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Research on Comprehensive Evaluation Model of Metal Mine Emergency Rescue System Based on Game Theory and Regret Theory

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Abstract: In view of the complexity, vagueness, and systematization of metal mine emergency rescue system evaluation, regret theory was introduced, and a comprehensive evaluation model of the metal mine emergency rescue system was established. Firstly, from four perspectives, including pre-emergency prevention, pre-emergency preparation, emergency rescue during an event, and post-disaster recovery and reconstruction, 26 influencing factors were selected to build a comprehensive evaluation index system of metal mine emergency rescue systems. Secondly, the G1 method and the anti-entropy weight method were used to determine the subjective weight and objective weight of the evaluation indicators, respectively, and the comprehensive weight of the indicator was determined based on game theory. The final evaluation level was determined by calculating the total evaluation value of the object to be evaluated. Finally, the established comprehensive evaluation model of a metal mine emergency rescue system based on game theory and regret theory was applied to Chengchao Iron Mine in Ezhou City, Hubei Province, and the evaluation results of this model were compared with those of fuzzy comprehensive evaluation and set pair analysis. The results showed that the calculation results of the evaluation model are reasonable and reliable, which can provide a new means of evaluating emergency rescue systems in metal mines.

Keywords: emergency rescue system; game theory; regret theory; metal mine

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1. Introduction

China is a major mining country of mineral resources, and the mining industry has become an important foundational industry driving the national economy. As the mineral resources on the surface and buried in shallow parts of the country are gradually mined, the comprehensive development of deep metal mining is being promoted. However, the environment for deep metal mines is complex and changeable. Influenced by a variety of factors, major safety accidents occur frequently [1,2]. Emergency rescue is an important measure that can control the severity of emergencies, recover major economic losses, and reduce casualties [3]. Emergency response to major mining accidents is a disaster prevention and mitigation work that involves scientific and technological fields, as well as planning and management departments. The "Decision of the State Council on Further Strengthening Work Safety" also explicitly stated that the overall requirement is to accelerate the construction of China's safety emergency rescue system. In recent years, China's emergency rescue system has developed rapidly, and the ability to manage mining emergencies has been greatly improved, providing certain guarantees for the national economy and the safety of miners [4]. The scientific and reasonable evaluation of the emergency management system for metallic mining is an important aspect of promoting and improving China's emergency management system construction by identifying and improving existing problems.

At present, numerous experts and scholars have conducted extensive research in the field of mining emergency rescue and have achieved a series of results. Shi et al., 2022 [5], established the dynamic bi-objective optimization model with the minimum rescue time and the minimum risk level for selecting the emergency rescue path, which improves the initiative of the decision-makers in the emergency rescue decision-making process. Jun Zhang [6] briefly expounded on the development status and existing problems of the Chinese mine emergency rescue system and proposed measures from three aspects: improving the legal and regulatory system, improving the mine emergency rescue fund guarantee system, and strengthening the construction of safety and risk avoidance systems. Li et al., 2021 [7], established an emergency rescue resource allocation model based on the technique for order preference by similarity to ideal solution (TOPSIS) and calculated the weights of evaluation indicators affecting emergency rescue using the analytic hierarchy process (AHP) and entropy weight method. The feasibility of the model in solving problems such as unreasonable allocation and low efficiency of emergency rescue resources in a rock burst accident at a mine was verified. Shu et al., 2019 [8], studied the oxygen supply performance of potassium superoxide plate under natural convection conditions in a sealed environment. The results showed that the increase in air temperature and humidity accelerated the generation of oxygen. Increasing the number of plates could meet the oxygen generation needs of underground shelters, providing a direction for the design of air recovery systems for underground mine refuge stations. Considering the practical problem of multi-base and multi-resource allocation in emergency rescue in mines, Jiang et al., 2012 [9], proposed a double constraint resource allocation model based on the "shortest travel time" and "minimizing the number of rescue points" and optimized the model by using a geographic information system (GIS). Kai et al., 2011 [10], calculated the index weight based on the Analytic Hierarchy Process (AHP) theory, simulated the mine tunnel using MATLAB software, and used an adaptive ant colony algorithm to optimize the shortest path of emergency rescue; the method realized the minimum emergency rescue time and the maximum efficiency. Based on the above research results, it is found that there are relatively few studies on the evaluation of the emergency system in mines, and the relevant research results cannot yet guide the development and construction of the emergency rescue system in metal mines.

The evaluation of a metal mine emergency rescue system is a complex and systematic evaluation, which involves many components, most of them being qualitative indicators with the characteristics of uncertainty and ambiguity, and it is difficult to apply effectively by conventional mathematical methods. Loomes et al., 1982 [11], proposed regret theory based on human partial rationality, which is a multi-attribute decision-making method that can comprehensively consider decision-maker behavior. It has the advantages of relatively easy calculation, relatively intuitive comparison, and strong operability. Therefore, it has become one of the research hotspots in evaluation and decision-making theory and gradually demonstrated strong adaptability. Liang et al., 2021 [12], used regret theory in the comprehensive evaluation of probabilistic interval values. The feasibility of the method in solving practical problems was verified. Huang Lin, 2022 [13], proposed a new EDM method by integrating regret theory and evaluation based on distance from the average solution to ensure that an emergency response can be made efficiently. The superiority and practicality of the designed method are further justified through a comparative analysis with other EDM methods. Ziyi et al., 2020 [14], used the theory of maximum and minimum regret to evaluate the risk of electricity-selling companies in decision-making regarding volume and price and finding the optimal solution of risk. Zhao et al., 2022 [15], introduced cooperative game and MSR, Weber's law, and regret theory to establish an economic model of blue carbon international cooperation. The influence of psychological factors on the decision-making of blue carbon international cooperation is also discussed.

