Comprehensive safety evaluation of metallurgical crane based on AHP and entropy weight method

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Abstract. The determination of safety evaluation weight of most engineering equipment mainly depends on the subjective experience of experts, which ignores the objective requirements of indicator status evaluation, is unable to satisfy the needs of the evaluation system with the advances in modern equipment health monitoring technology. Hence, the authors establish a safety evaluation model to form a comprehensive weight using experience factors, based on the objective weighting of the entropy weight method (EWM) and the subjective weighting of the analytic hierarchy process (AHP), to integrate the objective analysis data and subjective prior knowledge. Then, a safety evaluation system with state value as the main consideration was built on the combination of knowledge and fuzzy comprehensive evaluation. Finally, the availability of the proposed evaluation method was verified by the example.

Keywords: AHP, Entropy weight method, Safety Evaluation, Metallurgical crane

1. Introduction
Metallurgical crane is widely used as an important auxiliary machinery in modern industrial production. The safety of metallurgical cranes has received widespread attention, especially in recent years, because of the high accident rate and huge economic losses. Hence, it is vital to present a relative effective and comprehensive safety evaluation method for the safe operation of the crane. Nevertheless, the industry lacks a common and reasonable standard for crane safety evaluation. Traditional crane safety evaluation methods such as traditional empirical methods and fault tree analysis method are heavily rely on expert experience, and are unable to effectively avoid the influence of adverse subjective factors such as subjective arbitrariness, thinking uncertainty and cognitive ambiguity. Recent years, the AHP has been widely used in fault diagnosis and fuzzy evaluation of mechanical devices, and has achieved good results. Therefore, the AHP has attracted some researcher’s attention and be applied for the safety assessment of the crane. S Fei [1] proposed a safety performance assessment model for bridge cranes and uses the AHP to determine the weights of the indicators. D Sarkar and S Shah [2] employed the AHP to elicit subjective knowledge from the expert and formalized it into a set of weighted safety factors. The AHP is also used for giant shipbuilding tower crane safety evaluation [3]. Also, some scholars introduce the AHP for tower
cranes [4-6]. However, the standard AHP still depends on the experience and knowledge of experts and is too subjective to affect the accuracy of the evaluation results. The entropy weight method (EWM), a known objective weight evaluation method, is sometimes prone to give greater weight to the indicators with a small difference and then contrary to fact. This paper takes advantages of two methods and find a balance between subjective consciousness and objective data, to propose a comprehensive safety evaluation method for the metallurgical cranes based on the objective weighting of the EWM and the subjective weighting of the AHP. The empirical factors are used to form a comprehensive weight model to achieve the combination of objective analysis data and subjective prior knowledge, and then combined with fuzzy comprehensive evaluation to present an effective metallurgical crane safety evaluation method.

2. Comprehensive evaluation indicator system

2.1 Analytic hierarchy process

Analytic hierarchy process (AHP) is a multi-quasi-measurement decision-making method that combines qualitative and quantitative analysis established by T L Satty [7]. Four main steps are included in the AHP:

(1) Establish a hierarchical model

The whole system is decomposed according to the contained subsystems, and then the subsystems are decomposed into indicators to determine the evaluation value of each indicator

\[ U = \{ U_1, U_2, U_3, \ldots, U_n \} \]  

where \( U \) is the evaluation set, \( n \) is the number of the factors, and \( U_n \) is a single factor evaluation value.

(2) Construct judgment matrix

According to expert experience, the relative importance of each single factor evaluation indicator can be obtained by comparing each factor in pairs, and the judgment matrix can be obtained comprehensively:

\[
A = \begin{pmatrix}
a_{11} & a_{12} & \cdots & a_{1n} \\
a_{21} & a_{22} & \cdots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{n1} & a_{n2} & \cdots & a_{nn}
\end{pmatrix}
\]  

(2)

\[ a_{ij} = \begin{cases} 
1 & i = j (i, j = 1, \ldots, n) \\
\frac{1}{a_{ji}} & i \neq j
\end{cases} \]  

(3)

(3) Obtain weight

The weight is obtained by solving the eigenvalues of the judgment matrix

\[ \bar{A}W = \lambda_{\text{max}}W \]  

(4)

where \( \lambda_{\text{max}} \) is the maximum eigenvalue of the judgment matrix and \( W \) is the eigenvector.

