processes

MDPI

Article

Multidimensional Analysis of Ore Spontaneous Combustion Tendency Based on IAHP and Improved Interval Approximation

Huiling Xiong [1], Daobing Zhang [2,3], Ling Yan [1], Yang Zhang [1] and Huadong Yin [2,*]

[1] Safety Engineering Institute, Hunan Vocational Institute of Safety Technology, Changsha 410151, China; xhlaqzy@163.com (H.X.); 13973152078@163.com (L.Y.); zhangyangaqzy@163.com (Y.Z.)
[2] School of Resource Environment and Safety Engineering, Hunan University of Science and Technology, Xiangtan 411201, China; dbzhang@hnust.edu.cn
[3] Sanya Institute of Hunan University of Science and Technology, Sanya 572024, China
* Correspondence: hdyin1019@163.com

Abstract

To conduct a scientific and comprehensive analysis of the spontaneous combustion tendency of sulfide ores and improve the safety production level of sulfur mines, an indicator system for determining the spontaneous combustion tendency of sulfide ores and a comprehensive classification standard for the spontaneous combustion tendency of sulfide ores were constructed. Based on this, a multidimensional information comprehensive analysis model for ore spontaneous combustion tendency was constructed by combining the interval analytic hierarchy process (IAHP) and the improved interval approximation analysis method. The interval judgment matrix was constructed by the interval analytic hierarchy process, and the weight of the spontaneous combustion tendency for evaluation indicators was calculated. By improving the interval approximation analysis, the indicators of the ore spontaneous combustion tendency were analyzed in the form of interval numbers, and the information potential was deeply explored to obtain multidimensional information such as the grade of the ore spontaneous combustion tendency and the reliability of the ore spontaneous combustion tendency, and then the comprehensive grade of the ore spontaneous combustion tendency was determined. By using this model, a multidimensional information analysis was conducted on the spontaneous combustion tendency of each ore layer in a certain sulfur iron mine, with the indicators of the ore spontaneous combustion tendency as the interval number. It was found that the 30-day oxidation weight gain rate exerts the most significant influence on ore spontaneous combustion. The ore in ore layer no. 1 was prone to spontaneous combustion with relatively reliable results, while the ores in ore layers no. 2 and 3 were susceptible to self-heating with highly reliable results. This study provides a reference and guidance for the targeted prevention of ore spontaneous combustion in the mine.

Keywords: sulfide ore; spontaneous combustion; interval analytic hierarchy process (IAHP); interval approximation

Check for updates

Academic Editor: Albert Ratner

Received: 27 July 2026
Revised: 30 August 2026
Accepted: 9 September 2026
Published: 14 September 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

The spontaneous combustion of sulfide ores can easily result in casualties and property damage among mine personnel, as well as the destruction of mineral resources, posing a major safety hazard to mine safety and production. An accurate and comprehensive analysis and assessment of the spontaneous combustion tendency of sulfide ores can help

mining enterprises formulate targeted prevention and control measures against spontaneous combustion, thereby reducing the hazards associated with it [1–3]. Currently, the multi-indicator methods offer a comprehensive approach and a rigorous analytical process and have now become the mainstream method for assessing ore combustion propensity [4]. Relevant scholars have conducted research on methods for analyzing the spontaneous combustion tendency of sulfide ores. Zhou et al. [5] proposed a comprehensive factor analysis method, which determines the spontaneous combustion tendency of ore rocks through the simultaneous measurement of several indicators, including ore mineralogy, chemical composition, and oxidation rate. Yang et al. [6] selected the mass gain rate during low-temperature oxidation, the autoignition point, and the ignition point as discriminating factors for the comprehensive assessment of the spontaneous combustion tendency of sulfide ores. Using factor analysis, they established a model for determining the spontaneous combustion tendency of sulfide ores and applied this model to assess the spontaneous combustion tendency of sulfide ore samples. Huang et al. [7] selected the rate of weight gain due to oxidation, the autoignition temperature, and the ignition point as the primary influencing factors for ore spontaneous combustion tendency. By integrating the AHP method and TOPSIS, they constructed an evaluation model for ore spontaneous combustion tendency and conducted an analysis and evaluation of the spontaneous combustion tendency levels of the ore. Currently, all methods for analyzing and evaluating the spontaneous combustion tendency of ores treat indicator information as discrete point data for analysis and evaluation. However, for mining areas, sections, orebodies, and even the entire ore layer, the numerical values of indicators for determining spontaneous combustion tendency should fluctuate. The analysis results of the ore's spontaneous combustion tendency obtained by existing analytical and evaluation methods may be unreliable. Furthermore, traditional analysis and evaluation methods only classify the spontaneous combustion tendency of sulfide ores into grades. In fact, the spontaneous combustion tendency of sulfide ores may possess multiple attributes, and the classification into a specific grade is probabilistic. Only by conducting a comprehensive analysis of both the grade classification and the probability of each grade can comprehensive information be provided to aid in the prevention of spontaneous combustion in sulfide ores.

Interval approximation analysis can fully reflect the interval fluctuation characteristics of the numerical values of self-ignition evaluation indicators for sulfide ores, whereas traditional interval approximation analysis can only evaluate the system as a whole and cannot analyze system details or specific indicators. By applying improved interval approximation analysis to assess ore self-ignition tendencies, one can not only obtain overall analysis results but also determine the self-ignition tendencies of individual evaluation indicators. At the same time, by fully leveraging the analytical potential of interval approximation analysis, we can identify the multiple attributes of ore spontaneous combustion tendency and the probability confidence levels of each attribute, thereby enabling a comprehensive assessment of the propensity of sulfide ores to spontaneously combust and accurate assistance and guidance for preventing and controlling ore spontaneous combustion. Furthermore, by utilizing the IAHP, which contains more comprehensive information, to analyze the weights of ore spontaneous combustion tendency indicators, the accuracy of weight calculations is ensured.

