Maintenance decision of meta-action unit based on Grey-BWM

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Abstract. In order to reduce the maintenance cost, improve the availability, reliability, safety and product quality of the equipment, it is necessary to maintain the equipment. The choice of maintenance strategy is not only related to economic interests, and even endanger personal safety. Traditional maintenance decision-making often takes parts or the whole system as the decision object. Taking components or systems as decision-making objects, too large grains are easy to lead to wrong maintenance decisions, resulting in over repair or under repair; taking parts as decision-making objects, the analysis and decision-making of the system is too complicated. In this paper, the meta-action unit is taken as the research carrier, and the grey weight of each criteria is obtained by combining the grey system theory with the best worst method (BWM). The comprehensive grey value of the evaluation is calculated by the grey number algorithm and its comparison method, and the best maintenance scheme is obtained by comparison. The example analysis proves the effectiveness of the method.

1. Introduction

Equipment maintenance is an important means to maintain equipment function and ensure normal use of equipment [1]. Maintenance decision-making has always been the focus of maintenance research. It is understood that the maintenance cost of production equipment accounts for 15% - 70% of the production cost. Choosing the appropriate maintenance strategy can not only reduce the maintenance cost, but also improve the reliability and availability of the equipment, improve the product quality and extend the product life [2]. Maintenance strategies are mainly divided into four types: corrective maintenance (CM), periodic maintenance, condition based maintenance (CBM) and predictive maintenance. CM mainly aims at the situation that the failure consequence is not serious, and then repair the equipment after the failure or the performance is low; periodic maintenance is a time-based preventive maintenance method, which mainly for equipment with known failure rules, and the appropriate maintenance cycle is selected to maintain the equipment; CBM judges whether the equipment is operating abnormally according to the current status information of the equipment monitored by the sensor, and then repairs the equipment before the failure occurs; Predictive maintenance not only monitors the equipment, but also analyzes the monitored status to derive its development trend, and formulates a reasonable maintenance plan, which is conducive to the reasonable allocation of maintenance resources [2,3]. Li Dawei et al. [4] described the maintenance
effect of products based on the Poisson process, obtained the life distribution law, and proposed a maintenance strategy that combines periodic maintenance and preventive maintenance. Wang Xianzhi et al. [5] and Jiang Xiuhong et al. [6] focused on reliability, and studied the maintenance decision problems of CNC machine tools and the predictive maintenance decision problems of multi-state and complex redundant systems, respectively. Dai Bochao et al. [7] proposed a preventive maintenance method based on the prediction of system performance degradation in order to solve the disadvantages of "under repair" or "over repair" in the traditional maintenance methods of CNC machine tools. Liu Fanmao et al. [8] proposed a new opportunistic maintenance strategy for a series of multi-device serial-parallel system. Zuo Hongfu et al. [9] adopted the minimum cost method and the maximum availability method to determine the optimal maintenance strategy threshold, and discussed the aircraft engine CBM strategy based on the proportional risk model. There are some problems in the research of equipment maintenance decision-making in the above literature: ① The object of the appeal literatures research is mostly a system, component or part. Components or systems are the object of maintenance decision. The granularity is too large and not refined enough. The maintenance decision is rough, which can easily lead to errors in the maintenance decision, resulting in over- or under-maintenance. With parts as the decision-making object, the system's analysis and decision-making are too cumbersome and uneconomical. ② When calculating the weights of the criteria, and the uncertainty of expert evaluation is not taken into account, which may easily lead to inaccurate weight calculation.

Li Dongying [10] and Ran Yan [11] discussed the method of numerical control machine tools based on meta-action unit decomposition. The meta-action decomposition is a new method based on the refined control of CNC machine tools. The maintenance decision based on the meta-action unit makes the decision granularity more refined and the selection of decision strategies more accurate. At the same time, it is easier to detect, analyze and locate the fault by using the meta-action unit as the maintenance decision object. Grey system theory is an important theory for studying uncertainty. Grey number [12, 13] describes the uncertainty of criteria values. With the development of uncertainty theory, its applications will become more and more extensive. BWM is a pair comparison method, which is similar to AHP, but BWM has fewer comparisons with each other, high efficiency, and better consistency of results [1, 14]. At present, few literatures combine BWM with grey system theory to obtain criteria weights. In view of this, this paper combine grey evaluation and BWM to study the maintenance decision of meta-action unit.

