Comprehensive Evaluation of Mine Safety Based on Improved Game Theory

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Abstract. In order to better evaluate the mine safety, this paper uses the improved comprehensive weighting method based on game theory to comprehensively evaluate the mine safety. Firstly, this paper uses the analytic hierarchy process to subjectively weight the indicators and uses the entropy weight method to objectively weight the indicators, and analyzes the weights of the indicators including personnel, environment, management and equipment. Then, the game theory method is used to coordinate the proportion of the two weights, and the final comprehensive weight is obtained. In the scoring part, the triangular fuzzy number method is used to synthesize the qualitative and quantitative indicators and score them. Finally, the final score is obtained by combining the comprehensive weight and the comprehensive score. In the case analysis, the safety of the three mines is analyzed by this method. By comparing the scores of each other, the level of safety and the shortcomings of each mine can be judged.

Keywords: Analytic Hierarchy Process, Entropy Weight Method, Triangular Fuzzy Number, Game Theory, Mine Safety.

1. Introduction

Mining enterprises play an important role in the national economy. Maintaining the safe production of mining enterprises is an important prerequisite to ensure the sustainable and healthy development of mines[1].How to take the most effective method to evaluate mine safety has become the most concerned point. Through the safety evaluation of the mine, the overall risk of the mine can be directly presented, which helps managers and workers to understand the risk factors more clearly and prevent them well [2].The emergence of safety evaluation can reduce the possibility of accidents to a certain extent, and can improve the safety awareness of mine staff and urge enterprises to assess the special operators of mines, and constantly improve the work level of staff, so as to avoid some non-standard problems as much as possible and add a guarantee for mine staff. At the same time, it can strengthen the attention of enterprises to safety and reduce the occurrence of risks as much as possible.

At present, Chen Guangshen makes a fuzzy comprehensive evaluation of open-pit mines based on the analytic hierarchy process, and constructs an evaluation system from the aspects of geological conditions, personnel status, on-site production status and safety management[2]. Based on entropy data mining, Wei Xiaoling constructed a method of fuzzy comprehensive evaluation by defining index weight, determining effective value and calculating comparability[1].Based on the fuzzy evaluation method, Hao Xiaohua selected four first-level indicators of personnel, equipment, environment and safety management and 21 second-level indicators to comprehensively evaluate the safety of mining workplaces[3].Based on the analytic hierarchy process, Liu Chaosong evaluated the safety of bolt support in coal roadway from human factors, material factors, environmental factors, management factors and technical factors[4].Jiang Meng constructed a safety evaluation system based on principal component analysis and conducted case analysis in 8 mining areas[5].Wang Nan determined the weight of each index based on triangular fuzzy number, and established an evaluation system for technical personnel level, mine natural conditions, technical equipment level and safety management level through analytic hierarchy process[6].Gao Zhonghong established a safety evaluation system of mine ventilation system based on information entropy, and evaluated mine ventilation by five first-level indexes such as air volume and fan[7].Zhang Shuntang established the entropy weight variable fuzzy evaluation model of mine fire safety evaluation by coupling entropy weight method and variable fuzzy evaluation method[8].Chen Lijie established a safety index system by constructing an improved analytic hierarchy process to use a fuzzy evaluation model for each index weight[9].Liu Lancui established fuzzy modular neural network, through the establishment of human, machine, environment, accident, management level evaluation of fuzzy modular neural network prediction[10].According to the basic theory of hierarchical analysis method and fuzzy comprehensive evaluation method, Wang Junli proposed a three-scale improvement hierarchical analysis and optimization algorithm through several scales of comparative analysis hierarchical analysis method, and established the hierarchical structure system of coal mine electrical safety evaluation[11].Based on the actual situation of coal mining enterprises, Wang Yue established the evaluation index system of coal mine safety training management system based on the principle of evaluation index design, and used AHP and fuzzy comprehensive evaluation method to evaluate a certain system[12]. In order to improve the decision-making level of coal mine safety input and make the safety input better guarantee the safety production of coal mine, Jiang Fuchuan established the evaluation model of safety input scheme based on entropy right-approximate ideal solution sorting method (TOPSIS)[13].