2. Evaluation Indicator System and Classification Standards for the Spontaneous Combustion Tendency of Sulfide Ores

2.1. Evaluation Indicator System for the Spontaneous Combustion Tendency of Sulfide Ores

Referring to existing research [8], the indicators currently used to determine the spontaneous combustion tendency of sulfide ores are generally consistent, primarily including the

self-heating point, the autoignition point, and the rate of weight gain due to oxidation over a specific period. Based on experience, the rate of weight gain due to oxidation fluctuates significantly in the short term, whereas it stabilizes after 30 days. Therefore, this study constructs an evaluation indicator system for the spontaneous combustion tendency of sulfide ores using the 30-day oxidation weight gain rate, the self-heating point, and the autoignition point, as shown in Figure 1.

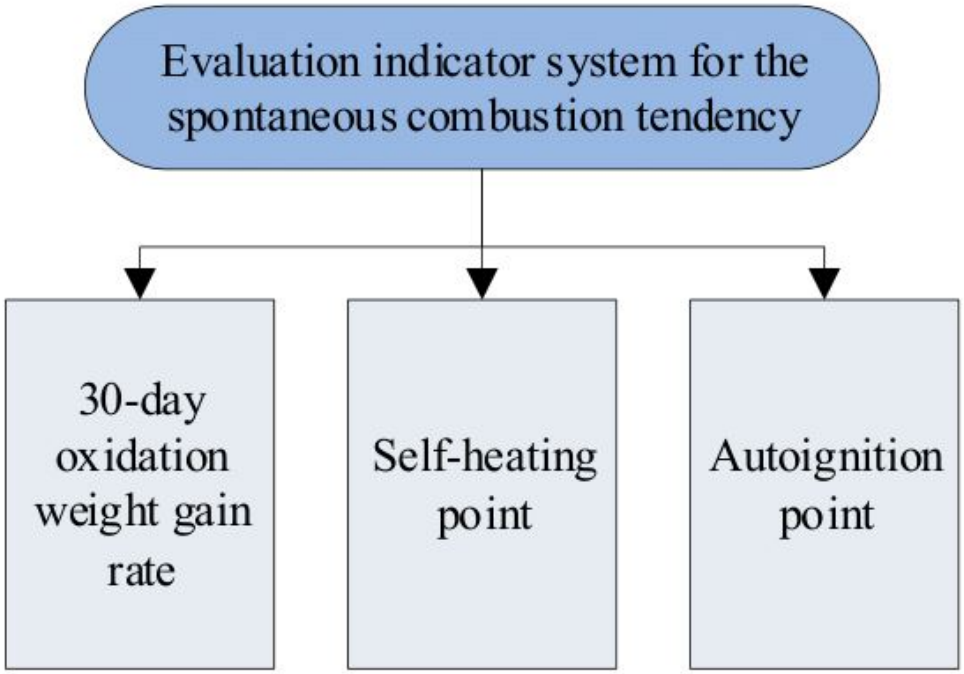


Figure 1. Evaluation indicator system for the spontaneous combustion tendency of sulfide ores.

2.2. Multidimensional Classification Criteria for the Spontaneous Combustion Tendency of Sulfide Ores

2.2.1. Classification of Spontaneous Combustion Tendency in Sulfide Ores

Existing studies generally agree on the classification of the spontaneous combustion tendency of sulfide ores, categorizing them into three types: prone to spontaneous combustion, prone to self-heating, and not prone to spontaneous combustion. This study adopts this classification standard; the classification criteria for spontaneous combustion tendency are shown in Table 1.

Table 1. Classification standards for spontaneous combustion tendency of sulfide ores.

Spontaneous Combustion Tendency Grade	Evaluation Indicators			Grade Description
	30-Day Oxidation Weight Gain Rate/%	Self-Heating Point/°C	Autoignition Point/°C	
I	>2.0	0~100	0~220	Prone to spontaneous combustion
II	1.0~2.0	100~250	220~350	Prone to self-heating
III	0~1.0	>250	>350	Not prone to spontaneous combustion

Note: In the table, the lower limit of the range includes the specified value, while the upper limit excludes it.

2.2.2. Classification of the Reliability of the Spontaneous Combustion Tendency of Sulfide Ores

The spontaneous combustion tendency of sulfide ores represents only one aspect of ore self-ignition. From a more comprehensive perspective, ore self-ignition is a probabilistic event; therefore, the spontaneous combustion tendency has a degree of reliability. After consulting relevant experts, the reliability classification of the spontaneous combustion tendency of sulfide ores is shown in Table 2.

Table 2. Reliability classification criteria for spontaneous combustion tendency of sulfide ores.

Reliability Grade for Spontaneous Combustion Tendency	Reliability Probability/%	Class Description
I	80~100	Highly credible
II	60~80	Fairly credible
III	0~60	Generally credible

Note: In the table, the lower limit of the range includes the specified value, while the upper limit excludes it.

