Research on the Maintenance Decision Model for Marine Equipment Based on Analytic Network Process

Ya Chen, Bo Yang
Dept. of Management Sci., Naval Univ. of Engineering, China, chenya07622@yahoo.cn

Abstract

Maintenance policy selection for vessel equipment is a multiple criteria decision making. To ensure security, reliability and efficiency of vessel equipment, a maintenance decision model based on risk, availability and cost was proposed according to the characteristics of vessel equipment maintenance. For modeling, analytic network process (ANP) has been employed. And the maintenance policies considered here are Corrective maintenance, Time-based maintenance and Condition-based maintenance. Meanwhile, due to the language of expert evaluation has the characteristics of uncertainty and fuzziness to some extent, interval number was introduced to improve the model. The case study of the fuel system of a certain type diesel engine is used to illustrate the methodology, and the optimized maintenance policies of the components are listed at last.

Keywords: Marine Equipment, Maintenance Decision, Analytic Network Process, Interval Evaluation

1. Introduction

The continuously developing of modernization degree of our marine equipment set a still higher demand on the quality of equipment maintenance management in the new era. Maintenance decision-making is very important content in equipment maintenance management, and selecting the optimal strategy for marine equipment is the important measure to strengthen equipment maintenance support efficiency [1]. The common maintenance modes adopted for marine equipment at present are Corrective Maintenance (CM), Time Based Maintenance (TBM) and Condition Based Maintenance (CBM).

Maintenance policy selection for vessel equipment is a multiple criteria decision making. Complication and precision are the characteristic of marine equipment, once fault happen during the mission, enormous economic loss will be made, and the effective implementation of the mission will be affected, even casualty will be caused. So the influences on economy, mission and security should be comprehensively considered when decision-makers make maintenance decision. The criteria considered in this paper are security risk, availability of equipment and cost of maintenance.

In recent years, emphasis has been placed on multi criteria decision-making approach in the field of maintenance strategy selection. Bevilacqua and Braglia (2000) suggested the use of AHP for selecting the maintenance strategy for an Italian oil refinery based on the criteria of cost, damages, applicability, and added value [2]. Al-Najjar, Alsyouf (2003) and Sharma, Kumar (2005) used fuzzy reasoning and fuzzy multiple criteria decision making method to select suitable maintenance strategy [3, 4]. Pe’l’ix and Jose’ (2006) made use of significance evaluation method to decide the optimal maintenance mode [5]. Bertolini and Bevilacqua (2006) presented a combined analytic hierarchy process and lexicographic goal programming approach to select the best maintenance policies for the maintenance of critical centrifugal pumps in an oil refinery [6]. Arunraj and Maiti (2010) also utilized the AHP and Goal Programming method for maintenance policy selection in chemical industry taking risk and cost as the criteria [7]. Godly Kumar and Maiti (2012) proposed fuzzy analytic network process method for maintenance policy selection in chemical industry, and compared the result with Arunraj and Maiti (2010) [8]. Comparing with analytic network process, AHP has characteristic of limitedness to some extent. [9] This paper adopts analytic network process to select the optimal maintenance policies for marine equipment, and introduces interval number to the step of expert evaluation. The interval numbers is used for decision variables instead of crisp values.
2. Applicability analysis and improved method of analytic network process

Analytic network process (ANP) was proposed by the world renowned professor name Thomas L. Saaty at Pittsburgh University of USA in 1996. It is based on analytic hierarchy process (AHP) which has been widely used in decision making process. The core of AHP is dividing the system into several levels namely, goal, criteria and alternatives which are connected top to bottom. The upper level does not depend on the lower levels and the elements present at the same level are also independent of each other. Although it simplifies no-structure or half-structure problems by converting them into hierarchical structures, it fails to solve decision-making problems about complexity systems. In actual problems or most decision-making problems, the complex interactions and feedbacks are present in the systems which AHP can not capture. Compared to hierarchy structure, network structure is more flexible. The interaction relationships between the elements at the same level and the feedbacks between different levels are considered in ANP which can eliminate some unnecessary assumptions, thus making problems closer to the actual matters. [10,11] This paper aims to study how to choose the optimal maintenance modes for marine equipment from corrective maintenance, time based maintenance and condition based maintenance, with considering the three criteria i.e. security risk, availability of equipment and cost of maintenance. The interactions and feedbacks are present in this decision-making problem, for example, if the cost is improved, the risk of failure may be reduced or the availability of equipment may be improved correspondingly. ANP can be used to solve this problem.