The subjective empowerment method mainly relies on the subjective experience of the evaluator, ignoring the true reflection of objective facts, and the weight has strong subjectivity. The objective empowerment method is based on the attributes of the indicator data itself and can fully reflect the essential characteristics of things, but it ignores the subjective initiative of people and is not ideal in handling problems such as information poverty and lack of information. In the evaluation process of a metal mine emergency rescue system, it is necessary to solve the problem of determining the index weight. Currently, the weight calculation is mainly divided into two categories: the subjective empowerment method and the objective empowerment method. Seyedmohammadi et al., 2019 [16], combined the G1 method with the hierarchical analysis method to evaluate the suitability of agricultural land. Ang Chen et al., 2022 [17], noted single assignment method could not obtain the exact membership grade; Wang et al., 2020 [18], found how combined subjective and objective empowerment modes could successfully construct the evaluation model with higher reliability.

Considering the complexity and systematic nature of the evaluation of metal mine emergency rescue systems, this paper proposes a comprehensive evaluation model based on the game theory–regret theory, using the G1 method, the anti-entropy weight method, and game theory to calculate the subjective weight, objective weight, and comprehensive weight, respectively, of the indicators. The model aims to provide a scientific and reliable evaluation method for the evaluation of metal mine emergency rescue systems. The applicability of the model is validated by conducting a comprehensive evaluation of the emergency rescue system of Chengchao Iron Mine in Ezhou City, Hubei Province, China. The analysis flow chart of this paper is shown in Figure 1.

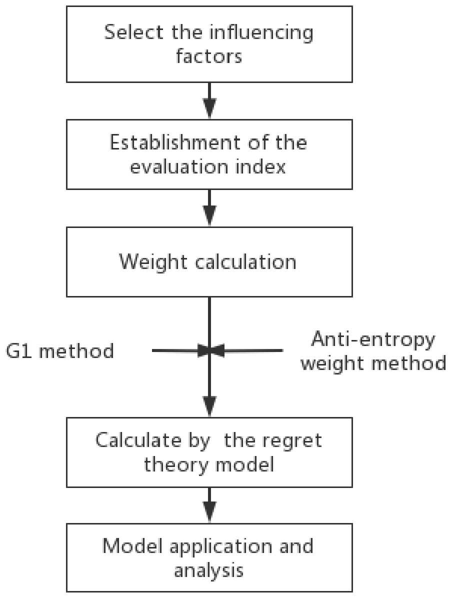

Figure 1. The analysis flow chart of model.

2. Establishment of the Evaluation Index

Building a comprehensive evaluation index system is a prerequisite for conducting a comprehensive evaluation of emergency rescue systems in metal mines. Considering the prominent characteristics of major accidents in metal mines, such as suddenness, destructiveness, secondary effects, and severity, many factors have a significant impact on the emergency rescue effect, such as the rescue environment, personnel, equipment, and organizational coordination and management. Based on [19], a comprehensive evaluation index system is constructed by considering multiple aspects, including hazard monitoring, early warning capability, emergency management, command capability, emergency resources, support capability, emergency response, control capability, post-disaster recovery, and handling capability. Another paper focuses on studying the efficiency and effectiveness of emergency management systems in mines, analyzing six aspects of daily work, including emergency organization structure, contingency plans and drills, emergency response actions, emergency resources and equipment, site cleanup and recovery, and building evaluation indicators for mine emergency management systems based on these aspects [20]. This paper comprehensively considers the characteristics of major accidents in metal mines and the characteristics of emergency management technology. Following the general process and stages of emergency management for major accidents, a comprehensive evaluation index system for the emergency management system in metal mines is constructed from four aspects: "pre-emergency prevention and preparation, during-emergency response, and post-emergency recovery and reconstruction", as shown in Figure 2.

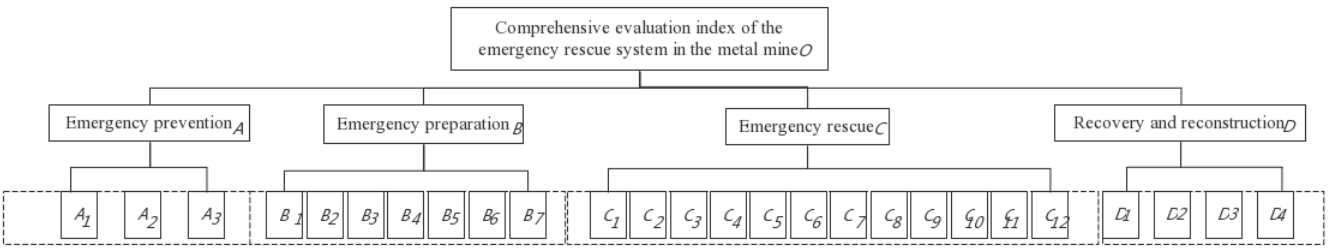

Figure 2. Comprehensive evaluation indicators for emergency rescue system of metal mines. A_1: legal provisions; A_2: the proportion of emergency rescue training personnel; A_3: real-time dynamic monitoring of hazard sources; B_1: the rationality of the emergency rescue organization system; B_2: rational of operation mechanism; B_3: timeliness; B_4: feasibility; B_5: frequency of emergency drills; B_6: material for emergency rescue; B_7: a special fund for emergency rescue; C_1: command; C_2: number of emergency linkage units; C_3: response; C_4: accuracy of information; C_5: comprehensiveness of plan; C_6: rationality of rescue process; C_7: total time of emergency rescue; C_8: internal emergency team; C_9: external emergency team; C_{10}: personal protective equipment; C_{11}: emergency rescue equipment; C_{12}: construction of the technical support system; D_1: clean situation on-site; D_2: accident recovery time; D_3: summary analysis; D_4: reward and punishment.