2.2.3. Comprehensive Classification of Sulfide Ore Spontaneous Combustion Tendency

Both the spontaneous combustion tendency grade and its reliability are crucial factors in assessing the consequences of ore self-ignition. Therefore, this study conducts a comprehensive analysis and classification of the spontaneous combustion tendency results for sulfide ores by integrating the spontaneous combustion tendency grade and reliability. Clearly, the comprehensive analysis of the spontaneous combustion tendency grade and reliability is necessary to determine the comprehensive classification results, as shown in Table 3.

Table 3. Comprehensive grading for spontaneous combustion tendency of sulfide ores.

Spontaneous Combustion Tendency Grade	Reliability Grade		
	I (Highly Credible)	II (Fairly Credible)	III (Generally Credible)
I (Prone to spontaneous combustion)	I	II	III
II (Prone to self-heating)	II	III	IV
III (Not prone to spontaneous combustion)	V	IV	III

Note: In the comprehensive classification, grade I indicates particularly severe consequences of spontaneous combustion; grade II indicates relatively severe consequences; grade III indicates generally severe consequences; grade IV indicates not very severe consequences; and grade V indicates not severe consequences.

When determining the comprehensive analysis of ore spontaneous combustion tendency, the priority of the spontaneous combustion tendency grade takes precedence over that of the reliability grade: first determine the ore's spontaneous combustion tendency grade, then use the reliability grade corresponding to that spontaneous combustion tendency grade to determine the comprehensive classification of the ore's spontaneous combustion tendency.

3. Comprehensive Analysis of the Spontaneous Combustion Tendency of Sulfide Ores

3.1. Analysis of Indicator Weights

3.1.1. Selection of Weight Calculation Methods

Indicator weights are classified into subjective weights [9], objective weights [10,11], and composite weights [12] based on the information foundation for weight calculation. To ensure that the analysis of the spontaneous combustion tendency of sulfide ores is not constrained by sample size, the weights of the evaluation indicators for determining spontaneous combustion tendency are represented as subjective weights. To further ensure the accuracy of the weight calculation results, the interval analytic hierarchy process (IAHP) is employed to calculate the indicator weights [13]. The interval analytic hierarchy process retains the analysis results of all experts regarding the relative relationships between indicators, uses interval values instead of point data to construct a judgment matrix, and thereby calculates the indicator weights [14].

3.1.2. Establishing the Judgment Matrix

The relative importance of evaluation indicators for assessing the spontaneous combustion tendency of sulfide ores is based on a relative importance grading method (on a scale of 1 to 9) [15–17]. To obtain more accurate analytical results, this study improved the precision of the grading scale, resulting in the following interval judgment matrix G for the weighted analysis:

$$G = \begin{bmatrix} [g_{11}^-, g_{11}^+] & [g_{12}^-, g_{12}^+] & \cdots & [g_{1n}^-, g_{1n}^+] \\ [g_{21}^-, g_{21}^+] & [g_{22}^-, g_{22}^+] & \cdots & [g_{2n}^-, g_{2n}^+] \\ \cdots & \cdots & [g_{ij}^-, g_{ij}^+] & \cdots \\ [g_{n1}^-, g_{n1}^+] & [g_{n2}^-, g_{n2}^+] & & [g_{nn}^-, g_{nn}^+] \end{bmatrix} \quad (1)$$

where g_{ij}^- is the lower limit of the relative importance scale, g_{ij}^+ is the upper limit of the relative importance scale, and n is the total number of indicators.

3.1.3. Consistency Test

Separate the g_{ij}^- and g_{ij}^+ elements from matrix G to form two matrices: $G = [G^-, G^+]$.

$$G^- = \begin{bmatrix} g_{11}^- & g_{12}^- & \cdots & g_{1n}^- \\ g_{21}^- & g_{22}^- & \cdots & g_{2n}^- \\ \cdots & \cdots & g_{ij}^- & \cdots \\ g_{n1}^- & g_{n2}^- & & g_{nn}^- \end{bmatrix} \text{ and } G^+ = \begin{bmatrix} g_{11}^+ & g_{12}^+ & \cdots & g_{1n}^+ \\ g_{21}^+ & g_{22}^+ & \cdots & g_{2n}^+ \\ \cdots & \cdots & g_{ij}^+ & \cdots \\ g_{n1}^+ & g_{n2}^+ & & g_{nn}^+ \end{bmatrix} \quad (2)$$

Calculate λ based on g_{ij}^+:

$$\lambda = \sqrt{\sum_{j=1}^{n} \frac{1}{\sum_{i=1}^{n} g_{ij}^+}} \quad (3)$$

Calculate β based on g_{ij}^-:

$$\beta = \sqrt{\sum_{j=1}^{n} \frac{1}{\sum_{i=1}^{n} g_{ij}^-}} \quad (4)$$

When $\lambda \leq 1$ and $\beta \geq 1$, matrix G passes the consistency test; otherwise, it is considered to have failed the consistency test and must be reconstructed as an interval judgment matrix [18].