In the process of network analysis, the language of expert evaluation is often expressed as crisp value. However, the results provided by experts generally are only crude approximations, thus the language of expert evaluation is vague to some extent. Crisp value can hardly indicates expert evaluation accurately and precisely. There, interval number is introduced in place of crisp value to improve the method of ANP. Since super matrix can only be calculated with crisp values, the interval priorities obtained in pair-wise comparison are converted into crisp priority vectors before input them in the super matrix.

3. Methodology

This paper proposes a combined analytic network process and interval evaluation approach to select the optimal maintenance policies for the maintenance of marine equipment based on security risk, availability of equipment and cost of maintenance. The maintenance policies considered are corrective maintenance (CM), time based maintenance (TBM) and condition based maintenance (CBM).

The methodology involves the following steps:

a) Development of the network structure for maintenance policy selection.

b) Collection of data for pair-wise comparison.

c) Estimation of the priority weights and conversion between interval number and crisp value.

d) Construction of the super matrix and calculation of the sorted result.

3.1. Development of the network structure for maintenance policy selection

A three level network structure is developed for the proposed model. The top level represents the goal of the analysis i.e. selection of maintenance policy; the second level represents the criteria namely security risk, availability of equipment and cost of maintenance; and the third level defines the alternative maintenance policies. There are dominance and feedback relationships between the criteria layer and the alternative layer. And interaction relationships also exist among the elements on the criteria layer. The network schema for the maintenance policy selection is shown in Fig.1.
3.2. Collection of data for pair-wise comparison

The weighing coefficients of the indexes are acquired by Delphi. Specific steps are as follows:

Five experts in the field (three maintenance engineers and two crews who manage the corresponding equipment) were asked three sets (A, B, and C) of questions.

Question A: To select an appropriate maintenance policy for the marine equipment, which of these three criteria elements (security risk, availability of equipment and cost of maintenance) is of greater importance (priority) to you and how much?

Question B1: Consider the criteria risk. Which of the three maintenance policies offers better risk reduction and by how much?

Question B2: Consider the criteria cost. Which of the maintenance policies costs lower and by how much?

Question B3: Consider the criteria availability. Which of the maintenance policies offers better availability improvement and by how much?

Question C1: Consider the maintenance policy “Corrective Maintenance (CM)”. Taking into account one of the three criteria, how much satisfied you are with its improvement of the other two criteria? For example, taking into account the cost of this policy, how much satisfied you are with its risk reduction capability and availability enhancement capability?

Question C2: Consider the maintenance policy “Time-based maintenance (TBM)”. Taking into account one of the three criteria, how much satisfied you are with its improvement of the other two criteria?

Question C3: Consider the maintenance policy “Condition-based maintenance (CBM)”. Taking into account one of the three criteria, how much satisfied you are with its improvement of the other two criteria?

Table 1. Interval number scale for pair-wise comparison.

<table>
<thead>
<tr>
<th>Language description for importance</th>
<th>Interval number</th>
<th>Language description for satisfaction</th>
<th>Interval number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Just equal</td>
<td>[1,1]</td>
<td>Not at all satisfied</td>
<td>[1/6,2/9]</td>
</tr>
<tr>
<td>Equally important</td>
<td>[1/2,2]</td>
<td>Satisfied to some extend</td>
<td>[1/5,1/3]</td>
</tr>
<tr>
<td>Weakly more important</td>
<td>[3/2,3]</td>
<td>Fairly satisfied</td>
<td>[2/7,2/3]</td>
</tr>
<tr>
<td>More important</td>
<td>[5/2,4]</td>
<td>Satisfied</td>
<td>[1/2,2]</td>
</tr>
<tr>
<td>Strongly more important</td>
<td>[7/2,5]</td>
<td>Very satisfied</td>
<td>[3/2,7/2]</td>
</tr>
<tr>
<td>Absolutely more important</td>
<td>[9/2,6]</td>
<td>Extremely satisfied</td>
<td>[3,5]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Absolutely satisfied</td>
<td>[9/2,6]</td>
</tr>
</tbody>
</table>