The metal mine emergency rescue system level is divided into excellent (level I), good (level II), average (level III), poor (level IV), and terrible (level V). In order to facilitate the quantitative analysis of the indicators of Figure 1, the quantitative index value and the quantitative score corresponding to each level are shown in Table 1.

Table 1. Quantitative values of each level.

Grade	Descriptive Grade	Rating Value
I	excellent	[8, 10]
II	good	[6, 8)
III	average	[4, 6)
IV	poor	[2, 4)
V	terrible	[0, 2)

3. Theoretical Basis

3.1. Weight Calculation

3.1.1. G1 Method

AHP is the most frequently applied subjective empowerment method to build a comparison matrix to calculate the index weight at present. This traditional hierarchical analysis method is based on the opinion of experts, which is combined with subjective experience to give the relative importance ratio of all indicators. But the subjective experience of experts greatly impacts the calculation process, especially in analyzing and dealing with the huge evaluation index system and complex index relationship. AHP often needs to adjust the comparison matrix for the normalization requirements in a relatively complex weight calculation process. Guo Yajun proposed the G1 method to improve the method of the AHP. In the process of G1 method weight calculation, the relative importance ratio is determined with a relative importance comparison of pairwise indicators, and the index weight is determined according to the relative importance. Compared with AHP, the G1 method reduces the requirement for evaluators' subjective cognition and eliminates the need for a consistency test process, making the calculation process more convenient, and has achieved satisfactory application results [21,22]. The specific calculation process is as follows:

(1) Determine the index sequence. Assume n evaluation indicators to evaluate the evaluation object. All the evaluators selected the most important indicators from the n indicators and recorded them as X_1; the weights are noted as w_1. Continue to select the most important indicators among the remaining $n-1$ indicators until the n indicators are all selected according to their relative importance and the index sequence (X_1, X_2, ... , X_n);

(2) Determine the relative importance ratio of the index. Next, calculate the relative importance ratio from the index sequence (X_1, X_2, ... , X_n); the index of relative importance is described in Table 2. r_j is defined as follows:

$$r_j = \frac{w_j}{w_{j-1}} j = 2, 3, \ldots\ n \tag{1}$$

Table 2. Values of relative importance ratio.

r_j	Relative Importance Situation	r_j	Relative Importance Situation
1.0	equally important	1.2	slightly more important
1.4	obviously more important	1.6	significantly more important
1.8	extremely more important	1.1, 1.3, 1.5, 1.7, 1.9	between the above situation

(3) Calculate the index weight. The calculation formula of the index weight is shown as follows:

$$w_n = (1 + \sum_{k=2}^{n}\prod_{j=k}^{n} r_j)^{-1} \tag{2}$$

(4) Calculate the weights of all indicators. Based on the relative importance ratio r_j, the weights of the other $n-1$ indicators are determined. The calculation formula is shown as follows:

$$w_{j-1} = r_j w_j \tag{3}$$

3.1.2. The Anti-Entropy Weight Method

At present, the entropy weight method is one of the common methods to determine the index objective weight. First, draw the concept of "entropy" in thermodynamics into the information theory; next, allocate index weight on the basis of index variation and provide the overall information, then keep the attributes of the data at the same time—this step can effectively reflect the correlation among the data. However, the traditional entropy weight method is too sensitive to the degree of index difference. The results of the traditional method may be inaccurate because of that impact. Therefore, this project used the anti-entropy weight method to calculate the objective weight, reduce the influence of the index difference degree on the weight calculation results, and avoid the above disadvantages. The specific calculation process is shown as follows [23,24]:

(1) Establish the original evaluation matrix.

Suppose that n evaluation indicators are selected, the m objects to be evaluated are evaluated, and the original evaluation matrix X is established according to the evaluation value of each index:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \tag{4}$$

X_{mn} is the measured value of the n evaluation index of the m evaluation object.

(2) Standardize the original evaluation matrix.

Considering the different attributes, dimensions, and magnitude of the evaluation indicators, a direct comparison cannot be carried out, so the indicators need to be standardized. Among them, the larger, better (benefit) index method adopts Formula (5), and the smaller, better (cost) index method adopts Formula (6) and finally obtains the standardized matrix Y.

$$y_{ij} = \frac{x_{ij} - \min_j\{x_{ij}\}}{\max_j\{x_{ij}\} - \min_j\{x_{ij}\}} \tag{5}$$

$$y_{ij} = \frac{\max_j\{x_{ij}\} - x_{ij}}{\max_j\{x_{ij}\} - \min_j\{x_{ij}\}} \tag{6}$$

$$Y = \begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots \\ y_{m1} & \cdots & y_{mn} \end{bmatrix} \tag{7}$$

The inverse entropy value E_j is calculated for the j evaluation index.
The reverse entropy value E_j of each index is calculated in Equation (8).

$$E_j = -\sum_{i=1}^{m} P_{ij} \ln(1 - P_{ij}) \tag{8}$$

$$P_{ij} = y_{ij} / \sum_{i=1}^{m} y_{ij} \tag{9}$$

(3) Calculate the index weight.