(4) Consistency judgment

A consistency test is required to avoid the logical confusion of indicators. The smaller value of \( CI \) suggests the better consistency of the matrix, and \( CI=0 \) means the judgment matrix is completely consistent.

\[ CI = \frac{\lambda_{\text{max}} - n}{n-1} \]  

(5)
2.2 logical hierarchical tree for safety evaluation

The indicators included strength, stiffness, weld, local deformation and corrosion are selected as the evaluation indicator for safety assessment of a double girder metallurgical crane based on the inspection and maintenance records. Zhang et al. [8] presented the detail evaluation method for the evaluation indicators. Therefore, the logical hierarchical tree for safety evaluation can be depicted with the obtained evaluation indicators, shown as figure 1.

![Figure 1. Logic hierarchy tree for safety evaluation of a double girder metallurgical crane.](image)

According to the figure 1, the logical hierarchy tree shows the evaluation indicators of the main girder 1. In addition, the evaluation indicators of the main girder 2, the end girder 1 and the end girder 2 are the same as the main girder 1.

2.3 Entropy weight method

Entropy in physics is the quantity related to the starting state and the ending state. N Weiner and C E Shannon [9] founded information theory in 1948. Shannon called the uncertainty of information source signals as information entropy. In information entropy, the increase in entropy indicates the loss of information. The greater the amount of information in the system, the higher the degree of order and the lower the entropy. Thus, the information is negative entropy, and entropy can be used to measure the amount of information. The procedure for EWM is presented as follows:

(1) Construct decision matrix

The set of the evaluation indicators and objects are defined as \( D = (D_1, D_2, \ldots, D_n) \) and \( M = (M_1, M_2, \ldots, M_m) \), respectively. The evaluation state value of each object set \( M_j \) against the indicator set \( D_i \) is expressed as \( x_{ij} (i = 1, 2, \ldots, n; j = 1, 2, \ldots, m) \), so the decision matrix \( X \) can be expressed as:

\[
X = \begin{bmatrix}
    x_{11} & \cdots & x_{1n} \\
    \vdots & \ddots & \vdots \\
    x_{m1} & \cdots & x_{mn}
\end{bmatrix}
\]

(6)

(2) Standardize decision matrix

According to the different attribute of indicators, the indicators can generally be divided into two categories: Efficiency-oriented and Cost-oriented indicator. As for efficiency-oriented indicator, the higher the state value of the indicator corresponds to the better state. The cost-oriented indicator is opposite, the higher state value means the worse state.

\[
v_{ij} = \begin{cases}
    \frac{x_{ij} - \min x_j}{\max x_j - \min x_j} & \text{Efficiency-oriented} \\
    \frac{\max x_j - x_{ij}}{\max x_j - \min x_j} & \text{Cost-oriented}
\end{cases}
\]

(7)

where \( v_{ij} \) is the standardized value of \( x_{ij} \), \( \max x_j \) and \( \min x_j \) are the maximum and minimum state value of the \( j \)th indicator, respectively.
(3) Calculate feature weight
As for the \( j \)th indicator, the greater difference among \( v_{ij} \) indicates that the greater the contribution of this indicator to the object being evaluated, the more evaluation information provided by this indicator.

The feature weight of the \( j \)th indicator of the \( i \)th object is \( p_{ij} \), defined as

\[
p_{ij} = \frac{v_{ij}}{\sum_{i=1}^{m} v_{ij}}
\]

(8)

(4) Calculate entropy

\[
e_{j} = -\frac{1}{\ln m} \sum_{i=1}^{m} p_{ij} \ln p_{ij}
\]

(9)

If \( p_{ij} = 0 \) or \( p_{ij} = 1 \), then \( p_{ij} \ln p_{ij} = 0 \).

(5) Calculate the coefficient of difference and weight
According to the Eq. (34), the information is negative entropy. The greater entropy value indicates the smaller difference among \( v_{ij} \). The coefficient of difference \( d_{j} \) is used to represent the difference of the \( j \)th indicator value of each object, defined as \( d_{j} = 1 - e_{j} \).

