An Improved Evaluation of Comprehensive for Mine Fire Risk

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Abstract. Because of the uncertainty of the influencing factors of coal mine fire in China, it will lead to the uncertainty of the evaluation results in the comprehensive evaluation of coal mine fire risk. Based on this, the goaf management, ventilation conditions, coal seam geological occurrence, and exploitation technology are used as first level evaluation indexes, and the fuzzy comprehensive evaluation method of fusion Dempster-Shafer evidence theory (D-S) is used to establish a comprehensive evaluation system for coal mine fire risk. The fire risk of Qiuji Coal Mine was comprehensively evaluated. The example shows that the fuzzy comprehensive evaluation method based on D-S can consider the uncertainty of influence factors more accurately and improve the accuracy and reliability of the comprehensive evaluation of coal mine fire risk.

1. Introduction
Gas gathering, coal spontaneous combustion and coal dust explosion often cause coal mine safety accidents, especially fire accidents [1-2]. It has seriously threatened the safety of coal mine production and the life of underground workers. Therefore, there is an urgent need for relevant fire assessment technology and means to solve the prominent problems affecting the safety of coal mines [3].

There are many factors leading to coal mine fires. According to the experience and the research of relevant experts, the influencing factors of fire are divided into mining area management, ventilation conditions, coal seam geological occurrence, and exploitation technology. Zhang et al [4-5] also agree with this view. However, all kinds of influencing factors have many kinds and uncertain characteristics, which make it difficult to determine the weight, resulting in the final evaluation and the actual situation is not consistent. The fuzzy comprehensive evaluation method can build a better index system, and is favored by experts in the evaluation process. However, the determination of the index weight in the method is mostly determined by the relevant experts themselves, which is too subjective. The evidence theory adopts the principle of “semi additivity” of reliability, which better deals with the contradiction between subjectivity and objectivity in the uncertainty reasoning. Therefore, based on the construction of the coal mine fire risk evaluation system, the conflict evidence synthesis method of D-S theory [6] is used to improve the traditional fuzzy comprehensive evaluation method for weighting, so that the determination of the weight is more realistic and objective [7-8].
2. Coal mine fire risk comprehensive evaluation system
It is the basis and premise to ensure the accuracy of evaluation to determine the reasonable level indicators. According to the current situation of coal mine fire research [9] and the actual situation of Qiuji coal mine, combined with the relevant opinions of experts, this paper constructs the first level indicators of goaf management, ventilation conditions, coal seam geological occurrence, development and mining technology, and the second level indicators of ventilation system, roof management, coal seam thickness and other 17 indicators. The index system of coal mine fire risk assessment is shown in Figure 1.

![Figure 1. Coal mine fire risk assessment index system](image)

3. Determination of the weight coefficient of D-S theory

3.1. D-S theory
D-S theory is a mathematical method for dealing with the problem of reasoning of unknownness and ambiguity [10-11].

Suppose there is a nonempty set with finite elements and mutually exclusive and independent elements, which is expressed as \( D = \{A, A_2, A_3, \ldots, A_n\} \), where \( n \) is the number of elements. The likelihood function, probability distribution function, and trust function of element \( A \) are respectively represented by \( P(I(A)), M(A), Bel(A) \). If \( 2^D \rightarrow [0,1], B \subseteq A \subseteq D \), then it must meet:

\[
\begin{align*}
M(\emptyset) &= 0 \\
\sum_{A \subseteq D} M(A) &= 1 \\
Bel(A) &= \sum_{B \subseteq A} M(B) \\
P(I(A)) &= 1 - Bel(\overline{A})
\end{align*}
\]

Let the element \( E, E_i \) be the evidence in \( D \), \( m_i, m \) is \( m_i \in [0,1] \), and the distance of \( m_i, m \), is:

\[
d(m_i, m) = \sqrt{\frac{1}{2} (m_i - m)\cdot D(m_i - m)}
\]
represents the similarity between two elements, \( \text{Sim}(m_i, m_j) \) represents the opposite degree between elements, according to complementarity: \( \text{Sim}(m_i, m_j) = 1 - d(m_i, m_j) \), the opposite degree \( \text{Sim}(m_i, m_j) \) can also be calculated by formula (1):

\[
\text{Sim}(m_i, m_j) = \frac{\sum_{k=1}^{m} m_{ki} m_{kj}}{\sqrt{(\sum_{k=1}^{m} m_{ki}^2) (\sum_{k=1}^{m} m_{kj}^2)}}
\]