The results of reverse entropy calculation determine the objective weight w of each index.

$$\boldsymbol{w}_j = E_j / \sum_{j=1}^{n} E_j \tag{10}$$

3.1.3. Determination of Index Comprehensive Weights Based on Game Theory

Assumes that N different weight calculation methods are selected, N different weight calculation results will be obtained. According to the game theory idea, the N species of weight calculation results can form a set of weight sets W={w_1, w_2, … , w_{N}}; with an arbitrary linear combination of these vectors $\boldsymbol{w} = \sum_{k=1}^{N} a_k \boldsymbol{w}_k^T$, calculate $\boldsymbol{w}$ and $\boldsymbol{w}_k$ based on an optimal strategy

$$\mathrm{Min}\left\| \sum_{k=1}^{N} a_k \boldsymbol{w}_k^T - \boldsymbol{w}_j^T \right\|^2, j = (1, 2, \ldots N) \tag{11}$$

According to the differential properties of the matrix, the optimization first derivative condition satisfies the following equation:

$$\begin{bmatrix} \boldsymbol{w}_1\boldsymbol{w}_1^T & \cdots & \boldsymbol{w}_1\boldsymbol{w}_N^T \\ \vdots & & \vdots \\ \boldsymbol{w}_N\boldsymbol{w}_1^T & \cdots & \boldsymbol{w}_N\boldsymbol{w}_N^T \end{bmatrix} \begin{pmatrix} a_1 \\ \vdots \\ a_N \end{pmatrix} = \begin{bmatrix} \boldsymbol{w}_1\boldsymbol{w}_1^T \\ \vdots \\ \boldsymbol{w}_N\boldsymbol{w}_N^T \end{bmatrix} \tag{12}$$

The coefficients are $(a_1, a_2, \ldots \ \ldots \ a_N)$. After the optimal weight coefficient is normalized, the comprehensive weight is

$$\boldsymbol{w}^* = \sum_{k=1}^{N} a_k^* \boldsymbol{w}_k^T \tag{13}$$

3.2. Regret Theory

Most emergency rescue comes down to qualitative evaluation in metal mines; decision-maker behavior has an important impact on the evaluation results. The regret theory model is simple to calculate, does not require many parameters, and can effectively reflect the decision-making behavior of decision-makers. Moreover, the regret theory is applied in the field of safety and risk assessment, which can effectively avoid risks, reduce unnecessary losses, and improve the accuracy and objectivity of decision-making. Therefore, this project used the regret theory to evaluate the emergency rescue in a metal mine. Regret theory holds that decision-makers will face multiple schemes in the decision-making process and make a comprehensive comparison between them. When the alternative scheme is better than the selected scheme, it is a regret, and when the selected scheme is better than the alternative scheme, it is a joy. Policymakers will avoid solutions that they regret when they choose them.

The safety evaluation method based on the regret theory model is shown as follows [19–21]:

(1) Establish an evaluation matrix.

Assuming the existence of m schemes and n evaluation indexes, the evaluation matrix $\boldsymbol{Q}$ is established according to the assignment situation of each index.

$$\boldsymbol{Q} = (q_{mn}) = \begin{pmatrix} q_{11} & q_{12} & q_{13} & \cdots & q_{1n} \\ q_{21} & q_{22} & q_{23} & \cdots & q_{2n} \\ q_{31} & q_{32} & q_{33} & \cdots & q_{3n} \\ \vdots & \vdots & \vdots & \ldots & \vdots \\ q_{m1} & q_{m2} & q_{m3} & \cdots & q_{mn} \end{pmatrix} \tag{14}$$

q_{mn} is the n index score value of the m scheme.

(2) Build the ideal point matrix.

According to the evaluation matrix $\boldsymbol{Q}$, then the construction ideal point matrix P is expressed as

$$\boldsymbol{P} = \begin{pmatrix} p_1 & p_2 & p_3 & \cdots & p_n \end{pmatrix} \tag{15}$$

P_{n} is denoted as the ideal value for each evaluation index. In order to reduce the degree of regret in the decision-maker, the minimum value in each scheme is taken.

(3) Establish a utility value matrix.

In calculating the index utility value of each evaluation scheme, a reasonable utility function should be selected first. Generally, the utility function selects a power function and is able to satisfy the hypothesis requirements of the regret theory. The utility function calculation formula is as follows:

$$h(q_{mn}) = (q_{mn})^{\alpha} \tag{16}$$

α is the parameter of the utility function, $0 < \alpha < 1$.
Utility value matrix H:

$$\boldsymbol{H} = \left((q_{mn})^{\alpha}\right) \quad (17)$$

(4) Establish a perceived utility matrix.

The construct regret–joy function value matrix R is

$$\boldsymbol{R}\left(a_{mp}\right)_{ij} = 1 - e^{-\beta(a_{mp})_{ij}} \quad (18)$$

In the equation, β is the parameter of the regret–joy function $\beta > 0$; the smaller the value is, the less obvious the decision-maker avoids the risk of regret. a_{mp} is used for the m scheme and the ideal point matrix utility difference.

According to Equations (18) and (19), the perceived utility matrix calculation formula is:

$$\boldsymbol{D} = (d_{mn}) = \boldsymbol{H} + \boldsymbol{R} = \left[(q_{mn})^{\alpha} + \left(1 - e^{-\beta(b(a_{mp})_{ij})}\right)\right] \quad (19)$$

(5) Determine the risk assessment results.

The final risk level is determined according to the risk assessment value. The specific calculation formula is

$$S_n = \frac{1}{m}\sum_{i=1}^{m}\sum_{j=1}^{n}\boldsymbol{w}_j d_{ij} \quad (20)$$

where S_n is the comprehensive risk assessment value, and w_j is the weight of the j evaluation index.

4. Model Application and Analysis

In order to verify the adaptability of the game theory–regret theory in the evaluation of the metal mine emergency rescue system, this paper takes the Chengchao iron mine in Ezhou, Hubei, as an example to evaluate and calculate its emergency rescue system using the method proposed in this paper.