2. Related concepts of meta-action theory

2.1. The concept of meta-action[15]
Mechanical products are decomposed into the meta-action layer according to Function-Motion-Action (FMA). Meta-action refers to the most basic form of motion that transfers motion and power in mechanical products. The concept of meta-motion was first developed by Professor Zhang Genbao of Chongqing University. The function of the mechanical product is guaranteed by the realization of the basic meta-action, and the motion performance of the meta-action is related to all the parts that realize the meta-action.

2.2. The concept of meta-action unit[15]
The whole of all related parts that realize a certain meta-action according to the structural relationship is called the meta-action unit. A meta-action unit is usually composed of five parts: motion input parts, motion output parts, middleware, fasteners and supports. The typical meta-action unit structure model is shown in Figure 1. The mechanical product is a whole composed of several meta-action units in a certain order. The failure of the mechanical product is reflected in the meta-action unit. Once the meta-action unit constituting the mechanical product is unavailable, the mechanical product will inevitably have malfunctions.
3. Basic knowledge

Grey number: The number that only knows the approximate range of the criteria value, and does not know its exact size is called the grey number.

3.1. Grey number kernel, relative kernel and accuracy [16]

Let the standard grey number $\tilde{a} = [a_1, a_2]$, $a_1$ and $a_2$ be the upper and lower bounds of $\tilde{a}$ respectively.

The kernel of $\tilde{a}$ is: $\hat{a} = \frac{a_1 + a_2}{2}$

The relative kernel $\delta(\tilde{a})$ of $\tilde{a}$ is: $\delta(\tilde{a}) = \frac{\hat{a}}{a_2 - a_1}$

The accuracy $p(\tilde{a})$ of $\tilde{a}$ is: $p(\tilde{a}) = 1 - (a_2 - a_1)$

3.2. Grey number comparison [16]

Let the standard grey number $\tilde{a} = [a_1, a_2]$, $\tilde{b} = [b_1, b_2]$. $a_1$, $b_1$ are the upper bounds of $\tilde{a}$ and $\tilde{b}$, and $a_2$, $b_2$ are the lower bounds of $\tilde{a}$ and $\tilde{b}$, respectively. The comparison criteria are as follows:

1. if $\delta(\tilde{a}) < \delta(\tilde{b})$, then $\tilde{a} < \tilde{b}$.
2. if $\delta(\tilde{a}) > \delta(\tilde{b})$, then $\tilde{a} > \tilde{b}$.
3. if $\delta(\tilde{a}) = \delta(\tilde{b})$:
   i. if $p(\tilde{a}) = p(\tilde{b})$, then $\tilde{a} = \tilde{b}$.
   ii. if $p(\tilde{a}) < p(\tilde{b})$, then $\tilde{a} < \tilde{b}$.
   iii. if $p(\tilde{a}) > p(\tilde{b})$, then $\tilde{a} > \tilde{b}$.

3.3. Grey number algorithm [16]

The four operations of interval grey numbers are different from the exact numbers, as follows:
Let the standard grey number \(\tilde{a} = [a_1, a_2]\), \(\tilde{b} = [b_1, b_2]\). \(a_1, b_1\) are the upper bounds of \(\tilde{a}\) and \(\tilde{b}\), and \(a_2, b_2\) are the lower bounds of \(\tilde{a}\) and \(\tilde{b}\), respectively.

