Research on the Expressway Electromechanical Device Comprehensive Maintenance Efficiency Evaluation Based on Set Pair Analysis Method

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Abstract. The expressway electromechanical device comprehensive maintenance is essential maintenance work. The scientifically evaluation on the comprehensive maintenance efficiency is very important to the expressway electromechanical device management office. Set pair analysis method is used to maintenance support evaluation. Firstly, the paper designed the evaluation index system of the expressway electromechanical device comprehensive maintenance. Secondly, the evaluation model of the comprehensive maintenance efficiency based on the set pair analysis method is built. Then the application steps of the set pair analysis method are introduced. At the end of the paper, a real application example is given. The results of the application indicated the model is feasible and effective. It can give strong support to improve the evaluation effect of the expressway electromechanical device maintenance support.

1. Introduction

China’s expressways are in a period of rapid development. More and more electromechanical device systems are used in expressway serving areas. The expressway electromechanical systems include tolls system, monitoring system, communication system, video image transmission equipment and power distribution systems, etc. To ensure the normal use of these devices, the expressway managers will specially assign personnel to perform inspection and maintenance of all systems. It is the evaluation of the device maintenance support resource assign, utilization efficiency, support effect and investment of the devices maintaining. The maintenance is a high consumption activity, and need to input many kinds of maintenance resources such as the manpower, material resources, financial resources and time. It is a multiple inputs and outputs activity. In order to improve the maintenance efficient, all kinds of resources and their input and output efficiency assigned in the whole serving procedure must be optimized and analyzed. The paper checked the maintenance process as the research subjects. A new model of expressway electromechanical device maintenance based on the set pair analysis method (SPAM) is attempted to be developed.

2. Fundamental principles of set pair analysis method

The set pair analysis method is a systemically analysis method about the certain and uncertainty system’s same, opposite and different degree. The method’s main idea is doing the dialectical logic analysis and mathematics processing on the existed certainty and uncertainty of the system. It thinks
the uncertainty is the essential attribute of the system. It carried on the synthetics investigation about the certainty and uncertainty in a system. This characteristic makes it become an effective method of dealing with problems uncertainty. The three abbreviations are “diversity”, "identity", and "opposite” are correlative mutually restricted and can exchange under certain conditions. The set pair means two sets with a certain relation forms a pair. The contract coefficient means the identity, diversity and opposite degrees of the pair’s common properties. The connection degree’s expression is: \( u = a + bi + cj \). The parameters, \( a, b, c \) are respectively for the identity degree, the diversity degree and opposite degree. \( a \) and \( c \) are relatively certain parameters and \( c \) is uncertainly one. \( a+b+c=1 \). \( i \) and \( j \) are respectively the coefficients of the pair’s diversity degree and opposite degree.

Currently set pair analysis method has been applied in many fields. Efficient evaluation is its main application field.

3. Establishment of Comprehensive Maintenance Index System

Defining input and output index is the key in applying set pair analysis method. The input and output vectors should be subordinated to evaluation project and can reflect it. The comprehensive maintenance efficient evaluation index system was build according to the characteristics and requirements of the evaluation. The paper chooses 10 input indexes and 5 output indexes among all the indexes. The indexes are tabulated in Table 1:

| First Level index name | Second Level Index name                                      |
|------------------------|--------------------------------------------------------------|
| Input                  | C1 Rate of personnel on location                             |
|                        | C2 Personnel fulfilled rate                                  |
|                        | C3 Utilization ratio of spare parts                          |
|                        | C4 Spare parts variety in readiness rate                      |
|                        | C5 Satisfied rate of support device number                   |
|                        | C6 Readiness rate of support device variety in all           |
|                        | C7 Satisfied rate of technical data number                   |
|                        | C8 Readiness rate of technical data variety                  |
|                        | C9 Funded rate of maintaining                                 |
|                        | C10 Reasonable degree of maintenance plan                    |
| Operation              | C11 Personnel skill level rate                               |
|                        | C12 Spare parts readiness rate                               |
|                        | C13 Support equipment readiness rate                          |
|                        | C14 Support equipment availability                            |
|                        | C15 Registration & statistics accuracy                       |
| Output                 | C16 Maintenance effect                                       |
|                        | C17 Maintenance cost                                         |
|                        | C18 Program fulfill rate                                     |
|                        | C19 Maintain qualification rate                               |
|                        | C20 Rate of products sent back for repair                    |

4. Evaluation model of comprehensive maintenance efficient

The steps of establishing the model by applying set pair analysis method are given as follows.