3.1.4. Calculation of the Weights

For the lower-bound matrix G^- of the matrix G that has passed the consistency test, its eigenvector $W^- = [w_1^-, w_2^-, \ldots, w_i^-, \ldots, w_n^-]$ is obtained. For the upper-bound matrix G^+, its eigenvector $W^+ = [w_1^+, w_2^+, \ldots, w_i^+, \ldots, w_n^+]$ is obtained. By combining and normalizing the eigenvectors W^- and W^+, the weights $W = [w_1, w_2, \ldots, w_i, \ldots, w_n]$ for the spontaneous combustion tendency evaluation indicators of sulfide ores are obtained, where

$$w_i = \frac{0.5(\lambda w_i^- + \beta w_i^+)}{\sum_{i=1}^{n} 0.5(\lambda w_i^- + \beta w_i^+)} \tag{5}$$

3.2. Analysis of the Spontaneous Combustion Tendency Levels of Sulfide Ores

3.2.1. Construction of the Interval Number Evaluation Matrix

The dataset of evaluation criteria for determining the spontaneous combustion tendency of a certain sulfide ore is represented as a vector of intervals $H_0([a_{01}^L, a_{01}^R], [a_{02}^L, a_{02}^R], \ldots, [a_{0n}^L, a_{0n}^R])$. If the spontaneous combustion tendency grade of the sulfide ore is s (as mentioned earlier, s = 3), then the vector H_0 and the set of self-ignition grading criteria U are combined to form the evaluation matrix X [19,20] for the spontaneous combustion tendency of the sulfide ore:

$$X = \begin{bmatrix} H_0 \\ U \end{bmatrix} = \begin{bmatrix} [a_{01}^L, a_{01}^R] & [a_{02}^L, a_{02}^R] & \cdots & [a_{0n}^L, a_{0n}^R] \\ [u_{11}^L, u_{11}^R] & [u_{12}^L, u_{12}^R] & \cdots & [u_{1n}^L, u_{1n}^R] \\ [u_{21}^L, u_{21}^R] & [u_{22}^L, u_{22}^R] & \cdots & [u_{2n}^L, u_{2n}^R] \\ \cdots & \cdots & [u_{ri}^L, u_{ri}^R] & \cdots \\ [u_{s1}^L, u_{s1}^R] & [u_{s2}^L, u_{s2}^R] & \cdots & [u_{sn}^L, u_{sn}^R] \end{bmatrix} \tag{6}$$

In Equation (6), u_{ri}^L represents the lower limit of the r-th classification standard for the i-th evaluation indicator, and u_{ri}^R represents its upper limit.

3.2.2. Numerical Processing of the Interval Analysis Matrix

Perform homogenization and normalization on matrix X.

Homogenization: When an indicator is a benefit-type indicator (where a larger value indicates a greater tendency toward spontaneous combustion), the indicator data require no processing. If an indicator is a cost-type indicator (where a larger value indicates a lesser tendency toward spontaneous combustion), the cost-type indicator must be converted to a benefit-type indicator:

$$\begin{cases} b_{0i}^L = \max(a_i^R) - a_{0i}^R \\ b_{0i}^R = \max(a_i^R) - a_{0i}^L \end{cases} \tag{7}$$

In Equation (7), $\max(a_i^R)$ is the upper limit of evaluation indicator i, b_{0i}^L is the lower limit of indicator i after unidirectional processing for the spontaneous combustion tendency evaluation, and b_{0i}^R is the upper limit after unidirectional processing.

Normalization [21]:

$$\begin{cases} y_{0i}^L = \frac{b_{0i}^L - \min(b_i^L)}{\max(b_i^R) - \min(b_i^L)} \\ y_{0i}^R = \frac{b_{0i}^R - \min(b_i^L)}{\max(b_i^R) - \min(b_i^L)} \end{cases} \tag{8}$$

In Equation (8), $\min(b_i^L)$ is the lower limit of evaluation indicator i, and $\max(b_i^R)$ is its upper limit. y_{0i}^L is the lower limit of evaluation indicator i after normalization, and y_{0i}^R is its upper limit after normalization.

The set of classification criteria U in matrix X is also subjected to unidirectional and normalization processing. The resulting analysis matrix Y is [22]:

$$Y = \begin{bmatrix} [y_{01}^L, y_{01}^R] & [y_{02}^L, y_{02}^R] & \cdots & [y_{0n}^L, y_{0n}^R] \\ [y_{11}^L, y_{11}^R] & [y_{12}^L, y_{12}^R] & \cdots & [y_{1n}^L, y_{1n}^R] \\ [y_{21}^L, y_{21}^R] & [y_{22}^L, y_{22}^R] & \cdots & [y_{2n}^L, y_{2n}^R] \\ \cdots & \cdots & [y_{ri}^L, y_{ri}^R] & \cdots \\ [y_{s1}^L, y_{s1}^R] & [y_{s2}^L, y_{s2}^R] & \cdots & [y_{sn}^L, y_{sn}^R] \end{bmatrix} \tag{9}$$

In Equation (9), y_{ri}^L is the lower bound of the r-th-level classification criterion for the i-th evaluation indicator after unidirectional processing and normalization, and y_{ri}^R is its upper bound.

3.2.3. Analysis of Spontaneous Combustion Tendency Levels

By refining the indicators of traditional interval approximation analysis along with the calculation methods for the deviation distance and comprehensive distance from each grade standard, the distance d_{ri} between the i-th evaluation indicator of the calculation vector H_0 and the r-th grade of spontaneous combustion tendency is improved as follows:

$$d_{ri} = \max\left(\left|y_{0i}^L - y_{ri}^L\right|, \left|y_{0i}^R - y_{ri}^R\right|\right) \tag{10}$$

