A comprehensive maintainability evaluation methods for subsystems of CNC machine tools

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Abstract. Maintainability is used to evaluate product’s ability to return to normal operation state when a product is in use. In this paper, a comprehensive maintainability evaluation model for subsystems of CNC machine tools is proposed by building a hierarchy-structured model based on the AHP and incorporating information entropy method. The model is used to evaluate maintainability for subsystems of CNC machine tools. At last, we use a type of machining centers as an illustrative example to comprehensively evaluate maintainability of subsystems and draw the conclusion that CNC system has the best maintainability. The analysis result shows that the method is effective and feasible with important value in engineering application.

1. Introduction

As the foundation of equipment manufacturing, CNC machine tools should not only meet design and manufacture quality requirements before coming into the market, but also maintain quality during the whole life time. Therefore, CNC machine tools must maintain good performance and the ability to complete the required functions in use for a long term after sold. From this perspective, CNC machine tools should have good maintainability in addition to good reliability.

Maintainability is the product’s ability to maintain or return to specified state with specified maintenance procedures and methods under specified conditions and within the specified time. By definition, the maintainability is an important component of product performance factors, so making comprehensive evaluation for maintainability is the prerequisite for the assessment of service condition of CNC machine tools. Maintainability determines the reliability of machine tools in use. The better maintainability means that the ability to return to normal state after failure is stronger. Meanwhile, good maintainability can save the machine downtime caused by failure. Therefore, comprehensive maintainability evaluation is of great significance to the CNC machine tools and subsystems [1-5].

2. Maintainability analysis

2.1. Introduction of maintainability functions

Maintainability functions refer to the physical model or mathematical model established for the analysis and evaluation of product maintainability. The mathematical model is the basis of the analysis
and evaluation of product maintainability, including three basic mathematical functions: maintainability degree, probability density and maintainability rate [6].

1) Maintainability degree function
Maintainability degree of machine tools is the probability of maintaining or returning to specified state with specified maintenance procedures and methods under specified conditions and within specified time. The maintainability degree can be expressed as follows:

\[ M(\tau) = P(T \leq \tau) \]  

where T is the time to complete the maintenance under specified conditions, \( \tau \) is specified maintenance time.

2) Maintainability density function
Maintainability density is the derivative of maintainability degree. It can be expressed as follows:

\[ m(\tau) = \lim_{\Delta \tau \to 0} \frac{M(\tau + \Delta \tau) - M(\tau)}{\Delta \tau} \]  

3) Maintainability rate
Maintainability rate is the probability that the product which is not repaired at time \( \tau \) and is repaired within unit time after time \( \tau \). It can be expressed as follows:

\[ \mu(\tau) = \lim_{N \to \infty} \frac{n(\tau + \Delta \tau) - n(\tau)}{[N - n(\tau)] \Delta \tau} \]  

2.2. Establishment of maintainability functions
Methods of establishing maintainability functions and reliability functions are same. We can build models by empirical modelling methods, and the specific modelling process is described in references [1-2].

Repair time tends to follow lognormal distribution, and MLE(Maximum Likelihood Estimate) is used to estimate the parameters of the model in this paper. We define \( \tau_1, \tau_2, \ldots, \tau_n \) as n independent observed values of maintenance time, assuming that they follow lognormal distribution. Likelihood function can be expressed as follows:

\[ L(\tau; \mu, \sigma) = \prod_{i=1}^{n} f(\tau_i) = \prod_{i=1}^{n} \left\{ \frac{1}{\tau_i \sqrt{2\pi\sigma}} \exp \left[ -\frac{(\ln \tau_i - \mu)^2}{2\sigma^2} \right] \right\} \]  

Take the natural logarithm of both sides of equation (4):

\[ \ln L(\tau; \mu, \sigma) = -\sum_{i=1}^{n} \ln \tau_i - \frac{n}{2} \ln (2\pi\sigma^2) - \sum_{i=1}^{n} (\ln \tau_i - \mu)^2 / (2\sigma^2) \]  