A comparison scale was provided to the experts for providing their responses which is shown in table 1. Each of the experts gives an answer based on his knowledge and experience, according to the table. The average of the answers from these five experts is taken to create the corresponding pair-wise comparison matrices needed for the analysis as following. “ $\hat{a}_{ij}$ ” shows the degree of relative importance of the $i$ th element in comparison to the $j$ th element.
3.3 Estimation of the priority weights and conversion between interval number and crisp value

i) Using the algorithms of interval number to calculate the primary dominance.

\[ \hat{\lambda}_j = \left( d_j \right)_{m \times n} = \begin{bmatrix} [a_{11}, b_{11}] & \ldots & [a_{1n}, b_{1n}] \\ \vdots & \ddots & \vdots \\ [a_{m1}, b_{m1}] & \ldots & [a_{mn}, b_{mn}] \end{bmatrix} \]

ii) Converting the internal numbers to crisp values with these tips.

Firstly, the probability of \( \hat{S}_j > \hat{S}_i \) is calculated by:

\[ P(\hat{S}_j \geq \hat{S}_i) = \max \left\{ 1 - \max \left( \frac{d - a}{b - a + d - c}, 0 \right), 0 \right\} \]

where \( \hat{S}_i = [a, b] \), \( \hat{S}_j = [c, d] \)

Secondly, the probability of \( \hat{S}_j \geq \hat{S}_i \) (j = 1, 2, ..., n, j \neq i) is calculated by:

\[ P(\hat{S}_j \geq \hat{S}_i) = \min_{j=1,2,...,n} \left( P(\hat{S}_j \geq \hat{S}_i) \right) \]

Finally, the priority in crisp value form of the elements in comparison and judgment matrix is obtained by:

\[ W_{ij} = \frac{P(\hat{S}_j \geq \hat{S}_i)_{j=1,2,...,n,j \neq i}}{\sum_{k=1}^{n} P(\hat{S}_j \geq \hat{S}_i)_{j=1,2,...,n,j \neq k}} \]

3.4 Construction of the super matrix and calculation of the sorted result

There are three key steps to reach the sorted result.

i) The normalized feature vectors obtained from comparison and judgment matrices are inputted in the super matrix to get the unweighted super matrix.

\[ W = \begin{bmatrix} 0 & W_{12} & 0 \\ W_{21} & W_{22} & W_{23} \\ 0 & 0 & 0 \end{bmatrix} \]

Where, \( W_{12} \) is a 3x3 matrix which represents the relative weight of the alternative layer in comparison to the criteria layer; the \( 3 \times 3 \) matrix \( W_{21} \) represents the relative weight of the criteria layer in comparison to the alternative layer; the \( 3 \times 3 \) matrix \( W_{22} \) represents the interrelationships among the three criteria. and \( W_{23} \) represents the relative weight of the criteria layer in comparison to the goal layer. There is no feedback relationship between the criteria layer and the goal layer, and the alternatives are independent, so the inputs are zero.

ii) Every element \( W_{ij} \) in the super matrix \( W \) consists of normalized feature vectors, so the column sum is 1. But the matrix \( W \) has not been normalized. The matrix is converted to a normalized weighted matrix by using weight coefficient, in order to simply calculation.
iii) The limiting super matrix (Idempotent matrix) is obtained by using power method i.e. the method of squaring the weighted matrix. The values of this limiting super matrix are the priorities of the elements of the decision network with respect to the goal.

4. Case study: a maintenance strategy for the fuel system of a marine diesel engine

Diesel engine is a kind of mechanical device which transforms the chemical energy of the fuel to heat and mechanical energy in sequence and then makes the external power output. Diesel engines are widely used on vessels with the characteristics of high thermal efficiency, long service life, rapidity to boot, and convenience to maintain. This paper selects the fuel system of a certain type of marine diesel engine as study object, and elaborates the maintenance decision method for marine equipment based on analytic network process. The structure and elements of this fuel system is showed in Fig. 2.

4.1 Collection of the data

The pair-wise comparison data are collected by interviewing three maintenance engineers and two crews who manage the diesel engine to assess the relative priority weights of the elements (criteria and alternatives) and the degree of satisfaction brought by one criterion’s improvement to the other two. The interval average of the responses from these five experts is taken to create the corresponding pair-wise comparison matrices. For instance, the pair-wise comparison matrix of maintenance policies considering risk criterion for fuel pump is shown in table 2. The constructor methods for the other comparison matrices are similar to this one, and the matrices are omitted here.