By comparing the distance d_{ri} between indicator i of vector H_0 and each spontaneous combustion tendency grade, the spontaneous combustion tendency grade d_{0i} to which indicator i of H_0 belongs is determined as

$$d_{0i} = \min_{r=1}^{s} d_{ri} \tag{11}$$

The composite distance d_r between vector H_0 and the r-th-level decision vector H_r is

$$d_r = d(H_0, H_r) = \sqrt{\sum_{i=1}^{n} (w_i d_{ri}^2)} \tag{12}$$

Clearly, the spontaneous combustion tendency grade d_0 of the evaluation object's vector H_0 is determined by the minimum distance principle:

$$d_0 = \min_{r=1}^{s} d_r \tag{13}$$

3.3. Analysis of the Reliability of the Spontaneous Combustion Tendency of Sulfide Ores

For the interval vector H_0, the portion of indicator i belonging to grade r is

$$p_{ri} = \begin{cases} 0 & y_{0i}^R \le y_{ri}^L \text{ or } y_{0i}^L \ge y_{ri}^R \\ y_{0i}^R - y_{ri}^L & y_{ri}^L \le y_{0i}^R \le y_{ri}^R \text{ and } y_{0i}^L \le y_{ri}^L \\ y_{ri}^R - y_{0i}^L & y_{ri}^L \le y_{0i}^L \le y_{ri}^R \text{ and } y_{0i}^R \ge y_{ri}^R \\ y_{ri}^R - y_{ri}^L & y_{0i}^R \ge y_{ri}^R \text{ and } y_{0i}^L \le y_{ri}^L \\ y_{0i}^R - y_{0i}^L & y_{0i}^R \le y_{ri}^R \text{ and } y_{0i}^L \ge y_{ri}^L \end{cases} \tag{14}$$

Then, the probability that the entire spontaneous combustion tendency evaluation object belongs to grade r is p_r:

$$p_r = \frac{\sum_{i=1}^{n} (w_i p_{ri})}{\sum_{r=1}^{s} \sum_{i=1}^{n} (w_i p_{ri})} \tag{15}$$

3.4. Comprehensive Classification of the Spontaneous Combustion Tendency of Sulfide Ores

Based on the spontaneous combustion tendency grade r^* of the ore as determined by vector H_0, and by combining this with the probability p_{r^*} that its spontaneous combustion tendency belongs to r^*, which corresponds to the confidence level in Table 2, and by referring to Table 3, the comprehensive grading result for the ore's spontaneous combustion tendency can be obtained. The multidimensional analysis and modeling process for ore spontaneous combustion tendency, based on IAHP and improved interval approximation and including weight analysis, is shown in Figure 2.

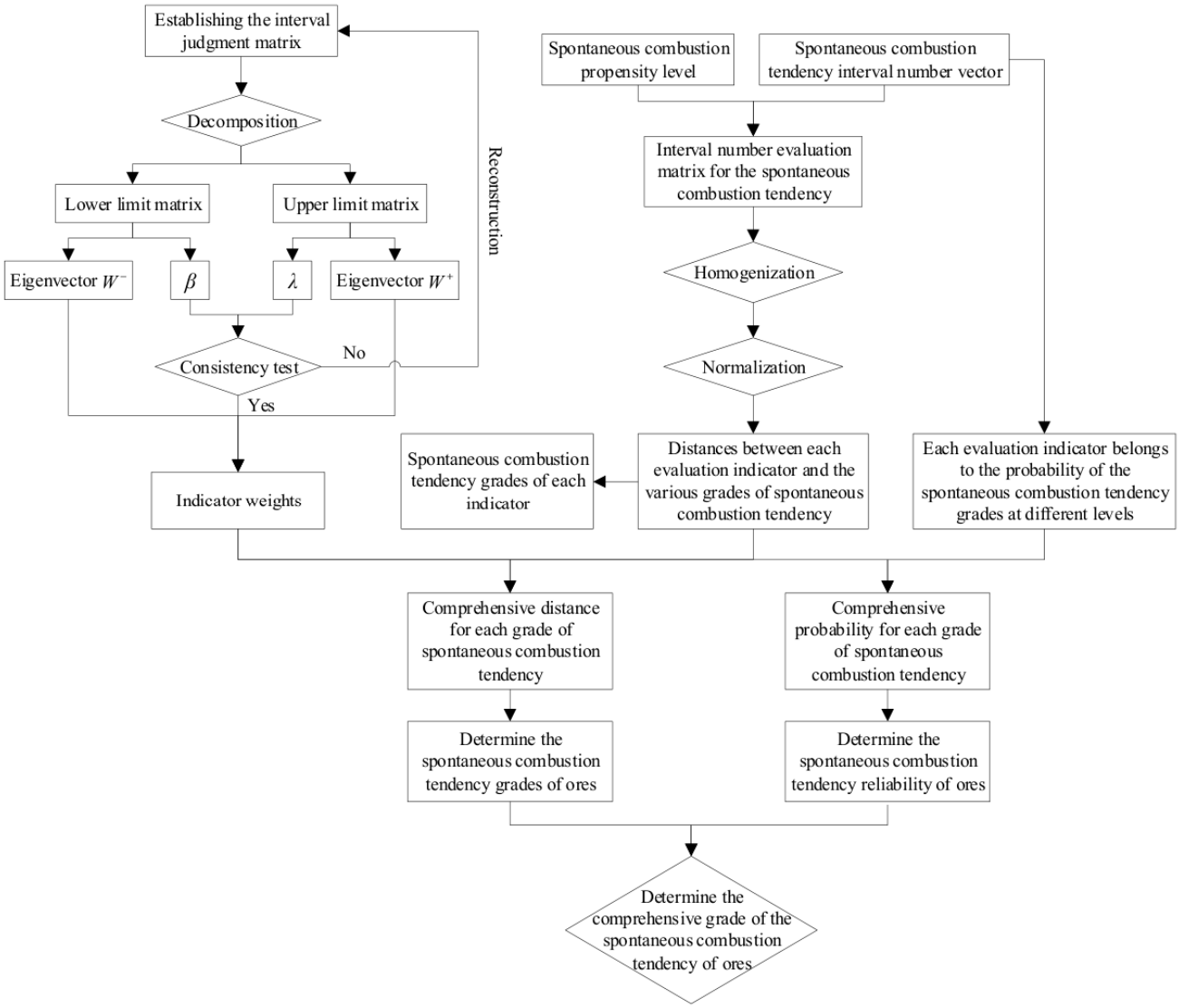


Figure 2. Multidimensional analysis modeling process of ore spontaneous combustion tendency.