To conduct a comprehensive and objective evaluation of the emergency rescue system in the mine, a five-person expert evaluation team was formed, consisting of two university professors, one senior engineer, and two on-site management personnel, all of whom have rich experience and long-time engagement in emergency rescue system evaluation. All the experts combined the situation of the mine emergency rescue system and related work reports with the form of on-site investigation and scored each index. The specific index assignment results are shown in Table 3.

Table 3. The expert scoring results of each index.

Expert Serial Number	Each Evaluation Refers to the Rating Situation													
	A_1	A_2	A_3	B_1	B_2	B_3	B_4	B_5	B_6	B_7	C_1	C_2	C_3	C_4
1	7.8	6.8	7.3	7.8	7.7	7.5	7.6	7.4	8.1	8.2	8.1	7.6	8.1	7.9
2	8.3	7.1	6.9	8.1	7.6	7.7	7.8	7.5	8.2	8.1	8.3	7.9	8.3	7.7
3	7.5	6.9	7.1	8.2	8.3	8.2	8.1	7.7	8.1	8.4	8.4	8.3	8.6	8.3
4	8.1	7.2	7.3	7.9	8.2	8.3	8.2	7.1	8.5	8.8	8.9	8.1	9.1	8.1
5	7.2	6.5	7.2	8.5	8.3	8.1	8.4	7.1	7.9	8.5	8.6	8.8	8.5	7.7
Expert Serial Number	Each Evaluation Refers to the Rating Situation													
	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	D_1	D_2	D_3	D_4		
1	7.7	7.4	8.1	7.9	7.6	8.5	7.5	7.3	7.2	7.9	7.4	8.1		
2	8.3	7.7	8.2	7.5	7.4	8.2	7.1	7.1	6.9	7.3	7.1	8.3		
3	8.5	8.2	8.4	8.3	7.9	8.3	7.6	7.5	7.5	7.8	7.2	8.8		
4	8.1	8.4	7.9	8.5	8.1	8.7	7.3	7.2	7.3	8.2	6.9	8.5		
5	8.4	7.9	8.6	8.2	7.7	9.2	6.8	6.7	7.4	8.5	7.3	7.9		

4.1. Calculation of the Index Weight

As mentioned earlier, the G1 method is used to calculate the subjective weights of indicators, the reverse entropy method is used to calculate the objective weights of indicators, and the game theory is used to calculate the comprehensive weights. The specific calculation process is shown as follows:

(1) Calculate the subjective weight of the indicators based on the G1 method.

This project constructs a multi-level comprehensive evaluation index system for metal mine emergency rescue. Therefore, according to Figure 1, the first-level index weight is calculated, and then the weight of each second-level index under the first-level index. For instance, there are four level indexes: emergency prevention is A level, emergency preparation is B level, emergency rescue is C level, and recovery and reconstruction is D level. According to the principle of the G1 method, based on full discussions and their own experiences, the experts formed a consensus on the relative importance ranking of the first-level indicators as $C > B > A > D$. The corresponding weights of each indicator are denoted as w_1, w_2, w_3, and w_4, and the relative importance ratios are given as $r_1 = 1.9$, $r_2 = 1.8$, and $r_3 = 1.6$. The corresponding index weights, $w_1 = 0.502$, $w_2 = 0.265$, $w_3 = 0.142$, and $w_4 = 0.091$, were obtained according to Equations (1)–(3). The first-level index weight is (0.142, 0.265, 0.502, 0.091).

Similarly, the second-level index weight under each primary index was obtained. The specific calculation result is shown as the weight of the three secondary indicators under emergency prevention is (0.351, 0.231, 0.418). The weight of the seven secondary indicators under emergency preparation is (0.232, 0.195, 0.073, 0.168, 0.155, 0.112, 0.065). The weight of the 12 secondary indicators under the emergency rescue is (0.128, 0.031, 0.059, 0.065, 0.158, 0.131, 0.065, 0.041, 0.026, 0.085, 0.121, 0.090). The weight of the four secondary indicators under recovery and reconstruction is (0.265, 0.345, 0.212, 0.178).

(2) Calculate the objective weight of the index based on the anti-entropy weight method.

The objective weight of the index according to the anti-entropy weight method was then determined, and the score value of each index listed in Table 3 was calculated. The weights of the 26 indicators in the index layer are (0.037, 0.034, 0.032, 0.044, 0.038, 0.036, 0.036, 0.047, 0.041, 0.044, 0.041, 0.040, 0.043, 0.053, 0.031, 0.037, 0.038, 0.033, 0.038, 0.052, 0.034, 0.032, 0.032, 0.034, 0.034, 0.040). The weights of the four first-level indicators of the criterion layer are (0.102, 0.285, 0.472, 0.141). Normalize the weights of secondary indicators under each criterion layer. The objective weight of the emergency prevention is (0.358, 0.327, 0.315). The weight of the emergency preparation is (0.153, 0.133, 0.125, 0.127, 0.166, 0.143, 0.153). The weight of the emergency rescue is (0.086, 0.085, 0.092, 0.112, 0.067, 0.077, 0.081, 0.070, 0.081, 0.110, 0.072, 0.067). The weight of the recovery and reconstruction is (0.229, 0.246, 0.242, 0.283).

(3) Calculate the comprehensive weight of indicators.