In order to obtain \( \mu \) and \( \sigma^2 \) which can make \( \ln L(\tau; \mu, \sigma) \) reach maximum value. We need to take the partial derivative of \( \ln L \) with respect to \( \mu \) and \( \sigma^2 \) respectively, and that is:

\[ \begin{align*}
\frac{\partial \ln L}{\partial \mu} & = -\sum_{i=1}^{n} 2(\ln \tau_i - \mu)(-1) / (2\sigma^2) = 0 \\
\frac{\partial \ln L}{\partial \sigma^2} & = -\frac{n}{2\sigma^2} + \sum_{i=1}^{n} (\ln \tau_i - \mu)^2 / (2\sigma^4) = 0
\end{align*} \]  

We can obtain the result of equations, and that is:

\[ \hat{\mu} = \frac{1}{n} \sum_{i=1}^{n} \ln \tau_i \]  

\[ \hat{\sigma}^2 = \frac{1}{n} \sum_{i=1}^{n} \left( \ln \tau_i - \hat{\mu} \right)^2 \]
After the model is established, the goodness-of-fit test method is used to test model.

2.3. Selection and calculation of comprehensive evaluation indexes

The comprehensive evaluation indexes, which include repair time, equivalent repair time and maintenance man-hours etc., are used to measure maintainability. Repair time can be measured as follows: mean time to repair, maximum repair time, median repair time. This paper selects mean time to repair, equivalent repair time and maintenance man-hours as comprehensive maintainability evaluation indexes of CNC machine tools.

(1) Mean time to repair (MTTR)

Mean time to repair is the mean value or mathematical expectation of repair time. Its mathematical expression is as follows:

$$MTTR = \int_0^T m(\tau)d\tau$$

In engineering practices, we often use ratio of total repair time $\tau$ to repair times $n$ as maintenance time. It can be expressed as follows:

$$MTTR = \frac{1}{n} \sum_{i=1}^{n} \tau_i$$

(2) Equivalent repair time (ERT)

Equivalent repair time is calculated according to characters of maintenance activities, and it also indicates equivalent failure rate. It can be expressed as follows:

$$ERT = \frac{\sum_{i=1}^{m} \varepsilon_i \tau_i}{\sum_{i=1}^{m} \tau_i}$$

Where $\tau_i$ is number of type $i$ maintenance activities, $\tau_i$ is maintenance time of type $i$ maintenance activities, for $i = 1, 2, 3, \ldots, m$, $m$ is number of maintenance activity categories. $\varepsilon_i$ is equivalent repair coefficient of type $i$ maintenance activities. It is determined by difficulty of maintenance, and specific values are presented in Table 1.

| Difficulty Degree | Harder | Hard | Easy | Easier |
|------------------|-------|------|------|-------|
| Equivalent repair coefficient | 10    | 1    | 0.2  | 0.02  |

(3) Maintenance man-hours (MMH)

Maintenance man-hours is ratio of total maintenance man-hours to total work time under specified conditions and within the specified time[^6]. It can be expressed as follows:

$$M_I = \frac{M_{MMH}}{O_h}$$

Where $M_{MMH}$ is total maintenance man-hours within specified time, $O_h$ is total work hours within specified time.

3. Comprehensive maintainability evaluation of subsystems

Maintainability of subsystems directly determines maintainability of whole machine, so maintainability evaluation of subsystems is of practical significance to reliability improvement of whole machine. Meanwhile, the evaluation results can provide theoretical basis for the reliability design and improvement of similar products. Because the hierarchical structure can clearly reflect the relationships between the subsystems and the evaluation indexes, we construct the structural relationships between the subsystems and evaluation indexes based on the hierarchical method, and
finally we can realize the comprehensive maintainability evaluation for subsystems of CNC machine tools.

