The Evaluation of Coal Mine Safety Based on Entropy Method and Mutation Theory

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Abstract. In order to accurately evaluate the safety status of coal mines and improve the safety level of coal mines, the method of evaluating the state of coal mine safety combined with entropy method and mutation theory is proposed. By analyzing the influence factors of coal mine safety status, 17 evaluation indicators were established from the four aspects of employee quality, equipment facilities, natural conditions and safety management, and the evaluation index system of coal mine safety status was established. Based on this evaluation model and process, the safety status evaluation and analysis of the example coal mine are carried out, and the evaluation results are consistent with the actual safety status of the coal mine, which confirms the reasonable feasibility of the evaluation method. This method can be used to evaluate the safety status of coal mine and provide the basis for the formulation of safety countermeasures.

1. Introduction

According to China's National Administration of Coal Mine Safety, as of December 5, a total of 122 fatal accidents occurred in coal mines across the country in 2020, with 224 people killed or trapped. Among them, there were 10 major accidents and 49 people died. Since 2020, there has been one more serious coal mine accident than that in 2019, and the death toll has increased by 16, up 50% and 44% respectively. China's coal mine safety situation is still grim. Therefore, the establishment of an effective safety index system to ensure the safe development of coal mining enterprises is still the focus of social attention.

At present, there are many methods of coal mine safety evaluation in China, such as expert on-site inquiry and observation method, LEC, failure modes and effects analysis (FMEA), hazard and operability study (HAZOP), fuzzy mathematical methods, gray evaluation method, neural network evaluation method, probability risk assessment method, etc [1]. It is not possible to evaluate the safety status of coal mine objectively and comprehensively. Entropy method can effectively eliminate the influence of subjective factors on the weight of the index, and can better ensure that the weight of the index is not affected by human factors.

Most of the occurrence of coal mine accidents are uncertain, sudden, whether or not the occurrence of safety accidents or the occurrence of time is difficult to predict, even if the probability of accidents calculated, it is difficult to predict the degree of risk of accidents and the impact on coal mines. Mutation theory is a phenomenon and law that transitions from one stable pattern to another, and has the characteristics of explaining and predicting sudden phenomena in nature and society [2]. Applying
mutation theory to the evaluation of coal mine safety status can better highlight the advantages of mutation theory in evaluating coal mine safety status.

At present, some scholars have applied the theory of mutation to the safety evaluation of coal mine, and achieved some results, but the selection of coal mine safety evaluation index is not reasonable and accurate enough, and the specific method of safety evaluation should be optimized. This paper intends to carry out further research on the basis of the previous, improve the coal mine safety evaluation index, and use entropy method and catastrophe theory to combine qualitative evaluation with quantitative evaluation, with a view to minimizing the influence of human factors on the evaluation results, effectively ensuring the objectivity of safety evaluation results, providing reference for the research and progress of coal mine safety evaluation methods, and the sustainable development of coal mining enterprises.

2. Catastrophe Theory and Its Application

2.1. Basic principle
Mutation theory was founded in 1972 by the French mathematician Rene Thom [3]. In mutation theory, there are five basic models of common mutation theory, namely folding mutation, point mutation, swallowtail mutation, butterfly mutation and hut mutation [4,5]. The application of the catastrophe theory model requires that the first order derivative of the catastrophe potential function \( f(x) \) is taken to obtain a equilibrium surface, and then the second order derivative of \( f(x) \) is taken to obtain the bifurcations of the equilibrium surface. When the state variables are eliminated in the \( f'(x) = 0 \) and \( f''(x) = 0 \) equation, the bifurcation equation can be obtained. The condition to judge whether the system has a mutation is to judge whether the relationship between the control variables satisfies the bifurcation equation. Finally, the normalization formula can be derived by decompose the bifurcation equation [2,6]. Several common mutation models and normalization formulas are found in Table 1.

| Mutation model   | Control variable | State variable | Potential function                     | Normalization formula |
|------------------|------------------|----------------|----------------------------------------|----------------------|
| Folding type     | 1                | 1              | \( x^2 + ax \)                          | \( x_0 = a^{1/2} \)  |
| Sharp point type | 2                | 1              | \( x^4 + ax^3 + bx \)                   | \( x_0 = a^{1/2}, x_b = b^{1/3} \) |
| Dovetail type    | 3                | 1              | \( x^5 + ax^4 + bx^2 + cx \)            | \( x_0 = a^{1/2}, x_b = b^{1/3}, x_c = c^{1/4} \) |
| Butterfly type   | 4                | 1              | \( x^6 + ax^5 + bx^4 + cx^2 + dx \)     | \( x_0 = a^{1/2}, x_b = b^{1/3}, x_c = c^{1/4}, x_d = d^{1/5} \) |
| Hut type         | 5                | 1              | \( x^7 + ax^6 + bx^5 + cx^4 + dx^2 + ex \) | \( x_0 = a^{1/2}, x_b = b^{1/3}, x_c = c^{1/4}, x_d = d^{1/5}, x_e = e^{1/6} \) |

2.2. Evaluation principles
(1) The principle of "complementarity" refers to the obvious correlation between the indicators analyzed, and the principle of "complementarity" should take the mean value of each indicator mutation level as the mutation level value of the superior index.