(6) Calculate weight

\[
w_{j} = \frac{d_{j}}{\sum_{k=1}^{n} d_{k}} (j = 1, 2, \ldots, n)
\]

(10)

2.4 Determination for comprehensive weight
Supposing the subjective weight \( W_{1} \) is obtained by AHP, and \( W_{2} \) is the result calculated using the EWM, the comprehensive weight \( W \) can be obtained by linear combination of the two weights

\[
W = \alpha W_{1} + (1 - \alpha) W_{2}
\]

(11)

where \( \alpha (0 < \alpha < 1) \) is the scale factor. If the subjective weight is set as the main weight, it is generally taken as 0.618.

3. Fuzzy comprehensive evaluation method based on comprehensive weight
Fuzzy comprehensive evaluation method (FCEM) is featured by the ability to accurately cope with inaccurate and incomplete information. With the development of intelligent crane safety evaluation system, the fuzzy relation matrix of fuzzy comprehensive evaluation in hoisting machinery system is mainly obtained through expert experience, which is of low efficiency and high cost. Therefore, this paper proposes a new safety evaluation method based on comprehensive weight and fuzzy comprehensive evaluation method.

3.1 Fuzzy comprehensive evaluation method based on comprehensive weight
The standard FCEM consists of five element sets as follows:
(1) Set of evaluation indicator (\( U \))

The set composed by the attributes of the evaluation object can be expressed as

\[ U = \{u_{1}, u_{2}, \cdots, u_{n}\} \]

and \( u_{i} (i = 1, 2, \cdots, n) \) is the attribute of the evaluation object, respectively.

(2) Set of weight (\( W \))
The weight set is a set calculated by a comprehensive weight model, indicating that the importance of each attribute in the evaluation layer is different, expressed as \( W = [w_1, w_2, \cdots, w_n] \) and \( w_i (i = 1, 2, \cdots, n) \) is the membership of \( u_i \) to \( W \). Generally, \( w \) should meet the normalization and non-negative conditions as \( \sum_{i=1}^{n} w_i = 1 (w_i \geq 0) \).

(3) Set of evaluation (\( V \))

The evaluation set \( V \) is the set composed of attribute state values of the evaluation object, expressed as: \( V = [v_1, v_2, \cdots, v_m] \).

(4) Matrix of fuzzy relation (\( R \))

The fuzzy relationship between the evaluation index set \( U \) and the evaluation set \( V \) can be represented by a fuzzy relation matrix

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

(12)

\[ r_{ij} = \mu_i(u_i, v_j) \]  

(13)

\[ 0 \leq r_{ij} \leq 1 \]  

(14)

where \( r_{ij} \) denotes the degree to which the object makes judgment results \( v_j \) when considering attributes \( u_i \) and \( \mu_i(\cdot) \) is the membership function.

(5) Set of Fuzzy comprehensive evaluation index (\( B \))

The set of fuzzy comprehensive evaluation index would be gained with the obtained weight set \( W \) and fuzzy relation matrix \( R \), which is calculated by \( B = W \circ R \), and \( \circ \) is the fuzzy operator. Generally, the weighted average operator \( (\cdot,+) \) is chosen as the fuzzy operator. Consequently, the system state can be determined according to the obtained comprehensive evaluation indicator \( b_j (j = 1, 2, \cdots, m) \) and maximum membership principle.

Therefore, the detailed procedure for the proposed fuzzy evaluation method is shown as figure 2.

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**Figure 2. Safety evaluation algorithm of metallurgical crane**
The figure 2 shows that the comprehensive weight obtained via the AHP and EWM is combined with the fuzzy comprehensive evaluation method to evaluate the upper layer subsystem, and continuously, until the evaluation value of the overall structural system is obtained.

4. Example
This paper takes a single main girder of a 200t casting crane with four girders and four rails as an example for safety evaluation to demonstrate the validity of the proposed algorithm. The state values of the evaluation indicators are shown in table 1.

**Table 1.** The state values of evaluation indicators of metallurgical crane.

| Main girder | Strength | Stiffness | Local deformation | Weld | Corrosion |
|-------------|----------|-----------|-------------------|------|-----------|
| Dection 1   | 0.955    | 0.68      | 0.756             | 0.99 | 0.72      |
| Dection 2   | 0.912    | 0.685     | 0.747             | 0.97 | 0.71      |
| Dection 3   | 0.922    | 0.69      | 0.725             | 0.83 | 0.702     |
| Dection 4   | 0.91     | 0.68      | 0.724             | 0.65 | 0.7       |