3.1. Subsystems division
At present, subsystems division of CNC machine tools lacks uniform standards, and in most cases we divide CNC machine tools into subsystems according to actual needs of the project and experience. Considering different types of CNC machine tools, subsystems divisions have different results. Generally, according to structural characteristics, CNC lathes can be divided into subsystems as follows: basic component (BC), main drive system (MS), CNC system (CNC), hydraulic system (HS), feeding system (FS), electrical system (ES), lubrication system (LS), cooling system (CS), test system (TS), pneumatic system (PS), defense system (DS), chip removal system (CRS), tool magazine (ATC) and other machine tool accessories (OA). Specific division is shown in figure 1 as follows:

3.2. Establishment of hierarchy-structured model
According to the natures and contents of assessed objectives, a hierarchy-structured model is built. Considering comprehensive maintainability evaluation for subsystems of CNC machine tools, this paper has proposed a three-layer hierarchy-structured model. Three layers are as follows: the bottom which contains subsystems of CNC machine tools, the middle layer which contains evaluation indexes, the upper layer which is decision-making layer. The specific model is shown in figure 2.

3.3. Establishment of comprehensive evaluation model
Establishment of comprehensive evaluation model is generally divided into 4 steps. Firstly, we need to make indexes conversion according to the determined evaluation indexes; Secondly, because each index has a different role in the evaluation, we need to give weight to each index. Thirdly,
comprehensive evaluation matrix is constructed. Fourthly, we calculate comprehensive evaluation values according to the weights and evaluation matrix.

1) Calculation of evaluation indexes
Evaluation indexes are calculated according to formula(9)-(12).

2) Calculation of weights
Considering different orders of magnitude of the selected indexes and necessity to weaken subjective factors and coordinate objective factors, the subjective weighting and the objective weighting are combined to make combination weighting. Subjective weighting still uses root-squaring method, and objective weighting chooses information entropy method. Specific weighting process is shown in references [7-9]. Final combination weighting is as follows:

\[ \omega_i = \frac{\alpha_i \beta_i}{\sum_{i=1}^{m} \alpha_i \beta_i} \]  

Define \((\alpha_1, \alpha_2, \ldots, \alpha_m)\) as subjective weight vector. Define \((\beta_1, \beta_2, \ldots, \beta_m)\) as objective weight vector. Combination weight is as follows:

\[ \omega_i = \frac{\alpha_i \beta_i}{\sum_{j=1}^{m} \alpha_j \beta_j} \]  

3) Construction of comprehensive evaluation matrix
Comprehensive evaluation matrix is determined by target membership degree. According to target membership degree formula by L.A.Zadeh, if index becomes better when index becomes higher, the formula is as follows:

\[ \gamma_j = \frac{a_i \min(x_j)}{\max(x_j) - \min(x_j)} \]  

If index becomes better when index becomes lower, the formula is as follows:

\[ \gamma_j = \frac{\max(x_j) - a_i}{\max(x_j) - \min(x_j)} \]  

Where \(r_j\) is membership degree of evaluation index \(j\) of subsystem \(i\), \(a_j\) is value of evaluation index \(j\) of subsystem \(i\), \(\max(x_j)\) and \(\min(x_j)\) are maximum value and minimum value of evaluation \(j\) respectively. Then we can build comprehensive evaluation matrix which is as follows:

\[ R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ ... & ... & ... \\ r_{n1} & r_{n2} & r_{n3} \end{bmatrix} \]  

4) Calculation of comprehensive evaluation value
Comprehensive evaluation value is calculated as follows:

\[ B = \omega \times R \]  

Comprehensive maintainability evaluation values of different subsystems are obtained according to formula(17), and then we judge maintainability of subsystems.

4. Example
We use a type of machining centers as an illustrative example to comprehensively evaluate maintainability of subsystems. Failure repair time of machining centers is shown in table 2.

1) Calculation of evaluation indexes
According to data in table 2 and formula (9)-(12), evaluation indexes are calculated and is shown in table 3.
Table 2. Failure repair time of subsystems.