The value range of \( c_{ij} \) is \((0,1)\), and \( c_{ij} \) tends to 0, indicating that the evidence of two elements conflicts. If \( c_{ij} \) tends to 1, it means that the evidence of two elements is near. To represent the degree of similarity between the elements of the set \( D \), the similarity matrix is introduced as follows:

\[
S_{ij} = \begin{bmatrix}
1 & c_{i1} & c_{i2} & \cdots & c_{ij} & \cdots & c_{in} \\
\vdots & \vdots & \vdots & & \vdots & & \vdots \\
c_{i1} & c_{i2} & c_{ij} & & c_{in} & & \vdots \\
\vdots & \vdots & \vdots & & \vdots & \vdots & \vdots \\
c_{n1} & c_{n2} & \cdots & c_{nj} & \cdots & 1
\end{bmatrix}
\]

Evidence support is the sum of the similarity between each elemental evidence and other elemental evidence in the similarity matrix. Normalization of \( \text{Sup}(m_i) \) can give credibility. Its calculation formula is as follows:

\[
\text{Sup}(m_i) = \frac{\sum_{j=i, j\neq i}^{n} c_{ij}, i, j = 1, 2, \ldots, n}
\]

\[
\text{Crd}(m_i) = \frac{\text{Sup}(m_i)}{\sum_{i=1}^{n} \text{Sup}(m_i)}, i = 1, 2, \ldots, n
\]

In summary, the conflict evidence synthesis rule of the distance function between elemental evidence is:

\[
m(Y_{ki}) = \sum_{i=1}^{n} m(Y_{ki}) \times \text{Crd}(m_i)
\]

3.2. Determination of weight coefficient

Invite experts from coal mines and related fields to grade the evaluation indicators with reference to relevant literature and coal mines. Regard all experts as a set, each expert as element evidence, and the expert's distribution of indicators as probability distribution function \( M(A) \), so as to obtain the weight coefficient \( \lambda_i = m(Y_{ki}) \).

4. Construction of coal mine fire risk assessment model

4.1. Establishing a set of factors

The set of primary evaluation indicator factors is: \( U = (u_1, u_2, u_3, u_4) \)

The set of secondary evaluation indicators is: \( u_1 = (u_{11}, u_{12}, u_{13}) \), \( u_2 = (u_{21}, u_{22}, u_{23}, u_{24}) \), \( u_3 = (u_{31}, u_{32}, u_{33}, u_{34}, u_{35}) \), \( u_4 = (u_{41}, u_{42}, u_{43}, u_{44}, u_{45}) \)
4.2. Establish an evaluation set

The evaluation set \( C = (c_1, c_2, c_3, c_4, c_5) \) is established. \( c_1, c_2, c_3, c_4, c_5 \) indicate that the evaluation results are “dangerous”, “more dangerous”, “medium”, “safer” and “safe”. All possible evaluation results of experts are included in the evaluation set, and the quantitative relationship is shown in Table 1.

| Grade       | Danger | More dangerous | Medium | Safer | Safety |
|-------------|--------|----------------|--------|-------|--------|
| Interval    | (90, 100] | (70, 90] | (50, 70] | (40, 50] | (0, 40] |
| Quantitative | 95     | 80     | 60     | 45    | 20     |

4.3. Establish a weight set

Hire relevant experts to score the weight of the fire assessment index of Qiuji coal mine. Take the weight of the first level assessment index as an example, as shown in Table 2. The comprehensive weight of evaluation index can be obtained from the formula (1)-(5).

| expert | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | Comprehensive weight |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|----------------------|
| \( B_1 \) | 0.19 | 0.24 | 0.20 | 0.16 | 0.25 | 0.13 | 0.10 | 0.30 | 0.20 | 0.15 | 0.192 |
| \( B_2 \) | 0.10 | 0.09 | 0.40 | 0.15 | 0.15 | 0.10 | 0.30 | 0.15 | 0.18 | 0.20 | 0.182 |
| \( B_3 \) | 0.28 | 0.30 | 0.30 | 0.30 | 0.35 | 0.34 | 0.20 | 0.25 | 0.32 | 0.30 | 0.294 |
| \( B_4 \) | 0.43 | 0.37 | 0.10 | 0.39 | 0.25 | 0.43 | 0.40 | 0.30 | 0.30 | 0.35 | 0.332 |

