_0 \) of the secondary index can be obtained.

### 2.1.4 Maximum eigenvalue and eigenvector.

Taking the judgment matrix \( A_0 \) as an example, the calculation steps are as follows:

First, the elements in \( A_0 \) are normalized by column, that is,

\[
\bar{a}_{ij} = a_{ij} \left( \sum_{k=1}^{n} a_{ik} \right)^{-1}, (i, j, k = 1, 2, \ldots, n) \tag{1}
\]

Second, the weight is calculated by the following formula,

\[
a_i = \frac{1}{n} \sum_{j=1}^{n} a_{ij} \left( \sum_{k=1}^{n} a_{kj} \right)^{-1} \tag{2}
\]

Finally, the maximum characteristic root is calculated by the following formula,

\[
\lambda_{\text{max}} = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{1}{a_i} \sum_{j=1}^{n} a_{ij} \right) \tag{3}
\]

### 2.1.5 Consistency check.

The consistency index \( CR = CI / RI \) is used to test the consistency of the judgment matrix.

\[
CI = (\lambda_{\text{max}} - n)/(n-1) \tag{4}
\]

Determine the consistency index \( RI \) value according to the improved 1-9 scale.

### Tab.2 Average Random Consensus Index \( RI \)

| Matrix order | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \( RI \)     | 0   | 0   | 0.1690 | 0.2598 | 0.3287 | 0.3694 | 0.4007 | 0.4167 | 0.7430 |

When \( CR \leq 0.1 \), the judgment matrix is considered to have satisfactory consistency; when \( CR > 0.1 \), the given judgment matrix is considered to be inconsistent with the complete consistency condition, and needs to be adjusted and corrected to generate a new judgment matrix until satisfactory consistency is achieved.

### 2.1.6 Determining the weight of index.

The index weight can be calculated by multiplying each index that must be passed from the total target to each node element. The weight matrix of the requirement index \( W = (w_j)_{n \times m}, j = 1, 2, \ldots, n \), can be determined by normalizing the multiplication.

### 2.2 Failure Mode Impact Analysis Based on Availability Requirement

#### 2.2.1 Building the correlation matrix of availability requirement and failure modes.

The division basis of the correlation coefficient from each failure mode to the availability requirement index is shown in Table 3. The correlation matrix, \( C = (c_{ji})_{n \times m} \), can be determined according to the table. Where \( c_{ji} \) is the correlation coefficient between the failure mode \( i \) and the requirement index \( j \), \( i = 1, 2, \ldots, m \).
2.2.2 The self-correlation matrix of failure mode.
The self-correlation matrix of failure mode, $F=(f_{ik})_{m \times m}$, can be obtained by analyzing the independent failure and related failure of the motorized spindle by pairwise comparison method. Where $f_{ik}$ is the correlation coefficient between the two failure modes.

2.2.3 Solving the comprehensive effect weight of failure mode.
For the availability house with $n$ failure modes and $m$ availability requirement indexes, there are the following steps to calculate its output matrix:

1) When only the correlation between requirement indexes and failure modes is considered, the effect weight of failure mode $i$, $U_{S0i}$:

$$U_{S0i} = \sum_j (w_j c_{ij})$$ (5)

2) The comprehensive effect weigh $U_S$ of the failure mode $i$ after considering the self-correlation of failure mode.

$$U_S = \sum_{k=1}^{m} \sum_{j} (f_{ik} w_j c_{jk})$$ (6)

According to Fig. 1, the formula (6) can be transformed into:

$$U_S = [F(W^T C)^T]_i$$ (7)

2.3 Availability function deployment of production chain dimension

2.3.1 Determining correlation matrix of failure mode to production chain.
The availability improvement design of the failure mode is mainly carried out through the specific links in the production chain. Therefore, this section will expand the availability function of the failure mode in the production chain.

In general, we divide the production chain $P$ into four links: outsourcing $P_1$, manufacturing $P_2$, assembly $P_3$, design $P_4$. The score basis for the correlation coefficient between failure mode and production chain factors is shown in Table 4.

| Tab 4: Correlation Coefficient Division Basis of Failure Mode→Production Chain |
|-------------------|-----------------------------|
| Value             | Meaning                     |
| 9                 | Production chain factor $l$ responds very strongly to failure mode $i$. |
| 7                 | Production chain factor $l$ responds strongly to failure mode $i$. |
| 5                 | Production chain factor $l$ has obvious response to failure mode $i$. |
| 3                 | Production chain factor $l$ has slightly response to failure mode $i$. |
| 1                 | Production chain factor $l$ has weak response to failure mode $i$. |
| 2,4,6,8           | Between the two adjacent levels. |