| Subsystems | Repair time (Hours) | Subsystems | Repair time (Hours) |
|------------|---------------------|------------|---------------------|
| MS         | 8 1 2 0.67 1 0.13   | 1 3 4 2 1 5 |
| CNC        | 0.92 0.95 0.5 0.97 1.5 2 | 3 0.17 0.67 0.67 0.07 0.17 |
| HS         | 2 1 3 3 2 2 ES 1.17 1.17 0.33 0.17 0.5 1 |
|            | 3 2 0.83 0.83 1 2 | 0.5 0.42 0.33 0.5 |
|            | 1.5 1               | 1 1 1 1 1 1 |
|            | 3 4 1 2 2 PS 1 1 0.5 2 2 |
|            | 2 8 1 2 5 4 CS 1 2 0.5 0.08 1.5 1 |
| FS         | 3 3 2 0.5 0.42 1.17 | 1 0.67 |
|            | 3 0.83              | 1 1 0.67 0.67 0.02 1 |
| DS         | 2 4 4               | 1.5 2 1 |
| CRS        | 1 1 9               | ATC |

Table 3. Evaluation indexes of subsystems.

| Subsystems | Evaluation indexes (Hours) |
|------------|---------------------------|
|            | MTTR | ERT | MMH |
| MS         | 2.1333 | 1.1377 | 0.0139 |
| CNC        | 1.14 | 0.383 | 0.0047 |
| HS         | 1.7971 | 0.461 | 0.0292 |
| FS         | 2.546 | 0.6991 | 0.0829 |
| ES         | 1.22 | 0.7705 | 0.034 |
| PS         | 1.1364 | 0.816 | 0.017 |
| CS         | 0.9688 | 0.6994 | 0.0054 |
| ATC        | 0.9844 | 0.7246 | 0.0075 |
| DS         | 3.333 | 0.3 | 0.0073 |
| CRS        | 3.6667 | 1.091 | 0.0236 |

(2) Calculation of weights
1) Subjective weighting

According to the criterion of determining elements in the judgment matrix given by the reference [6], the judgment matrix of the subsystems is obtained as follows:

\[
A = \begin{bmatrix}
1 & 3 & 5 \\
1/3 & 1 & 2 \\
1/5 & 1/2 & 1
\end{bmatrix}
\]

The geometric mean values of each row in the matrix are calculated as follows:

\[
m_1 = \sqrt[3]{1 \times 3 \times 5} = 2.466, \quad m_2 = \sqrt[3]{1 \times 1 \times 2} = 0.874, \quad m_3 = \sqrt[5]{1 \times 1} \times 1 = 0.464
\]

②Normalization
The normalization results for geometric mean values are as follows:

\[ \omega_1 = \frac{m_1}{\sum_{i=1}^{3} m_i} = \frac{2.466}{3.804} = 0.648, \quad \omega_2 = \frac{m_2}{\sum_{i=1}^{3} m_i} = \frac{0.874}{3.804} = 0.23, \quad \omega_3 = \frac{m_3}{\sum_{i=1}^{3} m_i} = \frac{0.464}{3.804} = 0.122 \]

That is: Eigenvector \( W = (0.648 \quad 0.23 \quad 0.122)^T \)

③ The maximum eigenvalue of judgement matrix \( A \) is calculated as follows;

\[
AW = \begin{bmatrix} 1 & 3 & 5 \\ 1/3 & 1 & 2 \\ 1/5 & 1/2 & 1 \end{bmatrix} \begin{bmatrix} 0.648 \\ 0.23 \\ 0.122 \end{bmatrix} = \begin{bmatrix} 1.948 \\ 0.69 \\ 0.367 \end{bmatrix}
\]

\[
\lambda_{max} = \sum_{i=1}^{n} (AW)_{ii} = \frac{1}{3} (1.948 + 0.69 + 0.367) = 3.0048
\]

④ Consistency test of judgment matrix \( A \) is shown as follows:

\[
CI = \frac{\lambda_{max} - n}{n-1} = \frac{3.0048 - 3}{3-1} = 0.0024
\]

Judgment matrix is a 3×3 matrix, so \( RI = 0.58 \).

That is:

\[
CR = \frac{CI}{RI} = \frac{0.0024}{0.58} = 0.004 < 0.1
\]

So judgment matrix \( A \) passes consistency test.

2) Objective weighting

Objective weighting is carried on according to references\[6-7\].