Taking emergency prevention, emergency preparation, emergency rescue, and recovery and reconstruction as examples, the subjective weights of the index are shown as W_1 = (0.142, 0.265, 0.502, 0.091), the objective, subjective weights of the index are shown as W_2 = (0.102, 0.285, 0.472, 0.141). According to Formula (9) and after normalization, $\lambda_1 = 0.9$, $\lambda_2 = 0.1$ is obtained. Finally, the combined weights of the four first-level indicators in the criterion layer can be calculated as W^* = (0.125, 0.267, 0.499, 0.109).

Similarly, the comprehensive weight of each second-level index under the first-level index was obtained. The comprehensive weight of emergency prevention is (0.352, 0.241, 0.407). The comprehensive weight of emergency preparation is (0.224, 0.189, 0.078, 0.164, 0.156, 0.116, 0.073). The comprehensive weight of the emergency rescue is (0.120, 0.041, 0.066, 0.074, 0.140, 0.120, 0.068, 0.047, 0.037, 0.090, 0.111, 0.086). The comprehensive weight of the recovery and reconstruction is (0.262, 0.338, 0.214, 0.186).

4.2. Evaluation and Calculation

Firstly, the index matrix to determine the ideal point matrix was evaluated, and then the utility value matrix, regret–joy value matrix, and perceived utility matrix were calculated to determine the criteria under the evaluation value. Finally, the value calculation through the comprehensive weight was evaluated. The emergency prevention calculation is taken as an example:

(1) According to the evaluation scoring value of expert indicators in Table 4, construct the original scoring matrix $\boldsymbol{Q}_A$:

$$\mathbf{Q}_A = \begin{bmatrix} 7.8 & 8.3 & 7.5 & 8.1 & 7.2 \\ 6.8 & 7.1 & 6.9 & 7.2 & 6.5 \\ 7.3 & 6.9 & 7.1 & 7.3 & 7.2 \end{bmatrix}$$

Table 4. Assessment of the results.

The Evaluation Model	Assessment Result
Fuzzy synthesis	II (6.957)
Set-pair analysis	II
Regret theory	II (6.405)

(2) Determine the ideal point matrix.

Select the minimum value of each evaluation index as the ideal point matrix $\boldsymbol{P}_A$ according to Equation (15):

$$\boldsymbol{P}_A = \begin{bmatrix} 7.2 & 6.5 & 6.9 \end{bmatrix}^T$$

(3) Utility matrix.

According to Equation (17), the utility matrix $\boldsymbol{H}_A$:

$$\boldsymbol{H}_A = \begin{bmatrix} 6.352 & 6.717 & 6.131 & 6.571 & 5.910 \\ 5.614 & 5.836 & 5.688 & 5.910 & 5.390 \\ 5.984 & 5.688 & 5.836 & 5.984 & 5.910 \end{bmatrix}$$

(4) Regret–joy value matrix.

According to Equation (18), the regret–joy value matrix $\boldsymbol{R}_A$:

$$\boldsymbol{R}_A = \begin{bmatrix} -0.441 & -0.807 & -0.221 & -0.661 & 0.000 \\ -0.223 & -0.446 & -0.298 & -0.519 & 0.000 \\ -0.296 & 0.000 & -0.148 & -0.296 & -0.222 \end{bmatrix}$$

(5) The perceived utility matrix.

According to Equation (19), the perceived utility matrix $\boldsymbol{D}_A$:

$$\boldsymbol{D}_A = \begin{bmatrix} 6.346 & 6.706 & 6.128 & 6.562 & 5.910 \\ 5.610 & 5.830 & 5.684 & 5.903 & 5.390 \\ 5.980 & 5.688 & 5.834 & 5.980 & 5.907 \end{bmatrix}$$

(6) Calculation of the comprehensive risk assessment value.

Similarly, the perceived utility matrix of B, C, and D are as follows:

$$\boldsymbol{D}_B = \begin{bmatrix} 6.352 & 6.568 & 6.640 & 6.423 & 6.856 \\ 6.277 & 6.205 & 6.710 & 6.638 & 6.710 \\ 6.131 & 6.276 & 6.637 & 6.709 & 6.565 \\ 6.205 & 6.350 & 6.566 & 6.638 & 6.782 \\ 6.055 & 6.127 & 6.272 & 5.836 & 5.836 \\ 6.571 & 6.643 & 6.571 & 6.859 & 6.427 \\ 6.643 & 6.571 & 6.787 & 7.073 & 6.859 \end{bmatrix}$$

$$\boldsymbol{D}_C = \begin{bmatrix} 6.571 & 6.715 & 6.787 & 7.145 & 6.930 \\ 6.205 & 6.422 & 6.710 & 6.566 & 7.068 \\ 6.571 & 6.715 & 6.930 & 7.287 & 6.858 \\ 6.423 & 6.278 & 6.711 & 6.567 & 6.278 \\ 6.278 & 6.711 & 6.855 & 6.567 & 6.783 \\ 6.058 & 6.275 & 6.636 & 6.779 & 6.420 \\ 6.569 & 6.641 & 6.785 & 6.425 & 6.928 \\ 6.421 & 6.131 & 6.709 & 6.852 & 6.637 \\ 6.203 & 6.058 & 6.420 & 6.564 & 6.275 \\ 6.860 & 6.644 & 6.716 & 7.003 & 7.359 \\ 6.124 & 5.833 & 6.197 & 5.979 & 5.614 \\ 5.978 & 5.832 & 6.123 & 5.905 & 5.540 \end{bmatrix}$$

$$\boldsymbol{D}_D = \begin{bmatrix} 5.907 & 5.688 & 6.125 & 5.980 & 6.053 \\ 6.419 & 5.984 & 6.347 & 6.635 & 6.851 \\ 6.053 & 5.834 & 5.907 & 5.688 & 5.980 \\ 6.569 & 6.713 & 7.071 & 6.857 & 6.425 \end{bmatrix}$$

According to Equation (20), the weighted sum evaluation value of each index, the figure of S_A is 5.991, S_B is 6.475, S_C is 6.505, and the figure of S_D is 5.9916.251. According to Formula (21), the total risk assessment value S is 6.405. According to Table 2, the comprehensive evaluation of the metal mine emergency rescue system is II (good).