4. Empirical Analysis

4.1. Engineering Background

A certain underground pyrite mine in Xinjiang produces 600,000 tons of ore annually. The orebody consists of three gently dipping orebodies—no. 1, no. 2, and no. 3—from top to bottom. The overall sulfur content of the orebody ranges from 24.2% to 28.1%, with the sulfur content in the ore layer no. 1 being significantly higher than that in the ore layers no. 2 and 3. Due to its high sulfur content, multiple spontaneous combustion incidents occurred during the early stages of mining, resulting in severe casualties and resource losses. Due to differences in sulfur and carbon content among the orebodies, the occurrence

and consequences of spontaneous combustion incidents varied. To implement targeted measures to prevent ore spontaneous combustion, it is proposed to analyze and determine the spontaneous combustion tendency of each ore layer. After sampling multiple locations in each ore layer, experimental analyses were conducted based on the assessment criteria in Table 1. The results of the spontaneous combustion tendency assessment for each ore layer are presented in Table 4.

Table 4. Statistics on the evaluation indicators of spontaneous combustion of ores in the mine.

Ore Layer Number	Spontaneous Combustion Evaluation Indicator		
	30-Day Oxidation Weight Gain Rate/%	Self-Heating Point/°C	Autoignition Point/°C
Ore layer No. 1	2.3~2.5	82~112	203~278
Ore layer No. 2	1.3~1.6	127~149	260~288
Ore layer No. 3	1.7~2.1	118~137	244~269

4.2. Calculation of Weighting for the Assessment Criteria

Multiple experts were invited to rank the relative importance of the evaluation indicators for assessing the spontaneous combustion of ore. The resulting relative importance relationships, expressed as numerical intervals, are shown in Table 5.

Table 5. Relative importance relationships between various indicators.

Evaluation Indicator	30-Day Oxidation Weight Gain Rate	Self-Heating Point	Autoignition Point
30-day oxidation weight gain rate	1.00~1.00	1.80~2.20	2.10~2.50
Self-heating point	0.45~0.56	1.00~1.00	1.30~1.60
Autoignition point	0.40~0.48	0.63~0.77	1.00~1.00

Based on Table 5, the interval judgment matrix G for the self-ignition evaluation indicator of the ore is

$$G = \begin{bmatrix} [1.00, 1.00] & [1.80, 2.20] & [2.10, 2.50] \\ [0.45, 0.56] & [1.00, 1.00] & [1.30, 1.60] \\ [0.40, 0.48] & [0.63, 0.77] & [1.00, 1.00] \end{bmatrix}$$

Calculations yield $\lambda = 0.94$ and $\beta = 1.06$. The consistency test for matrix G passes, confirming that matrix G is constructed reasonably. Matrix G is decomposed into the lower limit matrix G^- and the upper limit matrix G^+:

$$G^- = \begin{bmatrix} 1.00 & 1.80 & 2.10 \\ 0.45 & 1.00 & 1.30 \\ 0.40 & 0.63 & 1.00 \end{bmatrix}, G^+ = \begin{bmatrix} 1.00 & 2.20 & 2.50 \\ 0.56 & 1.00 & 1.60 \\ 0.37 & 0.77 & 1.00 \end{bmatrix}$$

Solving yields the eigenvector W^- of G^- as (0.5146, 0.2765, 0.2089), and the eigenvector W^+ of G^+ as (0.5123, 0.2796, 0.2081). Based on λ, β, W^-, and W^+, the weights W of the evaluation indicators are calculated according to Equation (5) as (0.5134, 0.2781, 0.2085).

4.3. Evaluation of the Ore Spontaneous Combustion Tendency and Analysis of the Results

4.3.1. Construction and Processing of the Analysis Matrix

For ore layer no. 1, the self-ignition evaluation indicators and the spontaneous combustion tendency classification criteria in Table 1 form the interval matrix for its spontaneous combustion tendency analysis. To facilitate subsequent analysis, upper limits were set for the evaluation indicators based on expert experience (when an indicator value exceeds the limit, it is directly assigned the upper limit): the upper limit for the 30-day oxidation weight gain rate is 3.0, the upper limit for the self-heating point is 400, and the upper limit for the autoignition point is 450. The resulting interval matrix X_1 for the spontaneous combustion tendency analysis of ore layer no. 1 is

$$X_1 = \begin{bmatrix} [2.3, 2.5] & [82, 112] & [203, 278] \\ [2.0, 3.0] & [0, 100] & [0, 220] \\ [1.0, 2.0] & [100, 250] & [220, 350] \\ [0, 1.0] & [250, 400] & [350, 450] \end{bmatrix}$$

The matrix Y_1 after homogenization and normalization is

$$Y_1 = \begin{bmatrix} [0.7667, 0.8333] & [0.7200, 0.7950] & [0.3822, 0.5489] \\ [0.6667, 1.0000] & [0.7500, 1.0000] & [0.5111, 1.0000] \\ [0.3333, 0.6667] & [0.3750, 0.7500] & [0.2222, 0.5111] \\ [0, 0.3333] & [0, 0.3750] & [0, 0.2222] \end{bmatrix}$$

4.3.2. Analysis of the Spontaneous Combustion Tendency Grades of Ores

The deviation distances between each evaluation indicator of the ore's spontaneous combustion tendency and the respective grading criteria were calculated using Equation (10). Subsequently, the grade of each evaluation indicator was determined using Equation (11), as shown in Table 6.