Then the first level evaluation weight set is: \( A = (0.192, 0.182, 0.294, 0.332) \)

For the same reason, the set of secondary evaluation indicators is: \( A_1 = (0.36, 0.32, 0.32) \), \( A_2 = (0.17, 0.21, 0.28, 0.34) \), \( A_3 = (0.09, 0.13, 0.21, 0.25, 0.32) \), \( A_4 = (0.06, 0.18, 0.23, 0.27, 0.26) \).

4.4. Fuzzy comprehensive evaluation process

Fuzzy comprehensive evaluation is to quantify fuzzy information and then evaluate it based on multiple factors. Fuzzy comprehensive evaluation includes primary evaluation, secondary evaluation and quantitative evaluation of evaluation results [12-13].

(1) The first level fuzzy comprehensive evaluation. It is to evaluate the second level evaluation index and obtains the evaluation results. According to the membership relationship between each index and the evaluation results, the membership of each index is classified and normalized. The evaluation formula is:

\[
B_i = A_i \bullet R_i
\]

Among them, \( A_i \) is the weight of the index evaluation factor; \( R_i \) is the membership degree matrix; \( B_i \) is the indicator evaluation set. \( i = 1, 2, 3, 4 \).

(2) The second level fuzzy comprehensive evaluation. It is based on the first level fuzzy comprehensive evaluation, and matrix operation is done to each kind of evaluation subset to get the total evaluation set. Its calculation formula is:

\[
B = A \bullet \hat{R}
\]

Among them, \( A \) is the secondary index evaluation weight set; \( \hat{R} \) is the membership degree matrix; \( B \) is the total evaluation set.
(3) Data quantization processing. It is to multiply each evaluation set by the quantitative value of its related evaluation results. The calculation formula is:

\[ V_i = \hat{V} B_i \]  

(8)

\( \hat{V} \) is the quantitative result of the evaluation result; \( V_i \) is the interval value of the evaluation result. In summary, the total risk of fuzzy evaluation is:

\[ V = \hat{V} B \]  

(9)

5. Engineering applications

5.1. Coal mine overview

Qiuji coal mine is located in Qihe County, Shandong Province, with an industrial reserve of 30.49 million tons. 11 coal seams are mined. The average thickness of the coal seams is 2.25 m, and the dip angle of the coal seams is 4°. It is a strip and layered structure. The explosive index of coal dust is 34.56%. The ignition temperature of the original coal seam is 307 °C ~ 367 °C, the difference between the reduction sample and the oxidation sample is 4 °C ~ 41 °C, and the spontaneous combustion tendency grade is class II.

5.2. Comprehensive fuzzy evaluation of coal mine fire risk

The fire risk comprehensive fuzzy evaluation index system of Qiuji coal mine is shown in Table 3.