In view of the above research, we have not got rid of the method of simply weighting from subjective weight or objective weight. The established evaluation index has obvious subjectivity and objectivity, and it is difficult to obtain a comprehensive weighting method.

This paper proposes a comprehensive evaluation method based on the combination of subjective and objective game theory and the method of triangular fuzzy number. Through the method of game theory, the subjective analytic hierarchy process and the objective entropy weight method are combined, and the weight ratio caused by the subjective and objective weights is compared with the reality. There is a large error, and the subjective and objective complement each other, which can effectively take into account the two effects of subjective and objective on the index. Therefore, this paper adopts the subjective and objective evaluation method based on game theory, which can well weigh the subjective and objective weights and obtain a comprehensive weight. In terms of scoring, the original direct scoring is improved to use the triangular fuzzy number method to score, which can well unify the quantitative indicators and qualitative indicators. By scoring, the qualitative indicators are compared with the quantitative indicators, and the indicators that are difficult to compare are more effectively expressed. Finally, the final comprehensive score is obtained by combining the weight with the score, and the results are compared and analyzed to provide an analytical basis for the comprehensive evaluation of mine safety.

2. Model Introduction

2.1. Weight determination

For the determination of the weight of the index of mine safety mining, it can be divided into subjective weighting, objective weighting and combination weighting method. The subjective weighting method relies on experts ' scoring and evaluation of indicators, which is easy to produce certain subjective deviations, resulting in the problem that the evaluation tendency is too obvious. The objective evaluation method relies too much on mathematical and statistical laws, and may not be able to evaluate the indicators in line with the actual situation. It is difficult to accurately evaluate the indicators by relying solely on the subjective evaluation method or simply using the objective evaluation method. The combination evaluation method can not only proceed from the subjective point of view but also take into account the objective data, which can more effectively evaluate the mine safety.

2.1.1 Determination of subjective weight

Mine safety indicators have a certain subjective tendency, and the use of analytic hierarchy process can better clarify the tendency of subjective indicators. The subjective analytic hierarchy process (AHP) is a systematic analysis method that can integrate qualitative and quantitative analysis methods. The train of thought is simple and clear, and the thinking process of decision makers is organized, quantitative and easy to calculate. There are mainly the following steps :

1.Build a hierarchical structure model :

Two layers are established : the target layer is the safety evaluation standard, and the decision layer is various indicators.

2.Construct judgment matrix :

According to the importance of the decision-making layer to the target layer, the relative importance of each target layer index is judged.Assume that A_i and B_i are the indicators of the target layer, the matrix we can construct is as follows:

$$W = \begin{pmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{n1} & \cdots & b_{nn} \end{pmatrix} \tag{1}$$

b_{ij} is the importance of the i-th index relative to the j-th index.

At the same time, we construct the importance evaluation index. The values are usually 1, 3, 5, 7, 9 and their reciprocals. Among them, 2, 4, 6, 8 represent the degree of transition, and the size of the value represents the importance of the former relative to the latter, as shown in Table.1.

Table.1. Index degree table

Index	Implication
1	both are equally important
3	the former is slightly more important than the latter.
5	the former is more important than the latter.
7	the former is much more important than the latter.
9	the former is the most important

3 . Consistency test :

The weight is obtained by solving the maximum eigenvalue and the corresponding eigenvector of the matrix.

$$AW = \lambda_{\max} W \tag{2}$$

$\lambda_{\max}$ is the maximum eigenvalue of A, and W is the corresponding eigenvector.

Then we define the consistency test indicators :

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{3}$$

If CI = 0, it is completely consistent. If CI is close to 0, the consistency is good. Similarly, the greater the CI, the worse the consistency. In order to judge the consistency of the matrix, the consistency index RI is introduced. The average consistency index test values are as follows :

Table.2. RI table of values

order	1	2	3	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	1.12	1.24	1.32	1.41	1.45	1.49	1.52	1.54	1.56	1.58	1.59

Therefore, we calculate the consistency ratio CR :

$$CR = \frac{CI}{RI} \tag{4}$$

If $CR \le 0.1$, it can be considered that the judgment matrix is consistent, and the resulting value is acceptable.

