Comprehensive Evaluation of Risk Factors of Coal Mine Safety Management Based on Combined Weighted Tissue Model

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Abstract. Safety management is an important guarantee for safe and efficient production of coal mines. In order to explore the cause of coal mine safety management risk, the questionnaire was combined with expert interviews to obtain risk factors, and the combination optimization TOPSIS evaluation model was used for evaluation. According to the calculated ideal solution and negative ideal solution, the relative progress is obtained. The coal mine safety management status is explained by comparing the relative proximity, and an example analysis is made. The example verification shows that the evaluation result of the model is basically consistent with the actual situation, which helps to pre-control the risk in time, eliminate hidden dangers, and effectively ensure the safety of mine production.

1. Introduction
The causes of coal mine safety incidents are safety management policies, procedures, supervision and training. Therefore, it is necessary to comprehensively evaluate the risk factors of coal mine safety management, prevent and pre-control the risk factors early, and avoid or reduce the occurrence of coal mine safety accidents.

2. Evaluation index weight calculation
2.1. Fuzzy analytic hierarchy process to calculate the subjective weight of indicators
① Firstly establish the fuzzy complementary matrix of risk indicators, compare the safety management risk indicators F1, F2, F3, and Fn, and use 0.1~0.9 scale to quantitatively describe the membership degree of fuzzy relations, and obtain the fuzzy judgment matrix B=(bij)n×n.
Table 1 Financial risk indicator fuzzy relationship membership scale value

| Scale value | Judge          | Description                                   |
|-------------|----------------|-----------------------------------------------|
| 0.5         | Equally important | two indicators are equal, equally important   |
| 0.6         | Slightly important | Comparison of two indicators. One indicator is slightly more important than another. |
| 0.7         | Significantly important | Comparison of two indicators, one indicator is significantly more important than the other. |
| 0.8         | Very important   | Comparison of two indicators. One indicator is more important than another. |
| 0.9         | Extremely important | Comparison of two indicators. One indicator is extremely important than the other. |
| 0.4, 0.3, 0.2, 0.1 | Complementary | The index N_j is a_{ji} for the indicator N_i, 0 ≤ bij ≤ 1 and bij+bji=1 |

Secondly, the fuzzy complementary matrix $A=(a_{ij})_{nxn}$ is summed by the line $d_i=\sum_{j=1}^{n}b_{ij}i,f=(1,2, ..., n)$, and transformed by the following formula to obtain the fuzzy uniform judgment matrix $D=(d_{ij})_{nxn}$, which satisfies the consistency check and does not need to be retested

$$d_{ij} = \frac{d_i - b_{ij} + 0.5}{2n}$$  \hspace{1cm} (1)

② Matrix $D=(d_{ij})_{n\times n}$ Calculate subjective weights as follows

$$\beta = (\beta_1, \beta_2, ..., \beta_n). \beta_i = \sum_{j=1}^{n-1}(i=1,2, ..., n)$$  \hspace{1cm} (2)

2.2. Entropy weight method to calculate the objective weight of indicators

Suppose there are m mines, n indicators, and each index is scored, and $A=(A_{ij})_{mxn}$ is obtained. The elements in $A=(A_{ij})_{mxn}$ are normalized according to (3) and (4) to obtain a standardized target matrix $U=(\chi_{ij})_{mxn}$.

$$\chi_{ij} \left\{ \begin{array}{ll} \frac{b_{mn} - b_{n_{min}}}{b_{n_{max}} - b_{n_{min}}} & \text{Benefit indicator (the bigger the indicator value, the better)} \\ \frac{b_{n_{max}} - b_{mn}}{b_{n_{max}} - b_{n_{min}}} & \text{Cost indicator (the smaller the indicator value, the better)} \end{array} \right.$$  \hspace{1cm} (3)

① Information entropy: $E_j=-Kx \sum_{i=1}^{b} p_{ij} \ln p_{ij}$, (j=1,2,3,......b). In the middle: $K=-\ln a_p = d_i/\sum_{i=1}^{n} d_i$, when $p_{ij}=0$, then $\lim_{p_{ij} \to 0} p_{ij} \ln p_{ij} = 0$. ② Calculate the information entropy $E_1, E_2, E_3, ... E_k$, then calculate the entropy weight according to the following formula, and define the entropy weight as then: $\omega_i = (1-E_i)/(b \sum E_i)$, (i=1,2,3,......, k). The greater the entropy weight, the more information is provided. The greater the importance of the indicator, the lower the importance.
3. Based on game theory combined empowerment