4.1. Determine the comparison space and get evaluation matrix

The evaluation factor is the criterion to estimate the evaluation object. The actual evaluation factor set is set up by analyzing and selecting the main require and necessary abilities, which can affect the comprehensive maintenance efficient evaluation. According to the evaluation index system of the annual equipment maintenance, the set pair analysis evaluation factor set can be constructed. In the
formula $S = \{s_1, s_2, \ldots, s_n\}$, $S$ represents the evaluation object system set. $s_k$ is the $k$th evaluated system. $C = \{c_1, c_2, \ldots, c_r\}$ represents evaluation reference index set. $c_i$ is the $r$th evaluation index. $c_1$ is the benefit index (the bigger the better). $c_2$ is the cost index (the smaller the better). Then $c_r, c_2 \subset C \land C_1 \cup C_2 = C \land C_1 \cap C_2 = \emptyset$. $W$ represents the index weight set. $W = \{w_1, w_2, \ldots, w_n\}$.

4.2. Construct an ideal evaluation index

The set pair analysis method holds that performance indexes have advantages and disadvantages in these existed effectiveness index evaluation results. It takes the best one of them and constitutes an ideal index for virtual. All the attribute values are the best. We take the ideal index as the optimal index. Then we find out the connection degree between other indexes and the ideal index. The optimal result in reality is determined according to the connection degree.

For the analysis in the same space, we determined the attribute values of the optimal evaluation index set according to the range of the index values. $U = \{u_1, u_2, \ldots, u_r\}$. The worst assessment set is constructed according to the same principle. $V = \{v_1, v_2, \ldots, v_r\}$. Among the set, $u_r$ and $v_r$ respectively the best and the worst index values in the evaluation index $c_r$. The comparing interval’s selection relates to the type of evaluation index. For $c_r \in C_1$, the comparing interval is $[v_r, u_r]$. For $c_r \in C_2$, the comparing interval is $[u_r, v_r]$. The best and worst evaluation sets constitute the comparison space.

(1) If $c_r$ is the benefit index, then $c_r \in C_1$ in the comparing interval $[v_r, u_r]$, $\frac{x_{kr}}{u_r + v_r} = \frac{x_{kr}}{u_r + v_r} \in [0, 1]$ indicates the close degree of $x_{kr}$ and $u_r$, $x_{kr}$ and $v_r$. The larger the value, the greater the close degree. At the same time, the more closely between $x_{kr}$ and $u_r$, the farer between $x_{kr}$ and $v_r$. It definite the identity degree $a_{kr}$ and the opposite degree $b_{kr}$ of the set pair $[x_{kr}, u_r]$ as

$$a_{kr} = \frac{x_{kr}}{u_r + v_r}$$

$$b_{kr} = 1 - a_{kr}$$

Because of $a + b + c = 1$, we can calculate the diversity degree $c_{kr}$.

$$c_{kr} = \frac{x_{kr}^{-1}}{u_r^{-1} + v_r}$$

The connection degree of the set pair $[x_{kr}, u_r]$ is defined as

$$R_{[x_{kr}, u_r]} = \frac{(u_r - x_{kr}) (x_{kr} - v_r)}{(u_r + v_r) x_{kr}} i + \frac{u_r v_r}{(u_r + v_r) x_{kr}} j + \frac{x_{kr}}{u_r + v_r} j$$

These kinds of indexes are good at the efficient evaluation, such as the maintenance c, repair fulfill rate etc. $x_{ij} = \max\{x_{ij} | 1 \leq j \leq m\}$

(2) If the $c_r$ is the cost index, $c_r \in C_2$ in comparison space $[u_r, v_r]$, there will be

$$R_{[v_r, u_r]} = \frac{u_r v_r}{(u_r + v_r) x_{kr}} i + \frac{(u_r - x_{kr}) (x_{kr} - v_r)}{(u_r + v_r) x_{kr}} j + \frac{x_{kr}}{u_r + v_r} j$$

These kinds of indexes are bad for the efficient evaluation, such as the maintenance cost, rate of products sent back for repair etc. $x_{ij} = \min\{x_{ij} | 1 \leq j \leq m\}$

In conclusion, the equation (4) and (5) can be combined as $R_{[x_{kr}, u_r]} = a_{kr} + b_{kr} i + c_{kr} j$.
4.3. Compute the connection matrix

In order to facilitate the calculation, we can discuss the close degree between one single index and the ideal index in the effectiveness evaluation index selected preference. Such as only the identity degree is concerned. The opposite degree and diversity degree are not concerned. The computing of the connection matrix means to calculate the identity degree between the evaluation index and the ideal index.