So we get the weight of $W = (w_1, w_2, \cdots w_n)$ for each index.

2.1.2 Determination of objective weights

In order to avoid the error of subjective assumption on the weight, the entropy weight method can solve this problem to a certain extent. The entropy weight method is an evaluation method based on objective data and is almost unaffected by subjective factors. The entropy weight method mainly performs the following steps : data normalization processing, calculation index variability, calculation information entropy and calculation weight. Figure 1 :

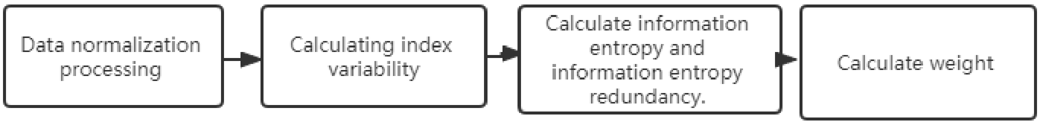

Figure 1. Flow chart

1 . Data normalization processing

Because the measurement unit of each index is not uniform, it is difficult to measure with a unified standard. Therefore, when calculating the weight, it is normalized to convert the absolute value of the index into a relative value, thereby eliminating the deviation caused by the inconsistency of the unit. At the same time, we make $x_{ij} = |x_{ij}|$

The positive indicators we get are :

$$x_{ij} = 0.998 \frac{x_{ij} - \min\{x_{1j}, \cdots x_{nj}\}}{\max\{x_{1j}, \cdots x_{nj}\} - \min\{x_{1j}, \cdots x_{nj}\}} + 0.002 \tag{5}$$

The negative indicators are :

$$x_{ij} = 0.998 \frac{\max\{x_{1j}, \cdots x_{nj}\} - x_{ij}}{\max\{x_{1j}, \cdots x_{nj}\} - \min\{x_{1j}, \cdots x_{nj}\}} + 0.002 \tag{6}$$

2 .Calculating index variability

To calculate the proportion of the ith scheme index under the jth index p_{ij}

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{7}$$

3 .Calculate information entropy and information entropy redundancy.

The information entropy of item j is :

$$e_j = -k \sum_{i=1}^{n} p_{ij} \ln p_{ij} \tag{8}$$

$$k = \ln n \tag{9}$$

Calculate the information entropy redundancy of item j :

$$g_j = 1 - e_j \tag{10}$$

4 .Calculate weight :

Calculate the weight of the jth indicator w_j

$$w_j = \frac{g_j}{\sum_{j=1}^{m} g_j} \tag{11}$$

2.1.3 Combination of subjective and objective weights based on game theory

Based on the objective and subjective evaluation methods, there are some deviations in the evaluation results. Therefore, the game theory method is used to study these conclusions, coordinate the contradictions and conflicts in each method, so that each method can play its role as much as possible, and obtain the consistency and compromise of each method. As far as possible to minimize the difference between the weight and the original weight, so as to obtain a new weight, the specific process is as follows[14]:

1 . Construct the basic weight set

The basic weight vector set obtained by weighting the l methods used.

$$u_k = (u_{k1}, u_{k2}, \cdots u_{k3}), k = 1,2\cdots,l \tag{12}$$

2 .Construct possible weight vector set

The l weight vectors are arbitrarily linearly combined to construct a possible weight vector set.

$$u = \sum_{k=1}^{l} a_k u_k^T \qquad a_k > 0, \sum_{k=1}^{l} a_k = 1 \tag{13}$$

Among them, u is the possible weight vector set, which is the weight set for the comprehensive processing of the weights under various methods.

3. Minimizing weights

Optimize the linear combination coefficient of the weights, and seek a compromise solution between the weights through game theory to minimize the deviation between u and u_k , that is :

$$\min\left|\sum_{k=1}^{l} a_k u_k^T - u_k\right| \qquad k = 1,2\cdots,l \tag{14}$$

Thus we obtain the corresponding linear equations.

$$\begin{pmatrix} u_1u_1^T & u_1u_2^T & \cdots & u_1u_l^T \\ u_2u_1^T & u_2u_2^T & \cdots & u_2u_l^T \\ \vdots & \vdots & \ddots & \vdots \\ u_lu_1^T & u_lu_2^T & \cdots & u_lu_l^T \end{pmatrix}\begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_l \end{pmatrix} = \begin{pmatrix} u_1u_1^T \\ u_2u_2^T \\ \vdots \\ u_3u_3^T \end{pmatrix} \tag{15}$$

The corresponding values can be obtained by MATLAB.