Correlation coefficient $C'_{S\rightarrow P} = (c'_{ik})_{m \times 4}$, from failure mode to production chain, can be constructed according to Table 4.
2.3.2 Solving the effect weight of production chain.
The effect weight of production chain $i$, $U_{pi}$:

$$U_{pi} = \sum_{j}^{n} (U_{Sj} e_{ji})$$  \hspace{1cm} (8)

The effect weight Matrix of production chain $U_p$:

$$U_p = U_{S}^{T} C_{S \rightarrow P}$$  \hspace{1cm} (9)

The improvement focus can be determined according to the $U_{pi}$ ranking.

3. Availability function deployment of motorized spindle

3.1 Availability requirement index weight of motorized spindle

According to Figure 2 and Table 1, the judgment matrix $A_0$, $R_0$, and $M_0$ of availability requirement indexes are constructed as follows.

$$A_0 = \begin{bmatrix} 1 & 5.5:4.5 \\ 4.5:5.5 & 1 \end{bmatrix}$$  \hspace{1cm} (10)

$$R_0 = \begin{bmatrix} 1 & 5.5:4.5 \\ 4.5:5.5 & 1 \end{bmatrix}$$  \hspace{1cm} (11)

$$M_0 = \begin{bmatrix} 1 & 4:6 & 7.5:2.5 & 6:4 & 2.5:7.5 \\ 6:4 & 1 & 8:2 & 7.5:2.5 & 4:6 \\ 2.5:7.5 & 2:8 & 1 & 3:7 & 2:8 \\ 4:6 & 2.5:7.5 & 7:3 & 1 & 3.5:6.5 \\ 7.5:2.5 & 6:4 & 8:2 & 6:5:3.5 & 1 \end{bmatrix}$$  \hspace{1cm} (12)

After testing, the above matrices all meet the consistency requirements.

According to the method of 2.1 section, the availability requirement index weight matrix $W$ of the motorized spindle is determined as follows.

$$W = (0.302, 0.2475, 0.0769, 0.1262, 0.0300, 0.0608, 0.1566)$$  \hspace{1cm} (13)

3.2 Failure mode comprehensive effect weight of motorized spindle

According to the failure characteristics of the motorized spindle, the failure modes are defined as follows: High-Temperature $S_1$, Insufficient Machining Accuracy $S_2$, Overcut Processing $S_3$, Cylinder Leaking $S_4$, Abnormal Tool Changing $S_5$, Abnormal Sound $S_6$, Abnormal Vibration $S_7$, Inaccurate Positioning $S_8$, Orientation Function Failure $S_9$, Electric Leaking $S_{10}$, Invalid Tool Loosing $S_{11}$, Wear $S_{12}$.

According to the section 2.2, we can construct the correlation matrix $C$ and the self-correlation matrix $F$, solve the $U_{S}$ and form the 'Availability house' as shown in the Fig.3.
3.3 Effect weight analysis of motorized spindle production chain

According to the value of Table 5, the correlation matrix $C_{S \rightarrow P}$ is constructed as follows.

| Failure Mode | $U_S$ | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
|--------------|-------|-------|-------|-------|-------|
| $S_1$        | 0.04  | 4     | 2     | 9     | 1     |
| $S_2$        | 0.14  | 1     | 3     | 9     | 1     |
| $S_3$        | 0.07  | 9     | 1     | 3     | 2     |
| $S_4$        | 0.05  | 9     | 1     | 1     | 1     |
| $S_5$        | 0.05  | 5     | 2     | 9     | 1     |
| $S_6$        | 0.08  | 5     | 4     | 9     | 1     |

According to the formula (9), we can calculate the effect weight analysis of production chain $U_P$.

$$U_P = [5.03, 2.12, 6.56, 2.63]$$

The rank of $U_P$: $P_3 > P_1 > P_4 > P_2$.

4. Conclusion

This paper takes the motorized spindle of machining center as the research object, constructs the availability house of motorized spindle, and forms the availability function deployment method of requirement→failure mode→production chain. Through the method of this paper, it can be determined that the key improvement directions of the motorized spindle production chain are assembly and outsourcing. This result is accordant to the engineering practice. So, if we improve the assembly and outsourcing, we will be able to quickly improve the availability of motorized spindle.

This paper transforms the user requirement for the availability of motorized spindle into the whole process of product development and production, and provides the technical support for enterprises to improve the availability of CNC equipment, which has broad application prospects.

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