(2) The principle of "non-complementary" refers to the relationship between the indicators without interaction, and the minimum value of the mutation level values of each indicator is used as the mutation level value of the superior indicators.
2.3. Evaluation steps
The steps for evaluating the use of mutation theory are mainly as follows [7]:

(1) Establish an evaluation system. Through the research and analysis of the evaluation object, according to the internal relationship of the research object, the evaluation object is divided into several evaluation subsystems composed of evaluation indexes, and the appropriate evaluation index system is established.

(2) Selection of mutation types. Different types of mutations were selected according to the number of indicators. The commonly used mutation types mainly included cusp mutation, swallowtail mutation and butterfly mutation. According to the determined evaluation index system, the appropriate mutation types were selected to evaluate the evaluation objects and the indexes of each layer in the evaluation system.

(3) Calculate the index weight. Based on the entropy method, the index weights were obtained, and the index importance was sorted.

(4) Normalization operation. Through the normalization formula of the mutation theory, the comprehensive quantitative recursion operation is carried out, and the total mutation membership value of the evaluation system is finally obtained by recursion from the bottom to the next level, which is the normalization operation.

3. Research on Coal Mine Safety Evaluation Indicators and Models

3.1. Construction of coal mine safety evaluation index system
Analysis of coal mine safety management system, combining with the actual situation of coal mine safety status in China [8], comprehensive research and industry expertise, and based on the unity of the index selection, scientific, applicability and operability principles, from human, machine, environment and management four aspects to analyze the influencing factors of coal mine safety state [9], and get the influence of coal mine safety evaluation index of four factors: quality of staff, equipment and facilities, natural conditions and safety management. These four factors are taken as the second-level indicators, represented by B1, B2, B3 and B4.

The factors that affect the total of 17 secondary indicators, respectively: Staff education level, staff operation technology level, security education and training, operators three violation rate, equipment and facilities intact rate, coal mining mechanization degree, general defense system reliability, safety monitoring and information, gas geological conditions, coal seam self-ignition tendency, hydrogeological conditions, ground pressure disaster conditions, coal dust explosion, safety institutions and staffing rate, safety capital investment, emergency rescue plans and equipment and safety rules and regulations. As a three-level indicator, it is represented by C1 to C17. In this way, a coal mine safety evaluation index system is established, as shown in Figure 1.

![Coal mine safety evaluation index system](image-url)
3.2. Establishment of abrupt change model for coal mine safety evaluation

Based on the evaluation index system established above, the cascade mutation model of the evaluation index system for coal mine safety is established, as shown in Figure 2. The model can be divided into two levels. At the first level, there are four different butterfly mutation models and hut mutation models, which are composed of C1~C17 as control variables and B1~B4 as state variables. The second level is a butterfly mutation model consisting of B1~B4 as control variables and A as state variables.

![Figure 2. The evaluation step mutation model of the coal mine safety evaluation index system.](image)

3.3. Grading standards of evaluation indicators

Through the analysis and evaluation of the factors affecting the coal mine safety state, the coal mine safety state is divided into five levels, as shown in Table 2.

| Security status level  | Level | Mutation of membership function values |
|------------------------|-------|----------------------------------------|
| Extra hazardous        | I     | [0,0.2]                                 |
| Dangerous              | II    | (0.2,0.5]                               |
| General safety         | III   | (0.5,0.7]                               |
| Safety                 | IV    | (0.7,0.9]                               |
| Very safety            | V     | (0.9,1.0]                               |

4. Analysis of Coal Mine Safety Evaluation Examples

4.1. Evaluation steps

Take Changcun Coal Mine in Shanxi Province as an example to analyze its safety status quo. According to the evaluation index system established above, 7 experts from relevant professional fields are invited to rate the 17 indicators affecting the safety status of the coal mine, with a value range of (0,1), and secondly, to construct an entropy method model, the steps are as follows:

(1) The average of the values assigned by 7 experts to each indicator and the grades divided by each indicator are constructed to construct a decision matrix X as follows:

\[
X = \begin{bmatrix}
0.77 & 0.87 & 0.88 & 0.84 & 0.84 & 0.83 & 0.82 & 0.85 & 0.83 & 0.82 & 0.79 & 0.83 & 0.89 & 0.87 & 0.88 & 0.86 & 0.84 \\
0.20 & 0.20 & 0.20 & 0.20 & 0.20 & 0.20 & 0.20 & 0.20 & 0.20 & 0.20 & 0.20 & 0.20 & 0.20 & 0.20 & 0.20 & 0.20 \\
0.50 & 0.50 & 0.50 & 0.50 & 0.50 & 0.50 & 0.50 & 0.50 & 0.50 & 0.50 & 0.50 & 0.50 & 0.50 & 0.50 & 0.50 & 0.50 \\
0.70 & 0.70 & 0.70 & 0.70 & 0.70 & 0.70 & 0.70 & 0.70 & 0.70 & 0.70 & 0.70 & 0.70 & 0.70 & 0.70 & 0.70 & 0.70 \\
0.90 & 0.90 & 0.90 & 0.90 & 0.90 & 0.90 & 0.90 & 0.90 & 0.90 & 0.90 & 0.90 & 0.90 & 0.90 & 0.90 & 0.90 & 0.90 \\
\end{bmatrix}
\]

(2) The above matrix X is transformed into standardized matrix Y by using linear proportional transformation method, Y' as follows:

(3) The entropy and weight values of each indicator are calculated.
4.2. Ranking of indicator importance
First, the weight value of the three-level indicator is calculated, and secondly, the weight value of the second-level index is calculated layer by layer. The weight value of the secondary indicator corresponds to the value of the weight of the three-level indicator. The weight values for each layer of metrics are shown in Table 3.

Table 3. Index weight value of each layer.

| Three-level index number | Three-level index weight | Second-level index weight |
|--------------------------|--------------------------|---------------------------|
| C1                       | 0.0362                   |                           |
| C2                       | 0.0498                   |                           |
| C3                       | 0.0660                   |                           |
| C4                       | 0.0331                   |                           |
| C5                       | 0.0551                   |                           |
| C6                       | 0.1302                   |                           |
| C7                       | 0.0425                   |                           |
| C8                       | 0.0488                   |                           |
| C9                       | 0.0360                   |                           |
| C10                      | 0.1170                   |                           |
| C11                      | 0.0437                   |                           |
| C12                      | 0.0511                   |                           |
| C13                      | 0.0563                   |                           |
| C14                      | 0.0882                   |                           |
| C15                      | 0.0444                   |                           |
| C16                      | 0.0539                   |                           |
| C17                      | 0.0479                   |                           |
As can be seen from Table 3, the ranking (descending) of the weight values of the second-level indicators is: {B₃, B₂, B₄, B₁}; The ranking (descending order) of the weight values of the three-level indicators is: {C₁₀, C₁₃, C₁₂, C₁₁, C₉}; {C₆, C₅, C₈, C₇}; {C₁₄, C₁₆, C₁₇, C₁₅}; {C₃, C₂, C₁, C₄}.

4.3. Safety evaluation
According to the standardized processed data and several primary mutation models shown in Table 1, the current state of coal mine safety is evaluated according to the evaluation steps of mutation theory.

4.3.1. Normalization of three-tier indicators. There are 4 factors affecting the quality of workers, equipment facilities and safety management, and 5 indicators affecting natural conditions are selected. The results of the normalization of the three-tier indicators are set out in Table 4.

| Secondary index | Normalization of three-level indicators |
|-----------------|-----------------------------------------|
| B₁              | Xc₃ = √0.883 = 0.9397, Xc₂ = √0.879 = 0.9579 |
|                 | Xc₁ = ⁴√0.769 = 0.9364, Xc₄ = ⁵√0.837 = 0.9650 |
| B₂              | Xc₆ = √0.837 = 0.9149, Xc₅ = ³√0.841 = 0.9439 |
|                 | Xc₈ = ⁵√0.851 = 0.9605, Xc₇ = ⁵√0.817 = 0.9604 |
| B₃              | Xc₁₀ = √0.824 = 0.9077, Xc₁₃ = ⁵√0.886 = 0.9605 |
|                 | Xc₁₂ = ⁴√0.831 = 0.9458, Xc₁₁ = ⁵√0.794 = 0.9549, Xc₉ = ⁴√0.831 = 0.9696 |
| B₄              | Xc₁₄ = √0.873 = 0.9343, Xc₁₆ = ⁵√0.860 = 0.9510 |
|                 | Xc₁₇ = ⁴√0.836 = 0.9562, Xc₁₅ = ⁵√0.880 = 0.9748 |