<table>
<thead>
<tr>
<th>Maintenance policies</th>
<th>CM</th>
<th>TBM</th>
<th>CBM</th>
<th>Interval dominance / Normalized feature vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>[1,1]</td>
<td>[1/4,2/5]</td>
<td>[1/6,2/9]</td>
<td>[0.0819,0.1324]</td>
</tr>
<tr>
<td>TBM</td>
<td>[5/2,4]</td>
<td>[1,1]</td>
<td>[1/3,2/3]</td>
<td>[0.2217,0.4626]</td>
</tr>
<tr>
<td>CBM</td>
<td>[9/2,6]</td>
<td>[3/2,3]</td>
<td>[1,1]</td>
<td>[0.4049,0.8163]</td>
</tr>
</tbody>
</table>

4.2 Calculation and conversion of the priority weights

The superiority weights in form of internal number of the maintenance policies based risk for fuel pump are computed by:

---

Figure 2. Basal structure of the fuel system

Table 2. The pair-wise comparison matrix of maintenance policies based on risk for fuel pump
\[ \tilde{S}_i = \sum_{j=1}^{k} \tilde{a}_{ij} \otimes \left[ \sum_{j=1}^{k} \sum_{j=1}^{k} \tilde{a}_{ij} \right]^{-1} = \left[ \frac{1}{12.25}, \frac{17.2889}{12.25}, 0.0819, 0.1324 \right] \]

Analogously,
\[ \tilde{S}_j = \sum_{j=1}^{k} \tilde{a}_{ij} \otimes \left[ \sum_{j=1}^{k} \sum_{j=1}^{k} \tilde{a}_{ij} \right]^{-1} = \left[ 0.2217, 0.4626, 0.4049, 0.8163 \right] \]
\[ \tilde{S}_i = \sum_{j=1}^{k} \tilde{a}_{ij} \otimes \left[ \sum_{j=1}^{k} \sum_{j=1}^{k} \tilde{a}_{ij} \right]^{-1} = \left[ 0.4049, 0.8163 \right] \]

The internal numbers are converted to crisp values (Numerical dominance) with these tips.
\[ P(\tilde{S}_i \geq \tilde{S}_j) = \max \left\{ 1 - \frac{0.4626 - 0.0819}{0.1324 - 0.0819 + 0.4626 - 0.2217}, 0, 0 \right\} = 0 \]
\[ P(\tilde{S}_i \geq \tilde{S}_j) = \max \left\{ 1 - \frac{0.8163 - 0.0819}{0.1324 - 0.0819 + 0.8163 - 0.4049}, 0, 0 \right\} = 0 \]
\[ P(\tilde{S}_i \geq \tilde{S}_j, \tilde{S}_j) = \min \left\{ P(\tilde{S}_i \geq \tilde{S}_j), P(\tilde{S}_j \geq \tilde{S}_j) \right\} = 0 \]

Analogously,
\[ P(\tilde{S}_j \geq \tilde{S}_i, \tilde{S}_j) = \min \left\{ P(\tilde{S}_j \geq \tilde{S}_j), P(\tilde{S}_j \geq \tilde{S}_j) \right\} = 0.0885 \]
\[ P(\tilde{S}_j \geq \tilde{S}_i, \tilde{S}_j) = \min \left\{ P(\tilde{S}_j \geq \tilde{S}_j), P(\tilde{S}_j \geq \tilde{S}_j) \right\} = 0.9115 \]
\[ W_j = 0.9115 \]
\[ W_j = \frac{\sum_{j=1}^{k} P(\tilde{S}_i \geq \tilde{S}_j, \tilde{S}_j)}{1} = 0.0885 \]

The results are listed in table 2. The computing methods for superiority degrees of the other comparison matrices are similar to the above, and they are omitted here.

### 4.3 Construction of the super matrix and organization the sorted results

The super matrix is obtained by assembling the normalized feature vectors from pair-wise comparison matrices in a matrix as shown in table 3.

