Evaluation model of coal mine emergency rescue resource allocation based on weight optimization TOPSIS method

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Abstract. In order to solve the problems of unreasonable allocation and low efficiency of emergency rescue resources in coal mine accidents, it is necessary to establish a coal mine emergency rescue resource allocation model by using comprehensive weight-approximation ideal solution (TOPSIS method). This paper takes rock burst in a coal mine as an example by extending this designed emergency rescue plan. Firstly, calculated the weight of the evaluation index affecting the emergency rescue is selected by AHP method and entropy weight method respectively. Then weight optimization is inspired by comprehensive weight method. Finally, the optimal scheme is selected by TOPSIS method, and the model is verified by AHP method approaching ideal solution and entropy weight method approaching ideal solution. The results shows that: (1) There are two influencing factors have great effect on the evaluation of coal mine emergency rescue model, which are rescue time and advance of rescue channel; (2) The optimal scheme is program 5 through comprehensive weight approaching ideal solution, which is consistent with the actual situation of the project, indicating that the model has high reliability.

1. Introduction
In the past 40 years, coal has made an important contribution to the rapid development of China's economy, and would support the steady development of China's economy in the future [1]. However, coal mining has also caused many safety accidents, such as coal dust, water disaster, fire, gas and roof accidents, which are sudden, destructive and repeated. Once these accidents happen, they will cause serious consequences, sometimes even form a certain disaster chain, which greatly brings serious casualties and huge economic losses to coal mining enterprises [2-3].

At present, the research on emergency rescue mainly focuses on natural disasters such as earthquakes, fires and floods, man-made accidents and public health incidents [4]. Most of the researches on emergency rescue in coal mines are to establish emergency management mechanism system and build emergency capability evaluation model, while the research on emergency resource allocation is rarely involved [5].

Based on the theory of emergency management, combined with previous scholars' research results and engineering practice analysis, the author established the evaluation index system of coal mine emergency rescue resource allocation, and then calculated the weight value of influencing factors by entropy weight method and analytic hierarchy process (AHP) method respectively. Finally, based on the
comprehensive weighted TOPSIS method to build coal mine emergency rescue resource allocation model, selected a more scientific and effective rescue package.

2. Evaluation Methods

2.1. AHP Method [6-7]

(1) Construction of a judgment Matrix \( A = (a_{ij})_{n \times n} \):

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

(2) Calculate the weight of each index. Combined with the scale value of AHP method, the weight of each factor of the judgment matrix \( A \) of the evaluation index is calculated. The specific calculation formula is shown:

\[
\varphi_{ij} = a_{ij} / \sum_{i=1}^{n} a_{ij}
\]

Where \( \varphi_{ij} \) is the normalization of the column vector of matrix \( A \).

\[
\kappa_i = \sum_{j=1}^{n} \varphi_{ij}
\]

Where \( \kappa_i \) is the sum of the \( i^{th} \) row vector.

\[
w_i = \kappa_i / \sum_{i=1}^{n} \kappa_i
\]

Where \( w_i \) is the actual weight after normalization.

\[
\omega_i = \left(w_1, w_2, \cdots, w_n\right)^T
\]

(3) Consistency test

Calculate the relevant parameters of the judgment matrix \( A \) of the evaluation index, including the maximum eigenvalue \( \lambda_{max} \) of each factor, the consistency index \( CI \), and the consistency ratio \( CR \).

\[
\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \left(Aw_i\right)_i / w_i
\]

Where \( (Aw)_i \) represents the \( i^{th} \) component of the vector \( Aw \).
If CR < 0.1, it means that the consistency of the judgment matrix is valid; otherwise, the judgment matrix needs to be further modified until the conditions are met.

2.2. Entropy Weight Method [8-9]
If there are m evaluation samples and n evaluation indicators, the established evaluation matrix is:

\[ A = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \tag{9} \]

(1) Standardization of indicators.
Standardization of positive indicators:

\[ x_{ij} = \frac{x_j - x_{\min}}{x_{\max} - x_{\min}} \tag{10} \]

Standardization of negative indicators:

\[ x_{ij} = \frac{x_{\max} - x_j}{x_{\max} - x_{\min}} \tag{11} \]

(2) Weight distribution of each indicator in the matrix:

\[ y_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{12} \]

Where \( y_{ij} \) refers to the weight of the \( i^{th} \) evaluation sample and the \( j^{th} \) evaluation index in the matrix.

(3) Calculate the entropy value of each indicator:

\[ z_j = -K \sum_{i=1}^{m} (y_{ij} \times \ln y_{ij}) \tag{13} \]

Where \( K \) is a constant value, \( K = y_{\text{ave}} \).