3.1. Calculating indicator weights

Use two methods to calculate the weights of each index. The basic weight vector set \( \mathbf{e}_k = \{ e_{k1}, e_{k2}, \ldots, e_{kn} \} \) \((k=1, 2, \ldots, K)\), \( n \) is the number of coal mine safety management risk indicators, and the number of weighting methods is \( K \), \( K = 2 \), so the weight coefficient \( \mathbf{\alpha} = \{ \alpha_1, \alpha_2, \ldots, \alpha_k \} \). Linear combination is:

\[
\mathbf{e} = \sum_{k=1}^{K} \mathbf{\alpha}_k \mathbf{e}_k
\]

(5)

3.2. Optimization combination

The minimum deviation of \( \mathbf{e} \) and \( \mathbf{e}_k \) is determined as the target, and the \( K \) linear weight combination coefficients in equation (3) are optimized to obtain the most satisfactory weight in \( \mathbf{e} \). The objective function is: \( \min \| \sum_{k=1}^{K} \mathbf{\alpha}_k \mathbf{e}_k - \mathbf{e}_k \| \) \((k=1, 2, \ldots, K)\). The linear equations optimized by equation (5) are:

\[
\begin{bmatrix}
\mathbf{e}_1 \cdot \mathbf{e}_1^T & \mathbf{e}_1 \cdot \mathbf{e}_2^T & \ldots & \mathbf{e}_1 \cdot \mathbf{e}_k^T \\
\mathbf{e}_2 \cdot \mathbf{e}_1^T & \mathbf{e}_2 \cdot \mathbf{e}_2^T & \ldots & \mathbf{e}_2 \cdot \mathbf{e}_k^T \\
\vdots & \vdots & \ddots & \vdots \\
\mathbf{e}_k \cdot \mathbf{e}_1^T & \mathbf{e}_k \cdot \mathbf{e}_2^T & \ldots & \mathbf{e}_k \cdot \mathbf{e}_k^T \\
\end{bmatrix}
\begin{bmatrix}
\mathbf{\alpha}_1 \\
\mathbf{\alpha}_2 \\
\vdots \\
\mathbf{\alpha}_k \\
\end{bmatrix} =
\begin{bmatrix}
\mathbf{e}_1 \cdot \mathbf{e}_1^T \\
\mathbf{e}_2 \cdot \mathbf{e}_2^T \\
\vdots \\
\mathbf{e}_k \cdot \mathbf{e}_k^T \\
\end{bmatrix}
\]

(6)

3.3. Normalization

The \( \mathbf{\alpha}_k \) is normalized to obtain \( \mathbf{\alpha}_k = \mathbf{\alpha}_k / \sum_{k=1}^{K} \mathbf{\alpha}_k \). Combine weights by the following formula \( \mathbf{e}^* = (\mathbf{e}_1^*, \mathbf{e}_2^*, \ldots, \mathbf{e}_n^*) \).

\[
\mathbf{e}^* = \sum_{k=1}^{n} \mathbf{\alpha}_k \mathbf{e}_k^*, \text{ } k=(1,2,3, \ldots, K)
\]

(7)

4. Constructing TOPSIS evaluation model for game theory combination weighting

There are \( m \) coal mining enterprises, the safety management risk factor sample set \( \mathbf{M} = (\mathbf{M}_1, \mathbf{M}_2, \mathbf{M}_3, \ldots, \mathbf{M}_m) \), there are \( n \) evaluation indicators, then the indicator set \( \mathbf{Q} = (\mathbf{Q}_1, \mathbf{Q}_2, \mathbf{Q}_3, \ldots, \mathbf{Q}_n) \). The decision value of \( \mathbf{M}_m \) corresponding index \( \mathbf{Q}_n \) is \( \mathbf{V}_{mn} \), and the risk evaluation decision matrix \( \mathbf{V} = (\mathbf{v}_{ij})_{m \times n} \). The matrix \( \mathbf{V} \) is transformed according to equation (4), and a normalized decision matrix \( \mathbf{U} = (\mathbf{u}_{ij})_{m \times n} \) is obtained. Second, multiply the matrix \( \mathbf{U} \) by \( \mathbf{e}^* \) to obtain a weighted normalization decision matrix

\[
\mathbf{Y} = (\mathbf{y}_{ij})_{m \times n}, \text{ } \mathbf{y}_{ij} = \mathbf{e}^* \mathbf{\chi}_j \text{ (i=1,2,\ldots,m; j=1,2,\ldots,n)}
\]

(8)

\( \mathbf{e}^* \) is the combined weight corresponding to the index of the \( j \) column.