4.3. Results Analysis

4.3.1. Analysis of the Weights Calculation

As it is mentioned above, in order to improve the objectivity and reliability of the evaluation results, this project introduced the subjective and objective combination empowerment method to calculate index weights, which is named the G1 method, and the anti-entropy weight method and game theory are used to calculate index subjective, objective, and comprehensive weights, respectively. Taking the first-level index as an example, the calculation index weight of the combination empowerment method and single empowerment method is shown in Figure 3. In Figure 3, the anti-entropy right method is used to calculate the objective weight of emergency prevention, emergency preparation, emergency rescue, and recovery and reconstruction, and the results are (0.102, 0.285, 0.472, 0.141). The weight of emergency prevention is obviously little, which results in the importance of emergency prevention in advance. In fact, emergency prevention in advance is the basis of accident emergency rescue work. Only preparation has been carried out; thus, it is possible to avoid accidents and reduce accident losses. Combining the G1 method with experts' subjective experience, the relative importance of each index is ranked. The comprehensive weight of the first-level index is (0.125, 0.267, 0.499, 0.109). Based on G1–anti-entropy–game theory, the results not only express the objective properties of things themselves but can give full play to the subjective initiative of experts in weight calculation. This makes the weight calculation results more consistent with the actual situation, and it is conducive to improving the accuracy and reliability of the evaluation results.

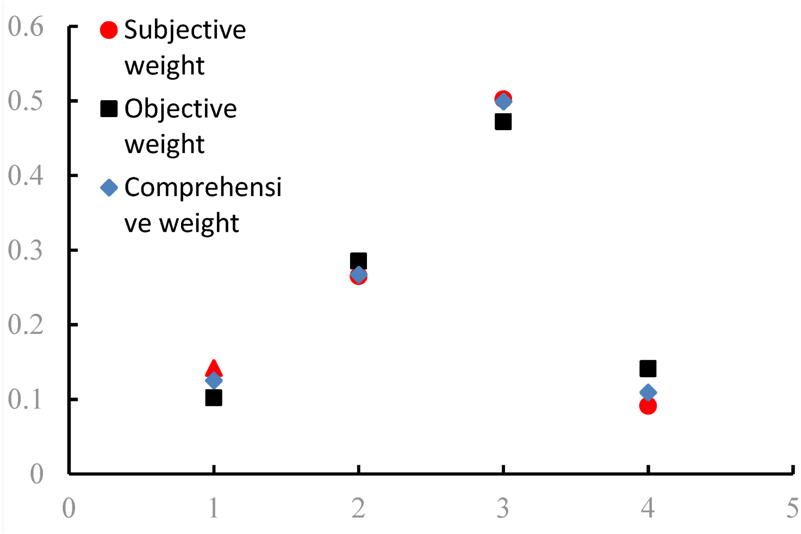

Figure 3. Comparison of the results of combined weighting and single weighting of primary indicators.

This paper adopts a combination of the G1 method and the reverse entropy method for indicator weighting. Depending on the different variation levels of indicators, some indicators are selected as research objects, and the weights are calculated using both the reverse entropy method and the entropy method. In Figure 4, there are seven corresponding secondary indicators of emergency preparation which were selected as the study objects. Compared their weights of entropy with the weights of the anti-entropy method, the trends are generally consistent, so the importance of the indicators reflected by the two calculation methods is basically in same; however, the weight of the entropy weight method is smaller than the weight of anti-entropy method, and the situation does not very well reflect the degree of deterioration among the indicators. The anti-entropy weight method is used to calculate the index objective weight; not only is the distinction between the various indicators obvious, but it is without extreme cases. So anti-entropy more objectively reflects the amount of information and the degree of difference in each index. And compared to the entropy weight method, the anti-entropy weight method is more beneficial in evaluating the rationality of the results.

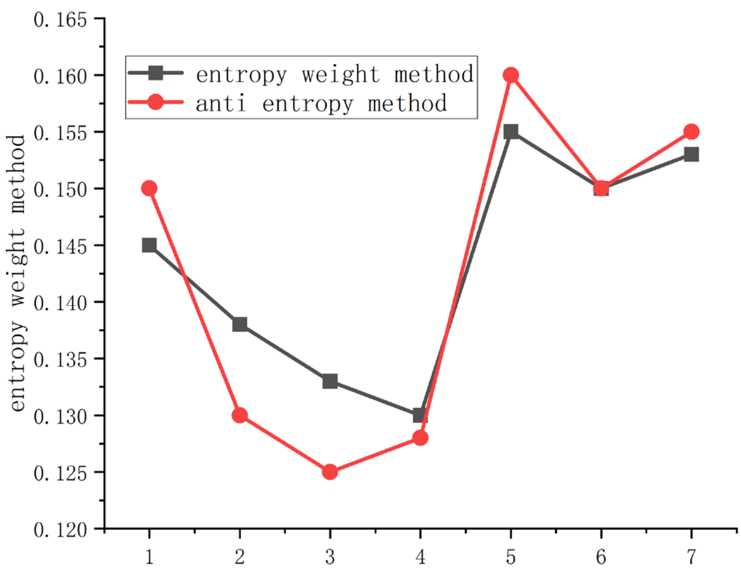

Figure 4. Comparison of weights between entropy weight method and anti-entropy method.