Table 6. Analysis and judgment results of evaluation indicators for the spontaneous combustion tendency for the no. 1 ore layer.

Evaluation Indicator	Offset Distance for Each Grade of Spontaneous Combustion Tendency			Offset Distance Minimum	Judgment Results
	Offset Distance from Grade I	Offset Distance from Grade II	Offset Distance from Grade III		
30-day oxidation weight gain rate	0.1667	0.4333	0.7667	0.1667	Grade I
Self-heating point	0.2050	0.3450	0.7200	0.2050	Grade I
Autoignition point	0.4511	0.1600	0.3822	0.1600	Grade II

According to Table 6, and taking into account the weighting of the indicators, the calculated composite distances from the spontaneous combustion tendency determination vector of ore layer no. 1 to the grade I determination vector are 0.2615, to the grade II determination vector are 0.3672, and to the grade III determination vector are 0.6902. The same analysis was performed for other orebodies, and the spontaneous combustion tendency grades for each indicator in each ore layer are shown in Figure 3.

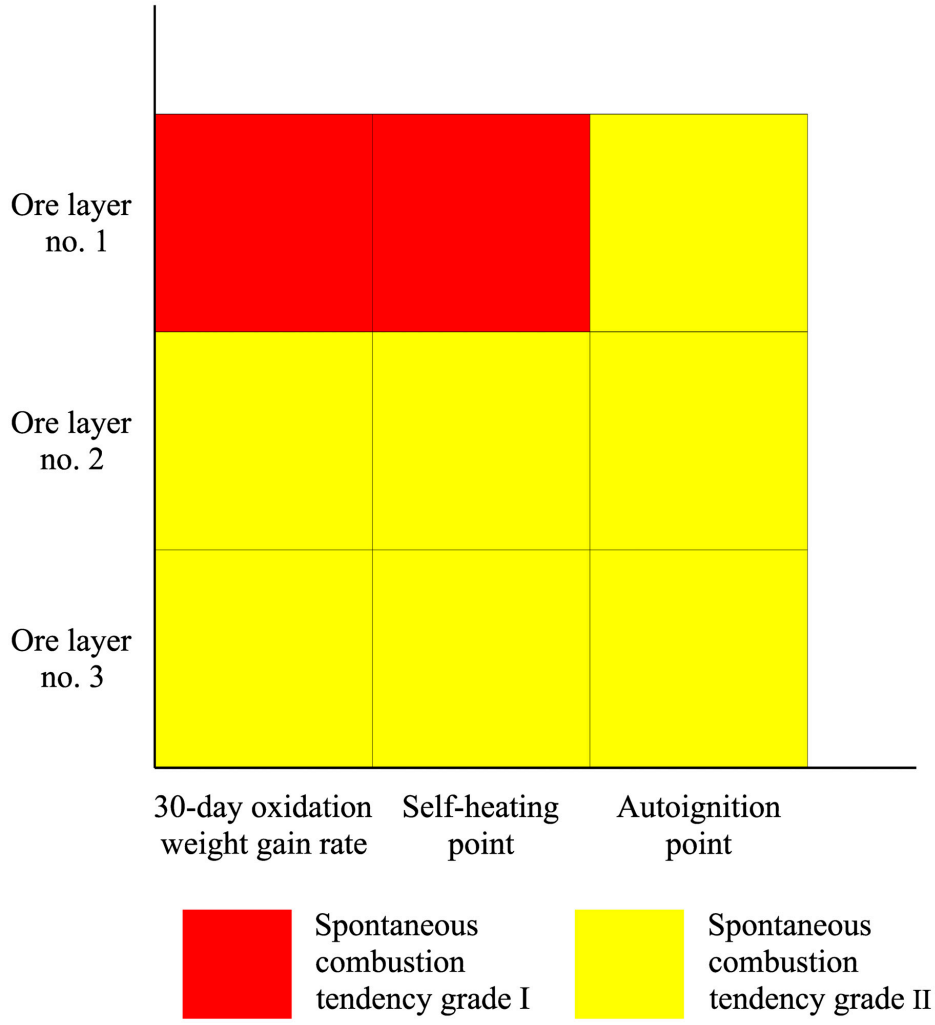


Figure 3. Heat map of evaluation indicator levels for spontaneous combustion tendency of each ore layer.

The comprehensive distances between the spontaneous combustion tendency determination vectors of each ore layer and the determination vectors of each grade, along with the determination results, are shown in Table 7. Based on the analysis results in Table 7, it can be concluded that the ore in ore layer 1 is prone to spontaneous combustion, while the ore in ore layers 2 and 3 is prone to self-heating.

Table 7. Analysis and determination results of spontaneous combustion tendency levels for each ore layer.