4.3.2. Catastrophe progression value of secondary indexes. According to the normalized results of the third-level indexes, the "complementary" or "non-complementary" principle is used to calculate the catastrophe progression value of the second-level indexes. In employee quality, there is a "complementary" relationship among employee's education level, employee's operation technology level, safety education and training, and the three violation rates of operators. The average value is taken as the catastrophe cascade value of employee quality B₁. In the equipment and facilities, the perfect rate of equipment and facilities, the mechanization degree of coal mining, the reliability of communication and prevention system, the safety monitoring and informatization are "non-complementary" relations, and the minimum value is selected as the catastrophe cascade value of equipment and facilities B₂. Among the natural conditions, the relation among gas geological conditions, spontaneous combustion tendency of coal seam, hydrogeological conditions, ground pressure disaster conditions and coal dust explosive is "non-complementary", and the minimum value is selected as the catastrophe progression value of natural condition B₃. In safety management, there is a "complementary" relationship between safety organization and personnel allocation rate, safety capital investment, emergency rescue plan, equipment and safety rules and regulations, and the average value is taken as the catastrophe cascade value of safety management B₄. Catastrophe progression values of the two-layer indexes obtained are shown in Table 5.
### Table 5. Catastrophe progression values of two-layer indicators.

| Influencer factors       | Evaluation principle       | Mutation-level value |
|--------------------------|----------------------------|----------------------|
| The worker quality       | Complementary             | $B_1 = \frac{X_{c1} + X_{c2} + X_{c3} + X_{c4}}{4} = 0.9498$ |
| Equipment and facilities | Non-complementary          | $B_2 = \min\{X_{C5}, X_{C6}, X_{C7}, X_{C8}\} = 0.9149$ |
| Natural conditions       | Non-complementary          | $B_3 = \min\{X_{C9}, X_{C10}, X_{C11}, X_{C12}, X_{C13}\} = 0.9077$ |
| Safety management        | Complementary             | $B_4 = \frac{X_{C14} + X_{C15} + X_{C16} + X_{C17}}{4} = 0.9541$ |

**4.3.3. Mutation membership value for coal mine safety.** After obtaining the mutation-level value of the secondary index, the mutation-level value of the first-level indicator is calculated, first of all, the first-level indicator is normalized, and the butterfly mutation model is used to process it according to the previous knowledge, that is $X_{b3} = \sqrt{0.9077} = 0.9527, X_{b2} = \frac{1}{4}\sqrt{0.9149} = 0.9708, X_{b4} = \frac{1}{4}\sqrt{0.9541} = 0.9883, X_{b1} = \frac{5}{4}\sqrt{0.9498} = 0.9898$.

After the normalization of the first-level indicators, due to the strong correlation of various factors affecting coal mine safety, such as strengthening the management of safety can reduce the rate of three violations of operators, increase the investment of safety funds can improve the intact rate of equipment and facilities, improve the degree of mechanization of coal mining, the enhancement of the reliability of the general defense system has an important impact on reducing the explosiveness of coal dust. Therefore, there is a "complementary" relationship among employee quality B1, equipment and facilities B2, natural condition B3, and safety management B4, and the total mutation membership value can be obtained as: $A = \frac{X_{b1} + X_{b2} + X_{b3} + X_{b4}}{4} = 0.9754$.

**4.4. Results analysis**

The mutation affiliation value of Changcun coal mine is 0.9754, and the safety level of the coal mine is V, and the status is safe.

**5. Conclusions**

Combined with the basic principles and characteristics of mutation theory, this paper analyzes the development process of coal mine accidents, and shows that the development of coal mine accidents conforms to the application conditions of mutation theory. Therefore, this paper puts forward a combination of entropy method and mutation theory, which can carry out the evaluation of coal mine safety state more accurately and provide the basis for the formulation of scientific and effective safety countermeasures.

In accordance with relevant laws and regulations such as the Law of the People's Republic of China on Safe Production and the analysis of coal mine accident cases, a system of coal mine safety evaluation indicators with a total of 17 indicators at level 4 has been established from the four aspects of staff quality, equipment and facilities, natural conditions and safety management.

The entropy method and mutation theory are effectively combined to analyze a coal mine in Shanxi Province as an example. According to the entropy method to judge the weight of each indicator, using the mutation series method recursive operation to get the total mutation membership value of the coal mine is 0.9754. The safety evaluation result is safety, and natural condition factors are the main factors leading to the lower safety level of the whole coal mine. Compared with the degree of membership of natural conditions, the corresponding affiliation values of the three factors of staff quality, equipment and facilities and safety management are high, and the evaluation results are safe. This result is related to the safety management input of the coal mine, conforms to the actual situation of the mine, shows the accuracy of the evaluation method, and makes it have been verified by practice.
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