Addition: \(\tilde{a} + \tilde{b} = [a_1 + b_1, a_2 + b_2]\)

Subtraction: \(\tilde{a} - \tilde{b} = [a_1 - b_1, a_2 - b_2]\)

Multiplication: \(\tilde{a} \times \tilde{b} = [\min(a_1 \times b_1, a_1 \times b_2, a_2 \times b_1, a_2 \times b_2), \max(a_1 \times b_1, a_1 \times b_2, a_2 \times b_1, a_2 \times b_2)]\)

Division: \(\frac{\tilde{a}}{\tilde{b}} = \min\left(\frac{a_1}{b_1}, \frac{a_1}{b_2}, \frac{a_2}{b_1}, \frac{a_2}{b_2}\right), \max\left(\frac{a_1}{b_1}, \frac{a_1}{b_2}, \frac{a_2}{b_1}, \frac{a_2}{b_2}\right)\)

4. Research methods

As shown in Figure 2. The maintenance decision process is as follows:

**Step 1:** determining the maintenance decision scheme of the meta-action unit. According to the previous research literature, as well as the maintenance strategies commonly used by enterprises, the maintenance strategies proposed in this paper are: CM (Strategy 1), RM (strategy 2), CBM (strategy 3) and Predictive maintenance (strategy 4). Considering all kinds of criteria, the optimal maintenance strategy of meta-action unit is selected by corresponding algorithm.

**Step 2:** determining maintenance decision evaluation criteria. Choose an appropriate maintenance scheme selection criteria and compare the advantages and disadvantages of different maintenance strategies. This paper considers different criteria such as reliability, availability, safety, maintenance cost, and maintenance time.

1) Reliability: the ability of the equipment to complete the specified functions under the specified time and specified conditions after being repaired.

2) Availability: the ability of the equipment to perform a specified function under specified conditions and within a specified time or time interval after maintenance.

**Figure 2.** Maintenance decision analysis flow chart
3) Safety: The ability to reduce equipment risk to an acceptable level after maintenance.

4) Maintenance time: different maintenance methods take different maintenance time.
   Maintenance time refers to the length of time from the beginning of the maintenance task to
   the end of the maintenance task.

5) Maintenance cost: Maintenance cost refers to the money spent on different maintenance
   methods.

**Step 3**

Using grey BWM to calculate the weight of each criteria. BWM and AHP have similar
functions and are used to compare different criteria, but BWM can reduce the number of pairwise
comparisons compared to AHP. For the mutual comparison between \( n \) criteria, AHP needs to compare
\( \frac{n(n-1)}{2} \) times, but BWM only needs to compare \( 2n-3 \) times. As the number of criteria increases,
the gap in the number of comparisons will increase, and the use of AHP will affect the efficiency of
expert scoring work [14]. At the same time, when comparing each criteria, there is a certain degree
of uncertainty in the expert evaluation, and only know that the importance ratio between each criteria
is within a certain interval. Therefore, the grey interval expert evaluation method considering
information uncertainty is introduced, and each criteria of maintenance decision evaluation is
compared using BWM to obtain a weight vector. The implementation process is as follows:

1) Select the most important and least important criteria based on the established criteria. Based
   on the criteria determined in the Step 2 above, the decision maker selects the most important
   and least important criteria for evaluating the merits of the decision scheme.

2) Determining the weighting of the most important criteria relative to other criteria. Because
   experts may be uncertain about the weight value of the most important criteria compared to
   other criteria, this paper uses grey intervals to express its weight value. See Table 1 for the
   pairwise comparison language terms of the guidelines. The language terms for criteria paired
   comparison are shown in Table 1.

| Language terms          | Codes | Grey interval |
|-------------------------|-------|---------------|
| Equally important       | E     | [1,2]         |
| Moderately important    | M     | [2,4]         |
| Strongly important      | S     | [4,6]         |
| Very strongly important | VS    | [6,8]         |
| Extremely important     | EX    | [8,9]         |

Vector \( \mathbf{B}_T \) obtained by pairwise comparison.

\[
\mathbf{B}_T = (\tilde{b}_1, \tilde{b}_2, \tilde{b}_3, \tilde{b}_4) = ([b_{11}, b_{12}], [b_{21}, b_{22}], [b_{31}, b_{32}], [b_{41}, b_{42}])
\] (1)

3) Determining the weighting of other criteria relative to the least important criteria. Grey ratio
   vector \( \mathbf{W}_T \) obtained by comparing other criteria to the least important criteria.

\[
\mathbf{W}_T = (\tilde{w}_1, \tilde{w}_2, \tilde{w}_3) = ([w_{11}, w_{12}], [w_{21}, w_{22}], [w_{31}, w_{32}])
\] (2)

Eq. (2) removes the grey ratio between the important criteria and the worst criteria, because there
is a comparison in Eq. (1).