| First level evaluation index | Secondary evaluation index | Affiliation |
|------------------------------|-----------------------------|-------------|
| Name                         | Name                        | Weight      | Danger | Moredangerous | Medium | Safer | Safety |
| Gob area management          | Closure situation           | 0.192       | 0.36   | 0            | 0      | 0     | 1      |
|                              | Equalizing ventilation      | 0.32        | 0      | 0            | 0      | 1     | 0      |
|                              | Nitrogen and grouting       | 0.32        | 0      | 1            | 0      | 0     | 0      |
|                              | resistance                 |             |        |              |        |       |        |
| Ventilation conditions       | Ventilation facility        | 0.182       | 0.17   | 0            | 0      | 0     | 1      |
|                              | ventilation system          |             | 0.21   | 0            | 0      | 1     | 0      |
|                              | Ventilation management      |             | 0.28   | 0            | 0      | 0     | 1      |
|                              | Ventilation method          |             | 0.34   | 0            | 0      | 0     | 1      |
| Coal seam geological         | Coal seam thickness         | 0.294       | 0.09   | 0            | 0      | 0     | 1      |
| occurrence                   | Coal seam lithology         |             | 0.13   | 0            | 0      | 1     | 0      |
|                              | Geological structure        |             | 0.21   | 0            | 0      | 1     | 0      |
|                              | Coal seam dip              |             | 0.25   | 0            | 0      | 1     | 0      |
|                              | Coal seam depth and ground  |             | 0.32   | 0            | 0      | 0     | 1      |
|                              | temperature                |             |        |              |        |       |        |
| Exploit mining technology    | Roof management            | 0.332       | 0.06   | 0            | 0      | 0     | 1      |
|                              | Mining direction and order  |             | 0.18   | 0            | 0      | 1     | 0      |
|                              | Digging and advancing speed |             | 0.17   | 0            | 0      | 0     | 1      |
|                              | Coal mining method and      |             | 0.27   | 0            | 0      | 1     | 0      |
|                              | process                     |             |        |              |        |       |        |
|                              | Pioneering method and       |             | 0.32   | 0            | 0      | 0     | 1      |
|                              | arrangement                |             |        |              |        |       |        |

(1) The first level fuzzy comprehensive evaluation. According to formula (6) and table 3, the membership matrix of goaf management, ventilation conditions, coal seam geological occurrence and development and mining technology can be obtained as follows:
(2) The second level fuzzy comprehensive evaluation. According to the membership matrix $R$ of the first level fuzzy comprehensive evaluation and the weight value $A$ of the first level index, the coal mine fire risk level $B$ can be obtained.

$$B = A \cdot R = (0.192 \ 0.182 \ 0.294 \ 0.332) \cdot \begin{bmatrix}
0 & 0.31 & 0 & 0.33 & 0.36 \\
0 & 0 & 0.21 & 0.28 & 0.51 \\
0 & 0 & 0.25 & 0.34 & 0.41 \\
0 & 0 & 0.27 & 0.18 & 0.55 \\
\end{bmatrix} = (0 \ 0.062 \ 0.201 \ 0.272 \ 0.465)$$

According to the principle of maximum membership, the coal mine is classified as “safe”, that is, there is no danger of coal mine fire in Qiuji Coal Mine.

(3) Data quantization processing. To make the evaluation more convincing, it is necessary to quantify the results of the evaluation. The calculation results are as follows:

Fire hazard in Qiuji Coal Mine: $V = V' B = (95 \ 80 \ 60 \ 45 \ 20) \cdot \begin{bmatrix}
0 \\
0.062 \\
0.201 \\
0.272 \\
0.465 \\
\end{bmatrix} = 38.560$

In the same way, the risk of gob management factors: $V_1 = 47.200$, ventilation factor risk: $V_2 = 35.400$, coalbed geological factors risk: $V_3 = 38.500$, exploit mining technology factors: $V_4 = 35.300$.

The fire risk quantitative value of Qiuji Coal Mine is 38.560, which belongs to the “safety” level; the mining area management belongs to the “safer” level; the ventilation condition belongs to the “safe” level; the coal seam geological occurrence belongs to the "safe" level; exploit mining technology belongs to the “safety” level. From the perspective of ventilation conditions, coal seam geological occurrence, and exploitation technology, the probability of fire is relatively low; from the perspective of goaf management, there is a possibility of fire, but it is relatively safe. In general, the fire risk of Qiuji Coal Mine is subject to the “safety” level, which is consistent with the actual situation.

6. Conclusion

(1) The conflict evidence synthesis method of evidence theory can eliminate the conflict between evidences and make the weight more reasonable and persuasive.

(2) Based on the current situation of coal mine fire, a coal mine fire risk evaluation index system is established, which takes goaf management, ventilation conditions, geological occurrence of coal seam, development and mining technology as the first level indexes, and 17 indexes such as ventilation system and ventilation management as the second level indexes. Five fire grades are divided, and the classification of grade gradients is accurate and meets the requirements of fire judgment.

(3) By using the improved fuzzy comprehensive evaluation method, the fire risk grade of Qiuji coal mine is "safety", which accords with the actual situation. This indicates that the fuzzy comprehensive evaluation method based on D-S theory has higher application value and higher credibility.

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