An Improved Method for Maintainability Allocation of Complex Equipment Considering Associated Failures

Yingzhi Zhang, Yang Yu, Yubin Zheng*, Yilong Zhang and Zhifu Tian
School of Mechanical Science and Engineering, Jilin University, No. 5988 Renmin Street, Changchun City, Jilin Province, China, 130022.
Email: zhangyz@jlu.edu.cn

Abstract. A maintenance allocation method for complex equipment that is intermittently turned on is proposed. Based on the IEC706-6 maintainability allocation method, the ISM method and entropy weight aggregation method are used to calculate the importance of the subsystem, and the maintainability redistribution is carried out with the calculation results. Objectively and efficiently, it provides a more realistic reference for maintainability analysis.

1. Introduction
Maintainability allocation is an important part of maintainability analysis. It is the work that is performed to assign the product's maintainability quantitative requirements to each component according to the given criteria. In general, maintainability allocation needs to be based on sufficient maintainability experience data. However, empirical data tends to increase the subjectivity of distribution, and the redundancy of empirical data increases the complexity of the allocation process, so the cost efficiency is higher for complex machine systems with multiple replaceable units. The method of sexual distribution has a very important practical significance.

The traditional maintainability allocation methods mostly select the appropriate parameters to solve the problem of combination allocation from the point of view of the repair time. However, in the case of complex equipment, the appearance features of a replaceable unit may be caused by other units. In fact, the maintenance allocation not only needs to consider the fault occurrence characterization, but also consider the relevance of the fault occurrence. From the point of view of the correlation of failures, faults can be classified into correlated faults and non-associated faults. For non-associated faults, the traditional maintenance method has solved the allocation problem well. This article does not make too many details. For the associated faults, besides the fault characterization unit, the fault occurrence unit is also considered, and the traditional maintenance method basis On the other hand, maintenance redistribution based on the failure mechanism can achieve the effect of prevention in advance from the maintenance point of view before the failure actually occurs.

This paper proposes a complex equipment maintenance allocation method considering associated faults. Based on the IEC706-6 allocation method, a topology model is constructed based on the failure mechanism analysis. The ISM method and entropy weighting method are used to calculate the importance of each replaceable unit. Finally, the final reassignment results are obtained by combining the results of IEC 706-6 allocation with the importance of normalization. Maintainability allocation based on IEC 706-6 method.
2. Calculation of the Importance of Associated Faults

2.1. Construction of Topology Model Based on Ism Method

The ISM method mainly uses qualitative analysis. The associated fault subsystem $a_1, a_2, \ldots, a_n$ is divided according to the failure mechanism, and $n$ is the number of subsystems. A directed graph is used to represent the fault connection between the subsystems. In the graph, the line segment is directed from the affected subsystem to the affected subsystem, and the line segment direction indicates the relationship of the associated faults. There is a one-to-one correspondence between the adjacency matrix 1 and the directed graph, which assumes that there is a matrix 2. In matrix 3, if the subsystem 4 has a fault effect on the subsystem 5, the 6 value is 1, or the value is 0, thus the adjacency matrix is obtained. Add a unit matrix 2 on 1, that is, 3, if 4 (if the Boolean operation is taken, if 5, then 6 is 1, or 0), the resulting matrix 7 is a matrix of the matrix 8 of the matrix 8. The reachability matrix represents the reachability of each subsystem through a length of no more than 9 paths, that is, the distribution of influence between each associated fault subsystem.

2.2. Determine Multidimensional Evaluation Parameters

The degree of node of subsystem $a_i$ is the number of other subsystems connected to the subsystem in the directed graph, also called the degree of association, denoted by $\alpha_i$. The larger the node degree of a subsystem is, the larger the proportion of the subsystem is in the whole associated fault system. The adjacency matrix 1 is treated as follows. For the subsystem $a_i$, all numerical sums of the $i$ line are added to $p_i$, and all values of the $i$ column are added as $q_i$, then the nodal degree $\alpha_i$ of the subsystem $a_i$ can be calculated by the formula (11).

$$\alpha_i = p_i + q_i$$

(1)

The comprehensive influence matrix $T$ is the basis for calculating the centrality of the node, so the matrix $A$ is first treated as the following formula (12) to get the normalization and direct influence of the matrix $C$.

$$C = \frac{1}{\max_{i \leq n} \sum_{j=1}^{n}} A$$

(2)

In the formula (12), after a series of normalization processing, $0 < c_{ij} < 1$ normalization directly affects the matrix $C$, the middle diagonal element is still 0. Bring the matrix $C$ into the following formula (13) to get the combined influence matrix $T$.