4.Normalization processing

After normalization, this paper obtains :

$$a_k^* = \frac{|a_k|}{\sum_{k=1}^{l} |a_k|} \tag{16}$$

5. Generate new weights

A new weight is obtained by using the normalized linear combination coefficient to synthesize the weights.

$$u_k^* = \sum_{k=1}^{l} a_k^* u_k^T \tag{17}$$

After that, this paper uses the new weight to calculate.

2.2. Triangular fuzzy number score part

The triangular fuzzy number F is constructed, and F is composed of (a, b, c) three parts, relying on these three values to represent the score of a thing, and F can satisfy the expression that its membership function is as follows[15] :

$$F(x) = \begin{cases} 0 & x < a \\ \dfrac{x-a}{b-a} & a \le x < b \\ \dfrac{c-x}{c-b} & b \le x < c \\ 0 & x \ge c \end{cases} \tag{18}$$

Through this formula, we determine the corresponding triangular fuzzy numbers. We write the i th triangular fuzzy number as F_i , where a, b, c are the minimum, most likely and maximum values, so we get $a < b < c$.

Define the following operations :

$$F_1 \oplus F_2 = (a_1, b_1, c_1) + (a_2, b_2, c_2) = (a_1 + a_2, b_1 + b_2, c_1 + c_2) \tag{19}$$

$$F_1 \otimes F_2 = (a_1, b_{1,}, c_1) \otimes (a_2, b_2, c_2) = (a_1 \times a_2, b_1 \times b_2, c_1 \times c_2) \tag{20}$$

Based on the above algorithm, we define F_{ij} to indicate the importance of index i over index j.

For this project, we selected m experts to evaluate p schemes, and n indicators to evaluate. We define the evaluation of the k th expert as :

$$F_{ij}^k = (a_{ij}^k, b_{ij}^k, c_{ij}^k) \tag{21}$$

Here, they represent the possible minimum, the most likely value, and the possible maximum.

After that, this paper averages the relative values of each index and index for each expert to obtain a comprehensive triangular fuzzy number.

$$F_{ij} = \frac{1}{m}\left(\sum_{k=1}^{m} a_{ij}^k, \sum_{k=1}^{m} b_{ij}^k, \sum_{k=1}^{m} c_{ij}^k\right) \tag{22}$$

Finally, we use the weighted average method to get the average value of each value (a, b, c), and get the specific score matrix :

$$\mathrm{A} = \begin{pmatrix} F_{11} & F_{12} & \cdots & F_{1n} \\ F_{21} & \ddots & & F_{2n} \\ \vdots & & \ddots & \vdots \\ F_{p1} & F_{p2} & \cdots & F_{pn} \end{pmatrix} \tag{23}$$

2.3. Comprehensive evaluation

The obtained combination weight and the obtained score matrix are combined to represent the score of m, as follows :

$$k_m = u_1^* F_{m1} + u_2^* F_{m2} + \cdots u_n^* F_{mn} \tag{24}$$

Among them, k_m is the score, and u_j^* is the weight of item j.

We sort by comparing the scores, so as to get the ranking of each project, and then get the advantages and disadvantages of each project.

3. Example calculation

3.1. Determination of index system

The unqualified body and technical level of mine personnel, the imperfect mine safety management, the mine working environment and the mine equipment are the important factors that mainly affect the mine safety. Based on literature review, consulting experts and previous studies, combined with the actual situation of the mine, comprehensive analysis, four first-level evaluation indicators based on personnel, environment, management and equipment factors were obtained, and 16 second-level indicators were further analyzed.Reference to Table.3 and Figure 2.