(4) Calculate the difference coefficient \( d_j \) of the \( j^{th} \) index:

\[ d_j = 1 - z_j \tag{14} \]
(5) Calculate the entropy weight of each index:

\[ w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \]  

(15)

Where \( \sum_{j=1}^{n} w_j = 1 \), \( \omega_i = (w_1, w_2, \ldots, w_n)^T \). From the above equation, it can be determined that the greater the entropy value and the smaller the entropy weight, the smaller the importance of the evaluation index.

2.3. Comprehensive Weighting Method \[10\]

The game theory method is used to comprehensively analyse the subjective weight and objective weight information, so that the calculation result of the comprehensive weight of the evaluation index is more comprehensive and scientific. A single weight vector can be expressed as \( \omega_i = (w_{i1}, w_{i2}, \ldots, w_{in}) \) \((i=1, 2, \ldots, L)\), The formula of combined weighting method is:

\[ \omega = \sum_{i=1}^{L} \alpha_i \cdot \omega_i^r \]  

(16)

Based on the concept of game theory, the coefficient \( \alpha_i \) was optimized to minimize the variance between the integrated weight vector \( \omega \) and the single weight vector \( \omega_i \), thereby obtaining an ideal weight vector.

\[ \min Z = \left\| \sum_{i=1}^{n} \alpha_i \cdot \omega_i^r - \omega \right\|_2 \]  

(17)

After the coefficient \( \alpha_i \) is obtained, it is normalized:

\[ \alpha_i' = \frac{|\alpha_i|}{\sum_{i=1}^{n} |\alpha_i|} \]  

(18)

The comprehensive weight vector is:

\[ \omega' = \sum_{i=1}^{L} \alpha_i' \cdot \omega_i^r \]  

(19)

2.4. TOPSIS method

TOPSIS method \([11-14]\) is a multi-objective decision-making method proposed in the early 1980s to approach the ideal solution, and then it has been widely used in social, medical, agricultural, engineering and other fields.

(1) Weighted operation of initial data

Suppose \( m \) is the evaluation index scheme and \( n \) is the evaluation index. The results of the comprehensive weight method are weighted and a weighted normalized matrix is obtained:
(2) Calculate positive and negative ideal solutions:

\[
R = \begin{bmatrix}
    P_{11}w_1 & P_{12}w_2 & \ldots & P_{1n}w_n \\
    P_{21}w_1 & P_{22}w_2 & \ldots & P_{2n}w_n \\
    \vdots & \vdots & \ddots & \vdots \\
    P_{n1}w_1 & P_{n2}w_2 & \ldots & P_{nn}w_n 
\end{bmatrix} \approx \begin{bmatrix}
    r_{11} & r_{12} & \ldots & r_{1n} \\
    r_{21} & r_{22} & \ldots & r_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{n1} & r_{n2} & \ldots & r_{nn} 
\end{bmatrix}
\]

(20)

\[
r^*_i = \left\{ \max_{j \in J_1} r_{ij} \mid \min_{j \in J_2} r_{ij} \right\} \text{ for } i = 1, 2, \ldots, m
\]

(21)

\[
r^{-}_j = \left\{ \min_{j \in J_1} r_{ij} \mid \max_{j \in J_2} r_{ij} \right\} \text{ for } j = 1, 2, \ldots, m
\]

(22)

(3) Calculate Euclidean distance:

\[
d^+_i = \sqrt{\sum_{j=1}^{n} (r^*_j - r^{+}_j)^2}
\]

(23)

\[
d^-_i = \sqrt{\sum_{j=1}^{n} (r^-_j - r^{-}_j)^2}
\]

(24)

(4) Determination of relative closeness:

\[
C_i = \frac{d^+_i}{d^+_i + d^-_i}
\]

(25)

According to the value of \( C_i \), the scheme of emergency rescue resource allocation is sorted, and the most suitable emergency rescue scheme is determined.

3. The case analysis

3.1. Overview of the study area

Taking the 1300 fully mechanized mining face of a mine in Heze City, Shandong Province as the research object, the buried depth of the coal seam is about 900m, the inclination length is 100m, and the thickness of the coal seam is 6.71m. The rock burst occurred near the heading face of 1303 drainage roadway, resulting in large area roof subsidence, internal extrusion of two sides and coal falling in the range of about 100m.

According to the investigation, 334 people went down the shaft on duty, and 22 people were trapped in the place where the accident happened. After receiving the risk report, the supervisors of coal mine immediately used the existing emergency rescue plan to launch rescue operations. The emergency rescue process is shown in Figure 1.
3.2. Determine the evaluation index of emergency rescue resource allocation

Based on the theory of emergency management, the author studies the disaster rescue plan in depth, considers the influence of secondary disasters and the timely rescue of major accidents and other factors, selects six evaluation indexes, and constructs the evaluation indexes of the allocation of coal mine emergency rescue resources. The specific content is shown in Figure 2.