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>CM</th>
<th>TBM</th>
<th>CBM</th>
<th>Risk</th>
<th>Cost</th>
<th>Availability</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alternatives</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CM</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0800</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>TBM</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0885</td>
<td>0.1920</td>
<td>0.4136</td>
<td>0.0000</td>
</tr>
<tr>
<td>CBM</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.9115</td>
<td>0.0000</td>
<td>0.5864</td>
<td>0.0000</td>
</tr>
<tr>
<td><strong>Criteria</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Risk</td>
<td>0.0000</td>
<td>0.3268</td>
<td>0.7132</td>
<td>0.0000</td>
<td>0.5000</td>
<td>0.5000</td>
<td>0.4445</td>
</tr>
<tr>
<td>Cost</td>
<td>1.0000</td>
<td>0.2188</td>
<td>0.0000</td>
<td>0.5000</td>
<td>0.0000</td>
<td>0.5000</td>
<td>0.1110</td>
</tr>
<tr>
<td>Availability</td>
<td>0.0000</td>
<td>0.4544</td>
<td>0.2868</td>
<td>0.5000</td>
<td>0.5000</td>
<td>0.0000</td>
<td>0.4445</td>
</tr>
<tr>
<td><strong>Goal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

The normalized weighted super matrix is obtained by using \( \mathbf{A} = [0, 0.5, 0.1, 0.5, 1, 0, 0] \) to weigh the super matrix. Using software MATLAB, infinite power of the weighted super matrix i.e. limiting super
matrix is calculated.

The numbers of the first three lines in the limiting super matrix are the superiority weights of CM, TBM and CBM respectively. The corresponding result is $[0.0873, 0.0731, 0.1729]^T$, and it is normalized to $[0.2619, 0.2193, 0.5188]^T$. The result of the last four lines is $[0.2512, 0.2159, 0.1996, 0]^T$.

According to the above results, CBM is the best maintenance policy for the fuel pump. These steps are repeated for the other components of the fuel system, and the results are shown in table 4.

Table 4. The superiority weights of maintenance policies and the optimal policies for components of the fuel system

<table>
<thead>
<tr>
<th>Components</th>
<th>Fuel pump</th>
<th>Fuel filter</th>
<th>Pressure governor</th>
<th>Fuel tank</th>
<th>Fuel injection pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>0.2619</td>
<td>0.2025</td>
<td>0.2627</td>
<td>0.3965</td>
<td>0.1650</td>
</tr>
<tr>
<td>TBM</td>
<td>0.2193</td>
<td>0.2763</td>
<td>0.4135</td>
<td>0.3277</td>
<td>0.3274</td>
</tr>
<tr>
<td>CBM</td>
<td>0.5188</td>
<td>0.5212</td>
<td>0.3241</td>
<td>0.2758</td>
<td>0.5076</td>
</tr>
<tr>
<td><strong>The optimal policies</strong></td>
<td><strong>CBM</strong></td>
<td><strong>CBM</strong></td>
<td><strong>TBM</strong></td>
<td><strong>CM</strong></td>
<td><strong>CBM</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Components</th>
<th>High pressure pipe</th>
<th>High pressure pump</th>
<th>Fuel return pipe</th>
<th>Overflow value</th>
<th>Fuel injector</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>0.2231</td>
<td>0.2219</td>
<td>0.2477</td>
<td>0.2618</td>
<td>0.2562</td>
</tr>
<tr>
<td>TBM</td>
<td>0.4255</td>
<td>0.2796</td>
<td>0.4257</td>
<td>0.4592</td>
<td>0.2916</td>
</tr>
<tr>
<td>CBM</td>
<td>0.3514</td>
<td>0.4985</td>
<td>0.3266</td>
<td>0.2790</td>
<td>0.4522</td>
</tr>
<tr>
<td><strong>The optimal policies</strong></td>
<td><strong>TBM</strong></td>
<td><strong>CBM</strong></td>
<td><strong>TBM</strong></td>
<td><strong>TBM</strong></td>
<td><strong>CBM</strong></td>
</tr>
</tbody>
</table>

5. Conclusions

Marine equipments play an important part in our battle effectiveness. The study of decision-making technologies should be constantly strengthened for keeping the equipments running well in peacetime and ensuring them make full use of fight efficiency in war. This paper uses analytic network process to construct the maintenance decision-making model for marine equipment based on security risk, availability of equipment and cost. The maintenance policies considered here are corrective maintenance, time based maintenance and condition based maintenance. For making the model more scientific and reasonable, interval number is introduced in place of crisp value to express expert evaluation. Finally, the case study of the fuel system of a marine diesel engine is used to illustrate the methodology, and the optimized maintenance policies of the components are obtained.

6. Reference