4.3.2. Analysis of the Evaluation Results

In order to further verify the application effect of regret theory in the evaluation of emergency rescue systems in metal mines, the evaluation results with the fuzzy comprehensive evaluation method and set-based analysis method were compared. Results of comprehensive evaluation results of the three evaluation methods are summarized in Table 4.

According to Table 4, it can be seen that the evaluation results of regret theory are consistent with those of the fuzzy comprehensive evaluation model and set pair analysis method, and all three evaluation models show relatively good results. This indicates that regret theory is adaptable in the evaluation of emergency rescue systems in metal mines, and the evaluation results can objectively and truly reflect the actual situation of the construction of the emergency rescue system in the mine. Meanwhile, the comprehensive evaluation value calculated based on the fuzzy comprehensive evaluation model is 6.957, while the regret theory evaluation model gives a comprehensive evaluation value of 6.405. This means that the comprehensive evaluation value calculated based on regret theory is slightly lower than that calculated by the fuzzy comprehensive evaluation model. This indicates that the evaluation method based on regret theory is relatively conservative in assessing the comprehensive evaluation level of the emergency rescue system in the metal mine, reflecting the inherent advantage of regret theory in risk aversion.

Regret theory can not only reflect the comprehensive situation of the metal mine emergency rescue system but also obtain the status of each criterion layer, which makes analyzing the existing problems from each criterion layer easier so as to improve the construction level of the emergency rescue system. For example, the weight of emergency prevention is 5.991, the weight of emergency preparation is 6.475, the weight of emergency rescue is 6.505, and the weight of recovery and reconstruction is 6.251. According to the emergency rescue system evaluation division standard, emergency prevention is at level III. Emergency preparation, emergency rescue, and recovery and reconstruction are at level II; among them, emergency rescue, compared to the other two aspects, is better.

The results indicate that the metal mine emergency rescue system should include a comprehensive emergency disposal plan, such as rescue process rationality, field command coordination, emergency rescue organization system, emergency rescue equipment advanced, real-time dynamic monitoring of hazards, etc. Therefore, mining enterprises need to pay special attention to the above indicators and take targeted measures to further optimize and improve in order to improve the level of emergency rescue and reduce economic losses and casualties.

The results indicate that this mine has formulated a relatively good emergency rescue plan, established a rescue organization system and an emergency mechanism, unified command, and achieved joint operations. The measures met the relevant laws and institutional requirements, and large investments were made in rescue settings and material matters, including being equipped with a certain number of advanced and more advanced rescue equipment and emergency communication equipment. Rescue efficiency is relatively high; during the implementation of the rescue efforts, emergency rescue can ensure scientific, rapid, and effective. Daily training improves emergency response ability, strengthens rescue capabilities, and ensures full priority is given to the rescue capabilities at the time of the rescue in case of flooding, fire, or roof collapse. Overall, the rescue level of this mine is relatively high. Since its establishment, the measures have met the requirements. Although many safety accidents occurred, this mine, with the effective emergency rescue, had no scale casualties or large economic losses.

However, there are some areas that need some urgent improvement, such as the intensity of emergency rescue training and drills, emergency rescue training system, self-protection and emergency treatment, emergency rescue workers, safety awareness, and emergency response capability. According to the geological characteristics and disaster nature, the mine should pay attention to the pertinence and effectiveness of training and drills. During the daily training sessions, the mine strengthens the simulation exercises to make the rescue drill consistent with the actual situation and to improve the overall level of rescue workers. The mine should strengthen real-time dynamic monitoring, make use of advanced monitoring and monitoring technology, and establish a comprehensive hazard control mechanism. The new monitoring system should be mature, sensitive, and reliable, and it should utilize real-time monitoring of toxic and harmful gases and hazardous sources. To improve the overall safety of the mine and further improve the emergency rescue technology and equipment, it is important to discover hidden dangers, eliminate hidden dangers, and reduce the risk of major accidents. Personal protective equipment and special equipment, equipment for handling various mine disasters, other testing and analysis instruments, communication equipment, and other equipment for handling all kinds of mine disasters and accidents are essential for emergency rescue. The disaster response must conform to the national standards, industry standards, and relevant provisions on mine safety. And for the improvement of technology and equipment level, it is necessary to update the equipment; it also needs regular maintenance, as does the existing technical equipment. In addition, to further improve rescue efficiency and shorten the rescue time, it is necessary to increase investment in rescue equipment and purchase advanced rescue equipment.

5. Conclusions

(1) The use of the G1 method and entropy weight method separately determine the subjective and objective weights of the indicators. Finally, based on the game theory, the comprehensive weight of the indicators is determined, avoiding the situation where the weight determination is either too subjective or too objective and improving the reliability of the evaluation results. This prevents the final evaluation result from being unreasonable;

(2) Because of the complexity and systematic characteristics of the metal mine emergency rescue system evaluation and that the evaluation indexes are mostly qualitative indicators, the comprehensive evaluation model combines game theory and regret theory to establish a comprehensive evaluation model. This project selected the four aspects of emergency prevention, emergency preparation, emergency rescue, and recovery and reconstruction and selected 26 indicators. Comparing the results with the analysis method and fuzzy comprehensive evaluation model, it was found that the established model is reliable and reasonable, which can provide new ideas and a method for the evaluation of the metal mine emergency rescue system;

(3) Due to the relatively few research results of metal mine emergency rescue system evaluation and the immature relevant theories, it is necessary to further improve the evaluation index system and to promote the development of metal mine emergency rescue system evaluation and improve the emergency rescue management capacity of metal mines.

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