![Figure 1. Rescue process of rock burst accident.](image1.png)

![Figure 2. Evaluation index of emergency rescue resource allocation.](image2.png)
3.2.1. **Team cooperation ability** ($x_1$). Team cooperation ability is the ability to exert team spirit and complement each other to achieve the maximum working efficiency of the whole rescue team on the basis of establishing rescue team, and plays an important role in the emergency rescue process of coal mine.

3.2.2. **Medical security** ($x_2$): The level of medical security directly affects the timely treatment of underground trapped people in coal mines, and also prevents possible accidents for rescue teams.

3.2.3. **Ability to deal with sudden secondary disasters** ($x_3$): In the process of underground emergency rescue, rescue personnel will encounter secondary disasters near the rescue channel (such as water seepage, gas accumulation, unstable surrounding rock and other emergencies), which will seriously affect the construction progress of the rescue process, so the rescue team needs to use professional equipment for effective treatment.

3.2.4. **Quantity of rescue equipment configuration** ($x_4$): In view of the selection of different rescue locations, in addition to the transportation of materials and equipment by rescue vehicles, a series of underground rescue equipment and facilities, such as pumps, ventilators, dangerous gas detection instruments, protective equipment, etc.\(^{[15]}\), the complete set of rescue equipment configuration is related to the speed of rescue progress and personal safety during rescue.

3.2.5. **Rescue time** ($x_5$): The length of rescue time plays an important role in whether the trapped people can be safely rescued. In the absence of food and water, the shorter the rescue time spent by emergency rescue workers, the higher the survival rate of trapped people.

3.2.6. **Advance degree of rescue channel** ($x_6$): Due to the underground emergency, the working face and main roadway are seriously damaged, so the rescue team needs to reopen the rescue channel with the help of manpower and mechanical equipment. Generally speaking, the faster the rescue channel advances, the more favorable it will be to rescue the trapped people in a shorter time.

4. **Weight calculation of coal mine emergency rescue resource allocation**

4.1. **Weight calculation by the AHP method**

The judgment matrix of coal mine emergency rescue resource allocation evaluation index is constructed by AHP method, and the weight of each evaluation index is calculated, and then the consistency test is carried out. The specific results are shown in Table 1.

| $A$ | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $\omega_j$ | Sort |
|-----|-------|-------|-------|-------|-------|-------|------------|------|
| $x_1$ | 1     | 4/3   | 1     | 1     | 3/4   | 3/4   | 0.1558     | 2    |
| $x_2$ | 3/4   | 1     | 3/4   | 3/4   | 9/16  | 9/16  | 0.1169     | 3    |
| $x_3$ | 1     | 4/3   | 1     | 1     | 3/4   | 3/4   | 0.1558     | 2    |
| $x_4$ | 1     | 4/3   | 1     | 1     | 3/4   | 3/4   | 0.1558     | 2    |
| $x_5$ | 4/3   | 16/9  | 4/3   | 4/3   | 1     | 1     | 0.2078     | 1    |
| $x_6$ | 4/3   | 16/9  | 4/3   | 4/3   | 1     | 1     | 0.2078     | 1    |

Consistency test results: $\lambda_{max} = 6, C.I. = 0, C.R. = 0 < 0.1$, so the matrix is consistent with the consistency test.
4.2. Weight calculation by the entropy weight method

The formula (12) ~ (15) is programmed by MATLAB software. The index parameters of the six schemes are put into the program to calculate the results. Finally, the entropy value $Z_j$ and entropy weight $\omega_2$ of each index are obtained, and the results are shown in Table 2.

| Evaluation index                                      | $Z_j$   | $\omega_2$ | Sort |
|-------------------------------------------------------|---------|------------|------|
| Team cooperation ability                               | 0.839 4 | 0.180 5    | 2    |
| Medical security                                      | 0.893 6 | 0.119 6    | 6    |
| Ability to deal with sudden secondary disasters       | 0.870 2 | 0.145 9    | 5    |
| Quantity of rescue equipment configuration            | 0.850 0 | 0.168 6    | 4    |
| Rescue time (h)                                       | 0.809 8 | 0.213 7    | 1    |
| Advance degree of rescue channel (m/d)                | 0.847 1 | 0.171 8    | 3    |

4.3. Weight calculation by the comprehensive weight method

Based on the idea and theoretical method of game theory, the calculation results of subjective weight method and objective weight method are brought into formula (17) ~ (19), and the weight coefficient $\alpha_1=0.737 9$ and $\alpha_2=0.262 1$ are determined. Finally, the comprehensive weight value $\omega'$ is calculated. The results are shown in Figure 3.