Supposing that the two set have n sorts of attributes in common. Among the n sorts of attributes, there are S sorts of same indexes and P sorts of opposite indexes. Then the different indexes will be .

\[ a = S / N \]

The same index connection degree (the identity degree)

\[ b = F / N \]

The different index connection degree (the diversity degree)

\[ c = P / N \]

The opposite index connection degree (opposite degree)

When the identity degree is computed, \( a = S / N \) then

\[ r_{ij} = \begin{cases} \frac{x_{ij}}{x_{oj}}, & x_{oj} \geq x_{ij} \\ \frac{x_{oj}}{x_{ij}}, & x_{ij} \geq x_{oj} \end{cases} \quad (6) \]

Then the connection matrix can be gotten

\[ R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \quad (7) \]

4.4. Synthesize the connection index

The weight of the index can be analyzed by the expert scoring analysis method or the analytic hierarchy process method. The weights are normalized \( W = \{w_1, w_2, \ldots, w_n\} \)

Linear combined of the weight coefficient matrix and the connection matrix, the weighted synthetic, can get the final evaluation matrix.

\[ Y = R \cdot W = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix} \quad (8) \]

4.5. Sorting the evaluation result

The value of \( y_1, y_2, \ldots, y_m \) sorted in sequence from big to small, can get different types of system efficiency of horizontal comparison. \( y^* = \max\{y_i | 1 \leq i \leq m\} \) is the most efficient system.

According to Eq. (6) and the algorithm of the interval number, the probability importance of the bottom event can be computed by the proposed method.

5. Application of the model

This paper selects 3 different team’s comprehensive maintenance as 3 independent evaluation systems. The set is expressed as \( U = \{U_1, U_2, U_3\} \). The 20 index play an important effect on the comprehensive maintenance of overall system performance formed a set. The set is expressed as \( C = \{C_1, C_2, C_3, \ldots, C_{20}\} \). Its computing result is shown in Table 2.
### Table 2: System Comprehensive Maintenance Data

| Index no | T₁(team1) | T₂(team2) | T₃(team3) | Index no | T₁(team1) | T₂(team2) | T₃(team3) |
|----------|-----------|-----------|-----------|----------|-----------|-----------|-----------|
| C₁       | 88.75%    | 93.27%    | 97.87%    | C₁₁      | 100%      | 80%       | 80%       |
| C₂       | 80.58%    | 83.33%    | 80.30%    | C₁₂      | 80.62%    | 80.36%    | 75.64%    |
| C₃       | 81.25%    | 85.84%    | 90.14%    | C₁₃      | 85.06%    | 87.42%    | 95.45%    |
| C₄       | 76.36%    | 78.62%    | 66.35%    | C₁₄      | 65.35%    | 78.62%    | 76.36%    |
| C₅       | 98.47%    | 91.05%    | 96.05%    | C₁₅      | 80%       | 80%       | 80%       |
| C₆       | 92.08%    | 84.35%    | 91.48%    | C₁₆      | 68.33%    | 71.20%    | 73.07%    |
| C₇       | 88.43%    | 89.41%    | 85.26%    | C₁₇      | 81.20%    | 82.50%    | 84.21%    |
| C₈       | 70.52%    | 66.71%    | 65.35%    | C₁₈      | 85.75%    | 82.67%    | 88.87%    |
| C₉       | 88.72%    | 85.08%    | 87.42%    | C₁₉      | 96.33%    | 94.80%    | 93.90%    |
| C₁₀      | 80%       | 100%      | 80%       | C₂₀      | 1.18%     | 1.02%     | 3.25%     |

5.1. Getting Evaluation Matrix

From the table 3 data, we can get the evaluation matrix in Eq. (9).