$$T = C + C^2 + \ldots + C^n = \sum_{i=1}^{n} C'$$

(3)

The influence degree of the sub-system $h_i$ is added to the element of the $i$ row in the matrix $T$, and the degree of influence $e_i$ of the sub-system $a_i$ is the addition of the element of the $i$ column in the matrix, then the center degree $\beta_i$ of the sub-system $a_i$ is shown by the calculation formula (14).

$$\beta_i = h_i + e_i$$

(4)

The first step to compute the clustering coefficient is to determine the neighborhood set of each subsystem, and then determine the scope of the neighborhood set. In this paper, we determine the range of the neighborhood of a subsystem is based on the average node degree of a directed graph, that is, the average of the degree of all nodes in a directed graph, such as formula (15).
\[
\alpha = \frac{\sum \alpha_i}{n}
\]  

(5)

In the directed graph, the adjacency set of the subsystem \( a_i \) is \( L(a_i) \), and \( |L(a_i)| = k_i \). The clustering coefficient \( \gamma_i \) of the subsystem \( a_i \) is obtained by calculating the ratio of the number of sides \( E_i \) to the total possible number of edges \( k_i(k_i-1) \) between the \( k_i \) subsystems, that is:

\[
\gamma_i = \frac{E_i}{k_i(k_i-1)}
\]  

(6)

Suppose an associated fault network has \( n \) nodes, the 3 subsystem importance parameter obtained by the above method can get a \( n \)-row and 3-column sort matrix \( B = \{b_{ij}\}_{m=3} \). The three columns of this sorting matrix are \( \alpha_i \), \( \beta_i \), and \( \gamma_i \). The following formula (17) is used to calculate the entropy of 3 parameters.

\[
\Phi_j = -K \sum_{i=1}^{m} \frac{b_{ij}}{\sum_{i=1}^{m} b_{ij}} \ln \frac{b_{ij}}{\sum_{i=1}^{m} b_{ij}}
\]  

(7)

In the form of the \( j \) \((j=1,2,3)\) dimensional data, the bigger the \( \Phi_j \), the greater the weight in the \( j \) dimensional data of the subsystem \( i \) \((1 \leq i \leq m)\); \( b_{ij} \) for the \( j \) dimension data, the sort value of the system \( i \); \( K \) for the Boltzmann constant, and \( K > 0 \), usually \( K = \frac{1}{m} \), \( m = n \).

The entropy weight formula for the \( j \) dimension data is:

\[
\phi_j = \frac{g_j}{\sum_{j=1}^{n} g_j} = \frac{1 - \Phi_j}{\sum_{j=1}^{n} \Phi_j}
\]  

(8)

In the formula, \( \phi_j \) is the entropy weight of the \( j \) dimension data; \( g_j \) is the difference coefficient.

\[
\sum_{j=1}^{n} \phi_j = 1 \geq 0; j = 1, 2, n
\]  

(9)

The use of entropy weights to aggregate all the data can get the final importance of the node \( \theta_i \).

\[
\theta_i = \phi \alpha_i + \phi \beta_i + \phi \gamma_i
\]  

(10)

2.3. Maintainability Allocation Considering Associated Faults

The importance degree \( \{\theta_i\} \) calculated by the 3.3 section improves the value of the maintainability based on the IEC706-6. Because subsystem \( a_i \) importance value \( \theta_i \geq 0 \) and \( \sum_{i=1}^{n} \theta_i 
eq 1 \). However, using importance as a weight to redistribute maintenance value will lose its objectivity and it is not realistic. Therefore, the importance degree \( \{\theta_i\} \) needs to be normalized first, so that the normalized importance satisfies \( \sum_{i=1}^{n} \theta_i' = 1 \).

The subsystem \( a_i \) maintainability assignment \( ACMT_i \cdot \lambda_i \) multiplied by normalized importance
θ' is called the maintainability allocation value, which is:

\[
(ACMT_i \cdot \lambda_i) = ACMT_i \cdot \lambda_i + ACMT_i \cdot \lambda_i \times \theta' = ACMT_i \cdot \lambda_i \times (1 + \theta') \tag{11}
\]

The \((ACMT_i \cdot \lambda_i)\) is the redistribution subsystem \(a_i\)'s maintainability allocation value.