4.4. Comprehensive evaluation model based on TOPSIS method

4.4.1. Positive ideal solution and negative ideal solution. The index parameters of each scheme are calculated by formula (20), and the weighted normalized matrix of coal mine emergency rescue resource allocation is established; the positive and negative ideal solutions are calculated by formula (21) and (22), and the calculation results are shown in Table 3.
Table 3. Positive and negative ideal solutions of each scheme.

| Schemes | The positive ideal solutions | The negative ideal solutions |
|---------|------------------------------|-----------------------------|
| 1       | 0.1805                       | 0                           |
| 2       | 0.1196                       | 0                           |
| 3       | 0.1459                       | 0                           |
| 4       | 0.1686                       | 0                           |
| 5       | 0                            | 0.2137                      |
| 6       | 0.1718                       | 0                           |

4.4.2. Calculation of relative closeness. According to formula (23) and (24), the Euclidean distance between each scheme and positive and negative ideal solutions is calculated, and then the relative closeness $C_i$ with the ideal solution is obtained according to formula (25). The calculation results are shown in Table 4.

Table 4. The closeness of each scheme to the positive and negative ideal solution.

| Schemes | 1    | 2    | 3    | 4    | 5    | 6    |
|---------|------|------|------|------|------|------|
| $C'$    | 0.4309 | 0.5347 | 0.3638 | 0.5698 | 0.5833 | 0.5256 |
| $C''$   | 0.4010 | 0.5505 | 0.3791 | 0.5590 | 0.6014 | 0.5108 |
| $C_i$   | 0.4230 | 0.5391 | 0.3681 | 0.5666 | 0.5881 | 0.5216 |

In order to compare the rationality of the models, the coal mine emergency rescue resource allocation model based on AHP approximation ideal solution and the coal mine emergency rescue resource allocation model based on entropy weight method approximation ideal solution are established respectively for verification. The relative closeness degree is expressed by $C'$ and $C''$. It can be seen from Table 4 that the relative closeness degree of the fifth scheme among the three evaluation models is the largest, which indicates that the fifth group scheme is the best emergency rescue scheme for coal mine. Therefore, the rescue team enters the underground main lane with the aid of auxiliary shaft to determine the position of trapped personnel and open the buried roadway to rescue the trapped personnel in the shortest time.

In order to further analyse the reliability of the model, the relative closeness degree under the comprehensive weight is compared with the relative closeness degree under AHP method and the relative closeness degree under entropy weight method, and the relative accuracy $\eta_1$ and $\eta_2$ are calculated in turn. The results are shown in Table 5.

Table 5. Improving accuracy by combining weight with relative closeness of ideal solution.

| Schemes | 1 | 2 | 3 | 4 | 5 | 6 |
|---------|---|---|---|---|---|---|
| $\eta_1$ | 1.87 | 0.82 | 1.17 | 0.56 | 0.82 | 0.77 |
| $\eta_2$ | 5.20 | 2.11 | 2.99 | 1.34 | 2.26 | 2.07 |

From Table 4 and Table 5, it can be seen that the relative closeness accuracy of the comprehensive weight-approximation ideal solution model is 1.00% higher than that of the AHP method-approximate ideal solution model; Compared with entropy weight method-approximate ideal solution model, the relative closeness accuracy of comprehensive weight-approximate ideal solution model is improved by 2.66% on average. It can be seen that the coal mine emergency rescue resource allocation model established based on the comprehensive weight-approximate ideal solution comprehensively considers the evaluation index weight value under the subjective and objective conditions, and the calculated accuracy value is higher, indicating that the model has better reliability. It can provide reliable help for coal mine emergency rescue resource allocation and rescue route selection to effectively solve similar accidents.
5. Conclusions
(1) Starting from engineering practice, comprehensively consider the evaluation indicators that affect the coal mine emergency rescue resource allocation model, and then use the comprehensive weight method to optimize the weight of the evaluation indicators, eliminating the adverse effects caused by a single method, which is beneficial to optimize the rescue indicator system;
(2) Using the comprehensive weight-approximation ideal solution model to select the optimal solution as Option 5, that is, enter the underground roadway through the auxiliary shaft and open the buried roadway in the shortest time to rescue the trapped persons, which is consistent with the on-site rescue situation;
(3) Through the model verification of AHP approach ideal solution model and entropy weight method approximate ideal solution model, it is confirmed that the model has high reliability, that is, the model can provide reliable help for mine rescue route selection and emergency rescue resource allocation of similar accidents;
(4) Comparing the accuracy of the relative closeness of the comprehensive weight-approximate ideal solution model with the relative closeness of the AHP method-approximate ideal solution model and the entropy weight method-approximate ideal solution model respectively, the accuracy is increased by 1.00% and 2.66% respectively. Further verify the superiority of the model.

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