4) Get the optimal weight vector of each criteria. The optimal grey weight vector can be solved
   by calculating the absolute value of the grey ratio of each weight to the most important criteria
   and other criteria and the ratio of other criteria to the least important criteria. It can be obtained
   by solving the optimal value of the following nonlinear constraint functions. Set the allowable
difference \( \tilde{\theta} = [\theta, \theta] \).
\[
\begin{align*}
\min \bar{\theta} \\
\text{s.t.} \quad \left[ \begin{array}{c}
[w_{j1},w_{j2}] \\
[w_{j1},w_{j2}]
\end{array} \right] \leq \left[ b_{j1},b_{j2} \right] \leq \left[ \theta, \theta \right] \\
\sum_{i=1}^{5} \left( 0.5 * w_{j1} + 0.5 * w_{j2} \right) = 1 \\
0 \leq w_{j1} \leq w_{j1} \\
i = 1,2,3,4,5
\end{align*}
\]

Eq. (3) belongs to the problem of constrained multivariate function seeking minimum value, and the optimal solution can be found through programming software such as Matlab.

Step 4: Ranking of maintenance strategies. First of all, experts will score each criteria for maintenance strategies. See Table 2 for scoring criteria.

| Criteria | Grey interval | Criteria evaluation | Grey interval |
|----------|---------------|---------------------|---------------|
| Highest  | [9,10]        | Relatively high     | [4,6]         |
| Extremely high | [8,9]    | Moderate            | [3,5]         |
| Very high | [7,8]        | Relatively low      | [2,4]         |
| High     | [6,8]        | Low                 | [1,3]         |
| Moderately high | [5,7] | Lowest              | [1,2]         |

For availability, reliability and safety, the better the quality is, the higher the corresponding score value is, which belongs to the benefit type criteria; for downtime and maintenance cost, the higher the downtime and cost is, the lower the score value is, which belongs to the cost type criteria.

Let \( S = \{ S_1, S_2, S_3, S_4 \} \) be the multi-criteria decision scheme set, and \( P = \{ P_1, P_2, P_3, P_4, P_5 \} \) decision plan criteria set. Evaluating the criteria \( P_i \) of the scheme \( S_i \), and obtain the evaluation grey interval value \( \tilde{a}_{ij} = [a_{ij1}, a_{ij2}] \), which constitutes matrix \( \tilde{A} = (\tilde{a}_{ij})_{i \times j} \). Due to different criteria dimensions, it is necessary to perform dimensionless processing on criteria values. This paper adopts the method described in [2] to perform dimensionless processing on each criteria value. After dimensionless processing, \( \tilde{A} = (\tilde{r}_{ij})_{i \times j} \) matrix is obtained.

1) For benefit-type criteria (reliability, availability, and safety):

\[
\begin{align*}
\tilde{r}_{j1}^i &= a_{ij1}^{j1} / \sqrt{\sum_{i=1}^{4} (a_{ij2}^{j1})^2} \\
\tilde{r}_{j2}^i &= \min(i) \sqrt{\sum_{i=1}^{4} (a_{ij1}^{j2})^2}
\end{align*}
\]

2) For cost-type criteria (maintenance time, maintenance cost):

\[
\begin{align*}
\tilde{r}_{j1}^i &= (1/a_{ij2}^{j1}) / \sqrt{\sum_{i=1}^{4} (1/a_{ij1}^{j1})^2} \\
\tilde{r}_{j2}^i &= \min(i) \sqrt{\sum_{i=1}^{4} (1/a_{ij2}^{j1})^2}
\end{align*}
\]