\[
\begin{bmatrix}
0.8875 & 0.8058 & 0.8125 & 0.7636 & 0.9847 & 0.9208 & 0.8833 & 0.7052 & 0.8872 \\
0.9327 & 0.8333 & 0.8594 & 0.7862 & 0.9105 & 0.8454 & 0.8942 & 0.6671 & 0.8582 \\
0.9787 & 0.8528 & 0.9014 & 0.7104 & 0.8602 & 0.8575 & 0.9633 & 0.8259 & 0.8267 \\
0.9787 & 0.8528 & 0.9014 & 0.8575 & 0.9633 & 0.8259 & 0.8267 & 0.9700 & 0.9102 \\
0.9787 & 0.8528 & 0.9014 & 0.8575 & 0.9633 & 0.8259 & 0.8267 & 0.9700 & 0.9102 \\
\end{bmatrix}
\]  

(9)

5.2. Constructing an Ideal Evaluation Index

Analysing the table 2 data, we can learn that the c₁, c₂, c₃, c₄, etc. are effective index. It should take the maximum value of evaluation indexes for the ideal attributes values. The index maintenance cost, re-repaired rate are cost index. It should take the minimum value of evaluation indexes for the ideal attributes values. The ideal indexes according to table 4 in the numbering sequence can be drawn from the index of the corresponding evaluation value. The result is shown in Eq. (10).

\[
\begin{bmatrix}
0.8875 & 0.8528 & 0.9014 & 0.7862 & 0.9847 & 0.9208 & 0.8833 & 0.7052 & 0.8872 \\
0.9327 & 0.8333 & 0.8594 & 0.7862 & 0.9105 & 0.8454 & 0.8942 & 0.6671 & 0.8582 \\
0.9787 & 0.8528 & 0.9014 & 0.7104 & 0.8602 & 0.8575 & 0.9633 & 0.8259 & 0.8267 \\
0.9787 & 0.8528 & 0.9014 & 0.8575 & 0.9633 & 0.8259 & 0.8267 & 0.9700 & 0.9102 \\
0.9787 & 0.8528 & 0.9014 & 0.8575 & 0.9633 & 0.8259 & 0.8267 & 0.9700 & 0.9102 \\
\end{bmatrix}
\]  

(10)

5.3. Computing the Connection Matrix

According to the equation (6) and (7), we can calculate the connection matrix in Eq. (11).

\[
\begin{bmatrix}
1.00 & 0.96 & 1.00 & 0.84 & 0.97 & 0.99 & 0.95 & 0.93 & 0.99 & 0.80 & 0.80 & 0.94 & 1.00 & 0.97 & 1.00 & 1.00 & 0.96 & 1.00 & 0.97 & 0.31 \\
0.95 & 1.00 & 0.95 & 1.00 & 0.92 & 0.92 & 1.00 & 0.95 & 0.96 & 1.00 & 0.80 & 0.99 & 0.92 & 1.00 & 0.97 & 0.98 & 0.93 & 0.98 & 1.00 \\
0.91 & 0.97 & 0.90 & 0.97 & 1.00 & 1.00 & 0.99 & 1.00 & 1.00 & 0.80 & 1.00 & 0.89 & 0.83 & 1.00 & 0.94 & 1.00 & 0.96 & 1.00 & 0.86 \\
\end{bmatrix}
\]  

(11)

5.4. Syntheses the Connection Index

The weight of the index had been gotten by the analytic hierarchy process method. The weights after normalized are in Eq. (12).

\[
\begin{bmatrix}
0.034 & 0.044 & 0.048 & 0.042 & 0.048 & 0.042 & 0.048 & 0.051 & 0.080 & 0.087 & 0.043 & 0.043 & 0.043 & 0.034 & 0.078 & 0.037 & 0.042 & 0.084 & 0.036 \\
0.956 & 0.956 & 0.9218 \\
\end{bmatrix}
\]  

(12)

Combine the weight matrix and the connection matrix

The final evaluation matrix is

\[
\begin{bmatrix}
0.9505 \\
0.9556 \\
0.9218 \\
\end{bmatrix}
\]  

(13)

The result shows that team2’s efficient is the highest.
6. Conclusions
This paper applied the set pair analysis method to the expressway electromechanical device comprehensive maintenance evaluation. An index system of comprehensive maintenance evaluation is proposed in this paper. Then an expressway electromechanical device maintenance evaluation model is built by the set pair analysis method. Finally the system is validated by an example. The application example reveals the feasibility and usability of this model. The result shows that the management efficiency of the expressway electromechanical device has been improved a lot. The application prospects for the model is wide and valuable.

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