3. Example Analysis

For the 12 subsystems of the already divided X-type machining center, its requirements are:

- Operating hours: \(T = 30 \times 8 \times 20 = 4800\text{h}\)

\[
\lambda = \frac{146}{T} = \sum_{i=1}^{12} \lambda_i;
\]

The average actual repair service time of the processing center is 15 minutes, so it can get \(MACMT = \frac{15}{60} = 0.25\text{h}\);

\[
ACMT_{95} = 40\text{min} = \frac{2}{3}\text{h}, \quad \text{As a result}, \quad \frac{ACMT_{95}}{MACMT} = \frac{8}{3} = 2.6667, \quad \text{because of} \quad Z_{p95} = 1.645, \quad \text{by the formula can get} \ \sigma = 0.782
\]

By analyzing the mechanism of the 146 fault data collected, 23 associated fault data are obtained. According to the failure mechanism of the key fault data, a topological map of the machining center is generated, as shown in Figure 1.

![Figure 1. Associated fault directed graph of machining center.](image)

According to entropy weight method, the entropy weight corresponding to the three parameters is calculated. Finally, the importance of each subsystem is calculated from the third column entropy weight in Table 1. The degree of importance of the subsystem is normalized to complete the redistribution of maintainability of the machining center subsystem.
Table 1. Maintainability Redistribution Table.

| Subsystem code | Subsystem name            | Importance | Normalization of | Maintenance redistribution |
|----------------|---------------------------|------------|------------------|---------------------------|
| M             | Tool library system      | 1.5340     | 11.1647          | 12.7147                   |
| L             | Lubrication cooling system | 0.8591    | 9.1496           | 9.8610                    |
| G             | Pneumatic system         | 0.9683     | 5.6463           | 6.1411                    |
| J             | Feed system              | 0.8733     | 6.1100           | 6.5930                    |
| V             | Electrical system        | 1.9055     | 5.8509           | 6.8599                    |
| S             | Spindle system           | 0.7158     | 6.0623           | 6.4550                    |
| NC            | CNC control system       | 2.7330     | 6.2502           | 7.7962                    |
| Q             | Protection system        | 0.0000     | 4.3995           | 4.3995                    |
| D             | Hydraulic system         | 0.0000     | 4.7299           | 4.7299                    |
| K             | Chip removal system      | 0.0000     | 4.1340           | 4.1340                    |
| B             | Basic components         | 0.5868     | 4.9529           | 5.2159                    |
| F             | server system            | 0.8733     | 1.5166           | 1.6364                    |

4. Conclusion
On the basis of the IEC706-6 maintainability allocation, a maintainability allocation method considering the associated faults is proposed. The topology diagram of the whole system fault mechanism is analyzed. The ISM method and entropy weight aggregation method are combined to calculate the importance of the subsystem. Finally, the maintainability is redistributed with the normalized importance. The result is more realistic and has considerable objectivity.

Each subsystem has different effects on the cascading failure of the whole machine, the greater the importance, the greater the impact, but the importance cannot reflect the failure of the subsystem itself, and further conclusions should be drawn from the actual fault statistics and the analysis of the corresponding fault mechanism.

In the modified distribution method of IEC706-6 maintainability allocation, only the relevant known conditions are listed, and the results similar to table 6 can be obtained by computer aided calculation. The artificial error can be reduced, and the simplicity and practicability are improved.

5. Acknowledgements
This work is supported by the Major Special Topic of China "High-end CNC Machine Tools and Basic Manufacturing Equipment" (Grant No. 2014ZX04015061) and Jilin Provincial Natural Science Foundation of China "Miscellaneous Propagation Modelling and Control of NC Machine Operational Faults" (Grant No. 20170101212JC).

6. Reference
[1] Liu Guojiang. Maintainability allocation method based on genetic algorithm and its application. Hunan: Changsha. National University of Defense Technology. 2010.
[2] Chen Yunxiang. Reliability and maintainability engineering. Beijing: National Defense Industry Press.2007. 11. 1-20.
[3] Jin Weidong, Wang Songling. Study on the maintainability allocation method of complex equipment system. Information and computer (theoretical version).2011 (6): 211-212.
[4] Shen Guixiang, he Yu, Zhang Yingzhi, et al. Analysis of CNC lathe related failures based on directed causality diagram. Journal of Jilin University (Engineering Edition). 2009 (S2): 328-331.
[5] Wang Quanwei, Jiang Liqiang, Wang Weixing. Research on the linear programming method of the Maintainability Distribution of weapon system. Journal of equipment College.2006, 17 (3): 33-36.
[6] Yang Bingxi, Li Jinguo. Analysis and improvement of IEC706-6-94 maintainability allocation method. Electronic products reliability and environmental test.1998, (5): 3-7.