① Weights of evaluation indexes are shown in table 4.

| Subsystems | Weights of MTTR | Weights of ERT | Weights of MMH |
|------------|-----------------|----------------|---------------|
| MS         | 0.1127          | 0.1606         | 0.0616        |
| CNC        | 0.0602          | 0.0541         | 0.0208        |
| HS         | 0.095           | 0.0651         | 0.1295        |
| FS         | 0.1345          | 0.0987         | 0.3676        |
| ES         | 0.0645          | 0.1088         | 0.1508        |
| PS         | 0.06            | 0.1152         | 0.0754        |
| CS         | 0.0512          | 0.0988         | 0.0239        |
| ATC        | 0.052           | 0.1023         | 0.0333        |
| DS         | 0.1761          | 0.0424         | 0.324         |
| CRS        | 0.1937          | 0.154          | 0.1047        |

② Objective weights are as follows;

\[
W^* = (0.3302 \quad 0.3437 \quad 0.3261)
\]

3) Combination weighting

Subjective weight vector of indexes is as follows:

\[
W = (0.648 \quad 0.23 \quad 0.122)
\]

Objective weight vector of indexes is as follows:
\[ W^* = (0.3302 \ 0.3437 \ 0.3261) \]

Combined weight vector is as follows:
\[ \omega_0 = (0.643 \ 0.2375 \ 0.1195) \]

(3) Construction of comprehensive evaluation matrix
Because indexes become better when indexes becomes lower, evaluation matrix is constructed according to formula (15), and specific result is as follows:
\[
R = \begin{bmatrix}
0.5684 & 0 & 0.8824 \\
0.9365 & 0.9009 & 1 \\
0.693 & 0.8078 & 0.6867 \\
0.4154 & 0.5236 & 0 \\
0.9069 & 0.4383 & 0.6253 \\
0.9379 & 0.384 & 0.8427 \\
1 & 0.5232 & 0.991 \\
0.9942 & 0.4931 & 0.9642 \\
0.1237 & 1 & 0.9668 \\
0 & 0.0557 & 0.7583
\end{bmatrix}
\]

(4) Calculation of comprehensive evaluation values
According to formula (17), comprehensive maintainability evaluation values of different subsystems are as follows:
\[ B = (0.4709 \ 0.9357 \ 0.7195 \ 0.3914 \ 0.7620 \ 0.7950 \ 0.8857 \ 0.8716 \ 0.4326 \ 0.1039) \]

The corresponding subsystems of values in B are as follows: main drive system (MS), CNC system, hydraulic system (HS), feeding system (FS), electrical system (ES), pneumatic system (PS), cooling system (CS), tool magazine (ATC), defense system (DS), chip removal system (CRS).

Comprehensive evaluation values are in descending order as follows: CNC system, cooling system (CS), tool magazine (ATC), pneumatic system (PS), electrical system (ES), hydraulic system (HS), main drive system (MS), defense system (DS), feeding system (FS), chip removal system (CRS). The result obviously indicates that CNC system has the best maintainability, and moreover cooling system and chip removal system have the second best and worst maintainability respectively.

CNC system failures mainly perform as damages of components or parts. Most of these failures can be repaired by simple maintenance. Normally, maintenance activities are easy, accessible and convenient, but the only problem is that detection and diagnosis is a little bit difficult. At the same time, components or parts involved in CNC system are conducted standardized and modular design, and have good interchangeability. So CNC system has good maintainability.

5. Conclusions
(1) Considering that it is not easy to evaluate maintainability for subsystems of CNC machine tools, this paper selected a number of indexes to make comprehensive maintainability evaluation. Considering that AHP is simple and explicit, a hierarchy-structured model is established for the subsystems of CNC machine tools and selected evaluation indexes.

(2) Taking into account the important role of the weight in the evaluation, a method combining subjective weighting and objective weighting is chosen to give different weights to all evaluation indexes. Finally, comprehensive maintainability evaluation matrix for subsystems of CNC machine tools is built to evaluate maintainability for subsystems of CNC machine tools.

(3) Taking a type of machining centers as an example, we verify the feasibility of the proposed comprehensive evaluation method. Meanwhile, we draw a conclusion that the CNC system of this batch machining centers has the best maintainability. In the same time, This method can be not only applied in different types of CNC machine tools or CNC equipments but also applied in some repairable products.
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