**Step 1.** Calculate the weight using the AHP
The judgement matrix can be expressed as

\[
A = \begin{pmatrix}
1 & 2 & 2 & 6 & 3 \\
1 & 1 & 1 & 3 & 2 \\
1 & 2 & 1 & 1 & 3 \\
1 & 1 & 1 & 1 & 1 \\
6 & 3 & 3 & 2 & 1 \\
3 & 3 & 3 & 2 & 1
\end{pmatrix}
\]  

(16)

then \( \lambda_{\text{max}} = 5 \) and eigenvector \( W_1 = (0.4, 0.2, 0.2, 0.07, 0.13) \) are obtained, and the result \( CI = \frac{\lambda_{\text{max}} - n}{n - 1} = 0 \) indicates the judgement matrix is completely consistent.

**Step 2.** Obtain the weight using the EWM \( W_2 = (0.0141, 0.0014, 0.0131, 0.9668, 0.0046) \).

**Step 3.** Calculate the comprehensive weight \( W = (0.2526, 0.1241, 0.1286, 0.4105, 0.0842) \).

**Step 4.** Establish fuzzy relation matrix
Chen et al. [10] provide a system evaluation membership function based on eight levels, shown as table 2.

**Table 2.** Classification of the result of safety evaluation

| Status value | Status description |
|--------------|--------------------|
| (0, 0.125)   | Disposal required  |
| (0.125, 0.25]| Discontinue use and overhaul required |
| (0.25, 0.375)| Overall maintenance and repair required |
| (0.375, 0.5)| Serious operation with fault and major structural parts repair required |
| (0.5, 0.625)| More serious operation with fault, pay attention to the structure and cracks, and structural parts repair required |
Belong to faulty operating state, focus on local deformation and micro-cracks. The additional regular inspections and damaged parts repair required.

Running in normal condition, strengthen inspection required.

Running in good condition

Thus, the fuzzy relation matrix of FCEM can be generated as following:

\[
\begin{bmatrix}
0 & 1\ 0.9 & R(x, 1) = 0.9 & R(x, 2) = 0.1 \\
0.28 & 0.72 & 0 & 0 & 0 & 0\ 0.104 & 0.896 & 0 & 0\ 0.4 & 0.6 & 0 & 0\ 0.2 & 0.8 & 0 & 0
\end{bmatrix}
\]

where \( X(2) = \frac{1}{8}, X(3) = \frac{1}{4}, X(4) = \frac{3}{8}, X(5) = \frac{1}{2}, X(6) = \frac{5}{8} \)

Thus, the fuzzy relation matrix of FCEM can be generated as following:

\[
\begin{bmatrix}
0 & 0 & 0 & 0 & 0.1 & 0.9 \\
0 & 0 & 0 & 0.28 & 0.72 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

\[
R = [0.625, 0.75]
\]

\[
(0.75, 0.875)
\]

\[
(0.875, 1.0)
\]

\[
\text{Step 5. Obtain the set of fuzzy comprehensive evaluation indicator}
\]

\[
B = [0.2292, 0.5182, 0.0253, 0.2273]
\]

According to the principle of maximum membership, it is shown that the safety state of the main girder system is the third level, i.e., the safety condition is general, and it belongs to the faulty operating state. Therefore, it is necessary to pay attention to the local deformation and micro-cracks, and the damaged parts should be repaired besides regular inspection. In general, the obtained result via FCEM based on comprehensive weight is consistent with the single factor feedback results of recent detection, which indicates that the proposed method is available to safety assessment of metallurgical crane.

5. Conclusions

This article builds a logical hierarchical tree for double-girder metallurgical crane safety evaluation contains five evaluation indicators and two-layer subsystem based on the AHP. Due to the weight factor determined by the AHP can only reflect the importance of strength indicator in the systematic evaluation, is unable to reflect the status factor of weld point, and the EWM excessively amplifies the importance of the weld point indicator and ignores the other evaluation indicators, thus this paper
proposes a comprehensive evaluation method combining with two methods. The main contributions of this paper can be summarized as
(1) The proposed comprehensive evaluation method cannot only reflect the current state of evaluation indicators, but also reflect the importance among the attributes of each evaluation indicator.
(2) The safety evaluation algorithm based on comprehensive weighting and fuzzy comprehensive evaluation method can reasonably reflect the system state value thus can be considered as an effective safety evaluation method for metallurgical crane.

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