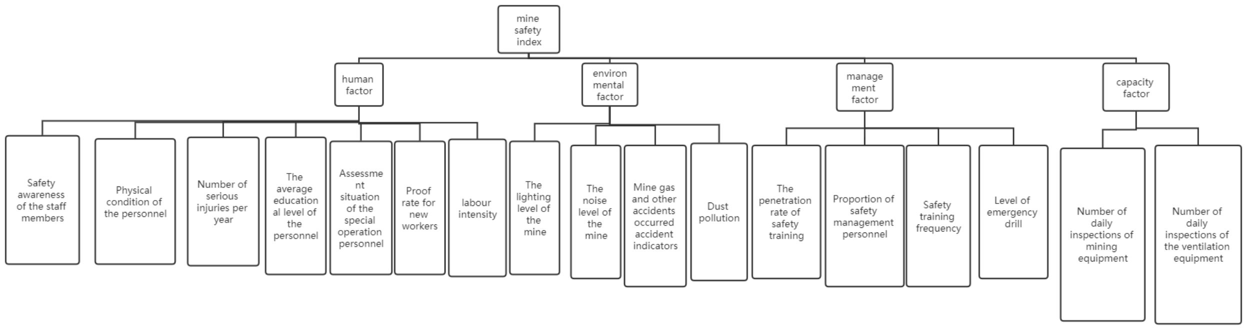

Figure 2. Relationship between first-level indicators and second-level indicators

Table.3. Mine safety mining evaluation index

metric	Index code	Index description	The calculation method of the indicators
Safety awareness of the staff members	a_1	Scores on regular safety knowledge questionnaires	Mean scores for all safety questionnaires during the year
Physical condition of the personnel	a_2	Proportion of persons with major diseases	Number of persons with serious diseases / all employees$\times$100%
Number of serious injuries per year	a_3	The number of people seriously injured by accidents every year	The number of serious injuries per year
The average educational level of the personnel	a_4	Proportion of undergraduate students in the total population	Number of undergraduate employees / total employees$\times$100%
Assessment situation of the special operation personnel	a_5	Professional knowledge assessment of special personnel	Average score of the professional knowledge assessment of special personnel
Proof rate for new workers	a_6	The proportion of the number of workers newly employed with certificates each year	New staff of the certificate every year / new staff of the year $\times$100%
labour intensity	a_7	Average working hours	Average working hours

The lighting level of the mine	a_8	Lighting brightness under the mine	Average lighting brightness of the mine
The noise level of the mine	a_9	Noise decibels of the mines	The average noise decibel of the mine
Mine gas and other accidents occurred accident indicators	a_{10}	Frequency of accidents per year	The number of accidents in a year
Dust pollution	a_{11}	Dust concentration in the mine	Average concentration of dust in mine work
The penetration rate of safety training	a_{12}	The proportion of personnel participating in safety training is in the whole mine	Personnel participating in the safety training / all employees of the whole mine×100%
Proportion of safety management personnel	a_{13}	The proportion of safety management personnel in the whole mine	Safety management personnel / total mine chief staff×100%
Safety training frequency	a_{14}	Frequency of conducting mine safety training	Number of mine training sessions in a year
Level of emergency drill	a_{15}	The rating level of the drill	Rating level for each drill
Number of daily inspections of mining equipment	a_{16}	Daily inspection times of mining equipment	Average daily inspection times of mining equipment in a year
Number of daily inspections of the ventilation equipment	a_{17}	Daily inspection times of the ventilation equipment	Average number of daily inspections of ventilation equipment in a year

3.2. Score and weight determination process

On the basis of the existing evaluation index system, combined with the relevant academic literature, on the basis of previous studies, after the expert 's score, we got two experts on a, b, c three mine safety mining evaluation index score. After Formula (20) and weighted calculation according to 1 : 3 : 1, we can get the comprehensive evaluation value of Table.4 by using the method of triangular fuzzy number and combining formula (17) ~ (21).