Ideal solution:

\[ y_j^+ = \max \{y_{1j}, y_{2j}, \ldots, y_{mj}\} \quad (j=1,2,3\ldots, n) \quad (9) \]

Negative ideal solution:

\[ y_j^- = \min \{y_{1j}, y_{2j}, \ldots, y_{mj}\} \quad (j=1,2,3\ldots, n) \quad (10) \]

Distance from positive and negative ideal solutions:

\[ d_i^+ = \sqrt{\sum_{j=1}^{n} (y_{ij} - y_j^+)^2} \quad d_i^- = \sqrt{\sum_{j=1}^{n} (y_{ij} - y_j^-)^2} \quad (11) \]

Relative proximity

\[ \theta_i = \frac{d_i^-}{d_i^+ + d_i^-} \quad (12) \]

The relative progress value is large, the higher the security management ability, the lower the risk value. Conversely, the status quo of safety management is poor and the risk factors are high.

5. Case analysis

① Taking five coal mining enterprises affiliated to a mining group in Jining as an example, an expert panel was selected to determine five major coal mine safety management risk factors, safety management organization S1, safety management supervision S2, safety management mode S3, safety management element S4, safety management ability S5. Compare the importance of these five indicators and score them.

Table 2. Evaluation indexes and sample data of safety management factors in coal mining enterprises

| index   | Type | Sample1 | Sample2 | Sample3 | Sample4 | Sample5 |
|---------|------|---------|---------|---------|---------|---------|
| organization | 1       | 87     | 87     | 86     | 79     | 83     |
| mode    | 1       | 88     | 83     | 90     | 86     | 88     |
| ability | 1       | 85     | 89     | 80     | 85     | 85     |
| Element | 1       | 91     | 79     | 91     | 75     | 90     |
| Monitoring | 1       | 90     | 75     | 83     | 79     | 87     |

Note: "0" is an indicator of efficiency, and "1" is an indicator of adult nature

② Evaluation index weight calculation Based on the game theory theory combination weighting, the combined weight w* is obtained.

Table 3. The various weight values of the indicators

| index | Subjective weight \( \beta_i \) | Objective weight \( \delta_i \) | Combination weight \( w^* \) |
|-------|---------------------------------|-------------------------------|-----------------------------|
| S1    | 0.163                           | 0.160                         | 0.162                       |
| S2    | 0.143                           | 0.155                         | 0.147                       |
| S3    | 0.145                           | 0.098                         | 0.125                       |
| S4    | 0.125                           | 0.087                         | 0.107                       |
| S5    | 0.123                           | 0.156                         | 0.131                       |
According to the combined weight, the importance ranking of five coal mine safety management factors can be known, namely S1>S2>S5>S3>S4. The coal mine enterprise safety management risk evaluation decision matrix \( V=(v_{ij})_{m \times n} \) will be transformed according to formula (4) to obtain the standardized decision matrix \( U=(x_{ij})_{m \times n} \).

\[
C = \begin{bmatrix}
0.1667 & 0.3333 & 0.8571 & 0.5455 & 0.3636 \\
0 & 0.5000 & 0.5714 & 0.9091 & 0 \\
0.3333 & 0 & 1.0000 & 0 & 0.9091 \\
0.5000 & 0 & 0.2857 & 1.0000 & 0 \\
0 & 0.8333 & 0 & 0.2727 & 0.9091 \\
\end{bmatrix}
\]

\[
Y = \begin{bmatrix}
0.027 & 0.0490 & 0.1071 & 0.0584 & 0.0463 \\
0 & 0.0735 & 0.0714 & 0.0972 & 0 \\
0.0540 & 0 & 0.1250 & 0 & 0.1191 \\
0.0810 & 0 & 0.057 & 0.1070 & 0 \\
0 & 0.1225 & 0 & 0.0292 & 0.1191 \\
\end{bmatrix}
\]

\[
y^+_j = \{0.0810, 0.1225, 0.1250, 0.1070, 0.1191\} \quad y^-_j = \{0, 0, 0, 0, 0\} \\
d^+_i = \{0.0163, 0.3612, 0.2836, 0.1839, 0.1680\} \quad d^-_i = \{0.1784, 0.1412, 0.1809, 0.1458, 0.1733\} \\
\delta_i = \{0.9163, 0.2810, 0.3895, 0.2990, 0.5048\}
\]

The relative progress reflects the ranking of the safety management level of the sample mines. The priority is: Sample 1 > Sample 5 > Sample 3 > Sample 4 > Sample 2. Sample 1 and Sample 5 of the Group are safely managed compared to the other three companies. It is better, so we should start from the weak link according to the weight of each factor.

### 6. Conclusion

Fuzzy tomographic analysis calculates subjective weights and circumvents the drawbacks of traditional computing models. The evaluation results are basically consistent with the actual situation, indicating that the constructed evaluation model has certain practicability and guiding significance, and the evaluation results are more scientific and accurate. The evaluation process is clear and simple, and has certain promotion and application value.

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