According to the weight of each criteria obtained by BWM, the dimensionless integrated value \( \tilde{V} \) of each criteria of each maintenance strategy is obtained.

\[
\tilde{V} = \sum_{i=1}^{5} w_i \tilde{r}_i = \sum_{i=1}^{5} \left[ \tilde{w}_{j1}, \tilde{w}_{j2} \right] \times \left[ \tilde{r}_{j1}^i, \tilde{r}_{j2}^i \right]
\]

Through calculation, it can be seen that \( \tilde{V} \) is distributed in the interval \([0, 1]\), which belongs to the standard grey number. Through the grey number comparison and sorting, the strategy corresponding to the largest grey number is the optimal maintenance decision of the meta-action unit.
5. Case analysis

As shown in Figure 2, this figure is an end-toothed disc indexing table schematic drawing of the CNC machine tool. The end-toothed disc indexing table contains dozens of parts. If a single part is used for maintenance decision, it needs to make dozens of decisions, which is too cumbersome. If the entire CNC turntable is used as the maintenance decision-making object, it seems too rough and the decision-making is not accurate enough. Wang Yang [17] obtained 12 meta-actions through FMA decomposition of the numerical control turntable. Among them, the structure diagram of the turbine rotation meta-action unit is shown in Figure 3. In this paper, the turbine rotation meta-action unit is used as an example to try to determine its best maintenance strategy. After scoring and judging by experts in the industry, the related score table is shown in Table 3.

![Figure 3. End-toothed disc indexing table schematic drawing[15]](image)

1. Plate 2. Male tapper 3. Sealed housing 4. Gear shaft 5. Gear shaft bearing 6. Motor 7. Worm 8. Worm gear 9. Rotary body bearing 10. Lift cylinder 11. Locking cylinder oil circuit 12. Lift cylinder oil circuit 13. Lower tooth disc 14. Upper tooth disc 15. Large spring 16. Pull stud 17. Claw 18. Female tapper 19. Positioning nail

![Figure 4. Turbine rotation-meta-action of the rotary table schematic diagram](image)

1. Worm gear 2. Stop washer for nut 3. Round nut 4. Lid 5. Key 6. Bolt 7. Slide 8. Correction circle 9. Bearing support 10. Bolt 11. Pin 12. Gear shaft 13. Bearing

| The most important criteria | Safety | Maintenance cost | Availability | Maintenance time |
|-----------------------------|--------|------------------|--------------|-----------------|
| Reliability                | [2,4]  | [4,6]            | [6,8]        | [8,9]           |

| The least important criteria | Reliability | Safety | Maintenance cost | Availability |
|-----------------------------|-------------|--------|------------------|--------------|
| Maintenance time            | [8,9]       | [6,8]  | [4,6]            | [2,4]        |

List the equations according to Table 4, and use Matlab to solve the nonlinear optimization problem. The solution results are shown in Figure 4 and Figure 5.

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Figure 5. Optimization process  
Figure 4. Grey weight solution results of each criteria

**Table 4.** Grey weight of each criteria

| Criteria       | Reliability | Safety  | Maintenance cost | Availability | Maintenance time |
|----------------|-------------|---------|------------------|--------------|------------------|
| Grey weight    | [0.463,0.469] | [0.2,0.334] | [0.108,0.191] | [0.06,0.103] | [0.044,0.046] |

**Table 5.** Expert evaluation of each maintenance decision criteria

| Maintenance schemes       | Maintenance cost | Maintenance time | Reliability | Availability | Safety |
|---------------------------|------------------|------------------|-------------|--------------|--------|
| Corrective maintenance    | [1,3]            | [6,8]            | [5,7]       | [4,6]        | [2,4]  |
| Periodic maintenance      | [3,5]            | [4,6]            | [6,8]       | [5,7]        | [8,10] |
| Condition-based maintenance | [6,8]         | [3,5]            | [7,8]       | [7,8]        | [6,8]  |
| Predictive maintenance    | [9,10]           | [2,4]            | [6,8]       | [7,8]        | [6,8]  |

According to Eq. (4) and Eq. (5), the data in Table 5 are dimensionless processed. The dimensionless data obtained are shown in Table 6.