Table.4. Comprehensive evaluation

index	a mine	b mine	c mine
a_1	3.55	3.25	3.7
a_2	4.05	3.35	3.6
a_3	3.8	4.4	4.35
a_4	3.4	3	2.65
a_5	2.5	3	2.65
a_6	4.7	3.5	4.75
a_7	4.25	4.15	4.1
a_8	3.9	3.7	3.85
a_9	3.5	3.65	4.05
a_{10}	4.25	3.85	4.15
a_{11}	3.45	3.85	4.05
a_{12}	3.6	4.65	3.1
a_{13}	3.35	4.45	4.35
a_{14}	3.58	4.55	3.7
a_{15}	3.45	4.05	3.7
a_{16}	4.45	4.65	3.05
a_{17}	3.65	4.15	4.5

On this result, we combine the weight ε_i obtained by the analytic hierarchy process of the subjective weighting method and the weight λ_i of the objective weighting method. Finally, based on the game theory method, the ε_i and λ_i of the two weighting methods are combined to obtain the final θ_i. Figure 3 is the weight radar chart of the first-level indicators.

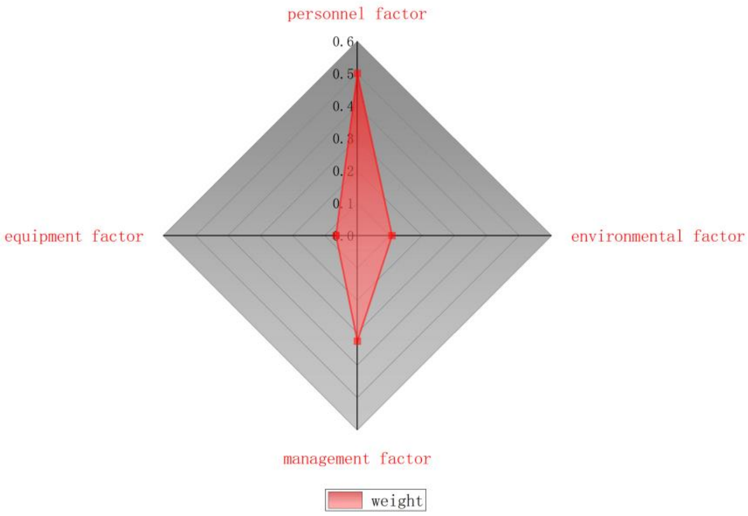

Figure 3. Weight radar chart

3.3. Evaluation results

After calculation, we get its score as Table.5 :

Table.5. grade of mines

mine	a mine	b mine	c mine
grade	3.6418	3.8414	3.7010

After comparison, we get the scores of the three mines, and the comparison result is b mine $> c$ mine $> a$ mine, so we can get that mine b has the highest safety among the three.

Among the indicators of mine safety, the safety awareness of staff, the average education level of staff, the assessment of special operators, the rate of new workers holding certificates, the penetration rate of safety training, the proportion of safety management personnel, the frequency of safety training, and the level of emergency drills account for a higher proportion. For a mine, the assessment of special operators, the average education level of personnel and other indicators are significantly lower, and these aspects should be strengthened. At the same time, the mine has a good performance in the number of daily inspections of mining equipment and the rate of new workers holding certificates, which should be maintained in the future. For b mine, its comprehensive score is the highest, but it still has obvious shortcomings in the average education level of personnel, the assessment of special operators, and the safety awareness of staff. For c mine, the average education level of personnel, the safety awareness of staff, the assessment of special operators and the daily inspection times of mining equipment have significant deficiencies. However, the daily inspection times of ventilation equipment are good, and should continue to be maintained in the future.

On the basis of game theory, the two weights are balanced by subjective evaluation method and objective evaluation method, and the final comprehensive weight is obtained, which overcomes the imbalance of evaluation system caused by subjective factors and better solves the imbalance between evaluation system and actual situation caused by objective factors.

4. Conclusions and discussions

In order to solve the problem of mine safety, this paper proposes a comprehensive weighting method based on game theory. Through the subjective and objective weighting method, the four first-level indicators including personnel, environment, management and equipment are comprehensively weighted to obtain the comprehensive weight. The comprehensive score obtained by the triangular fuzzy number is weighted by the comprehensive weight to obtain the final score. In the case analysis, the importance of personnel factors is recognized, and each mine can clarify its own advantages and weaknesses according to its own scores. The deficiencies in the case analysis are mainly reflected in the lack of consideration of environmental and equipment factors in the selection of indicators.

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