**Table 6.** Dimensionless data

| Maintenance scheme       | Maintenance cost | Maintenance time | Reliability | Availability | Safety |
|--------------------------|------------------|------------------|-------------|--------------|--------|
| Corrective maintenance   | [0.311,1]        | [0.186,0.436]    | [0.322,0.579] | [0.274,0.509] | [0.146,0.338] |
| Periodic maintenance     | [0.186,0.793]    | [0.248,0.655]    | [0.386,0.662] | [0.3425,0.594] | [0.583,0.845] |
| Condition-based maintenance | [0.117,0.396]  | [0.298,0.873]    | [0.450,0.662] | [0.4795,0.679] | [0.438,0.676] |
| Predictive maintenance   | [0.093,0.264]    | [0.372,1]        | [0.386,0.662] | [0.4795,0.679] | [0.438,0.676] |

Calculating the comprehensive grey evaluation value:
\[ \tilde{V}_1 = [0.2365, 0.6479], \quad \tilde{V}_2 = [0.3469, 0.8355], \quad \tilde{V}_3 = [0.3505, 0.7220], \quad \tilde{V}_4 = [0.3215, 0.7026] \]

Calculating the relative kernel of grey evaluation value for comparison:

\[ \delta(\tilde{V}_1) = \frac{(0.2365 + 0.6479) - 1}{2 + [1 + (0.6479 - 0.2365)]} = 0.3088 \]

\[ \delta(\tilde{V}_2) = \frac{(0.3469 + 0.8355) - 1}{2 + [1 + (0.8355 - 0.3469)]} = 0.3972 \]

\[ \delta(\tilde{V}_3) = \frac{(0.3505 + 0.7220) - 1}{2 + [1 + (0.7220 - 0.3505)]} = 0.3910 \]

\[ \delta(\tilde{V}_4) = \frac{(0.3215 + 0.7026) - 1}{2 + [1 + (0.7026 - 0.3215)]} = 0.3683 \]

Through calculation, we can get \( \delta(\tilde{V}_2) > \delta(\tilde{V}_3) > \delta(\tilde{V}_4) > \delta(\tilde{V}_1) \), the preferred maintenance strategy should be periodic maintenance. Through analysis, it is found that the calculated grey comprehensive evaluation value of periodic maintenance and condition-based maintenance is very close, which is also the embodiment of the decision-maker's concept during the current maintenance method transformation. Although more and more attention is paid to CBM, its scope of application needs to be improved in view of its relatively expensive maintenance costs and the limitations of sensor monitoring technology that increase unsafe factors. In this paper, it is calculated that the decision-making plan for selecting periodic maintenance of the meta-action unit is feasible and practical, with relatively high safety and relatively low maintenance cost. Although the cost of CM is the lowest, it is also the most unsafe, so CM can only be adapted to equipment with little consequence of failure. Predictive maintenance represents the cutting-edge maintenance technology. It is an extension of CBM technology. In view of the high maintenance cost, the immaturity of the technology, and the high comprehensive quality of maintenance management personnel, its applicability is limited. At present, it is not suitable for the maintenance of the turbine rotating meta-action unit. Therefore, it is reasonable to implement a periodic maintenance strategy for the turbine rotation-meta-action unit.

6. Conclusion

In the actual maintenance decision problem, it is difficult to make an accurate evaluation of the decision criteria. Too large or too small to evaluate the maintenance decision object may lead to wrong decisions. In this paper, for the maintenance decision problem of the meta-action unit, considering the uncertainty of experts' evaluation of the criteria. First, the expert's language evaluation terms are converted into grey numbers, and the weight of each criteria is calculated by the Grey-BWM. Then, the grey value of the comprehensive evaluation of each decision-making scheme is calculated. Finally, the maintenance decision-making scheme of the meta-action unit is determined by the comparison method of the grey number. The method is relatively simple to use, and the results of case analysis show the feasibility and effectiveness of the method.

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