Ore Layer	Comprehensive Distance for Each Grade of Spontaneous Combustion Tendency			Minimum Distance	Grade Determination
	Comprehensive Distance from Grade I	Comprehensive Distance from Grade II	Comprehensive Distance from Grade III		
Ore layer no. 1	0.2615	0.3672	0.6902	0.2615	Grade I
Ore layer no. 2	0.4601	0.1755	0.4826	0.1755	Grade II
Ore layer no. 3	0.3491	0.2359	0.5576	0.2359	Grade II

4.3.3. Analysis of the Reliability of the Spontaneous Combustion Tendency of Ores

For ore layer no. 1, calculations based on Equation (14) show that the portion of the 30-day oxidation weight gain rate classified as class I is 0.0667, with 0.0000 for class II and 0.0000 for class III; the portion of the spontaneous combustion tendency at the self-heating point as class I is 0.0450, with 0.0300 for class II and 0.0000 for class III; the portion of the spontaneous combustion tendency at autoignition point as grade I is 0.0378, the portion classified as Grade II is 0.1289, and the portion classified as Grade III is 0. Calculated using Equation (15), the probability that the spontaneous combustion tendency of ore layer no. 1 belongs to Grade I is 60.80%, to Grade II is 39.20%, and to Grade III is 0. Similarly, the membership distribution of the spontaneous combustion tendency evaluation indicators for each ore layer across the different grades can be analyzed, as shown in Figure 4.

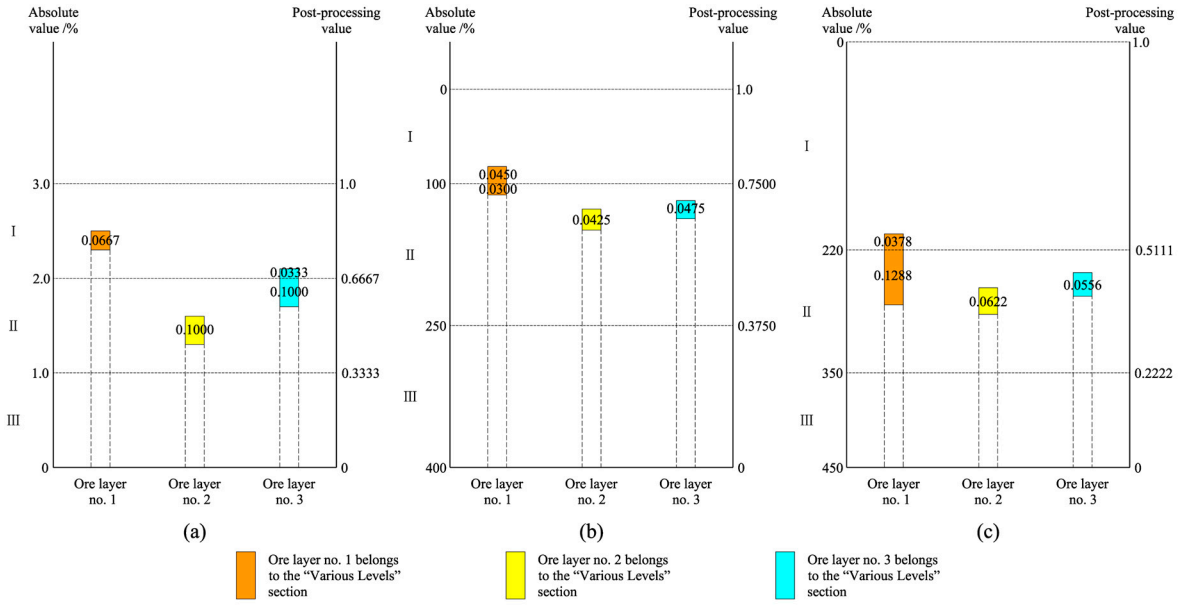


Figure 4. The membership distribution relationship between the evaluation indicators of ore spontaneous combustion tendency: (**a**) 30-day oxidation weight gain rate; (**b**) self-heating point; (**c**) autoignition point.

The probabilities and confidence levels for each ore layer's spontaneous combustion tendency falling into each grade, as calculated, are shown in Table 8.

Table 8. Probability and reliability of spontaneous combustion tendency of each ore layer.

Ore Layer	Spontaneous Combustion Tendency Grade I		Spontaneous Combustion Tendency Grade II		Spontaneous Combustion Tendency Grade III	
	Probability/%	Reliability Grade	Probability/%	Reliability Grade	Probability/%	Reliability Grade
Ore layer no. 1	60.80	Grade II	39.20	Grade III	0	Grade III
Ore layer no. 2	0	Grade III	100	Grade I	0	Grade III
Ore layer no. 3	18.35	Grade III	81.65	Grade I	0	Grade III

4.3.4. Comprehensive Classification of the Spontaneous Combustion Tendency of Ores

The spontaneous combustion tendency grades of each ore layer and their corresponding confidence levels are used to determine a comprehensive classification, as shown in Table 9. As shown in Table 9, the comprehensive classification of the spontaneous com-

bustion tendency for orebodies no. 1, no. 2, and no. 3 in this underground pyrite mine is Grade II, indicating that the consequences of ore self-ignition would be relatively severe.

Table 9. Comprehensive grading of spontaneous combustion tendency of each ore layer.

Ore Layer	Spontaneous Combustion Tendency Grade	Corresponding Confidence Level	Comprehensive Grade
Ore layer no. 1	I	II	II
Ore layer no. 2	II	I	II
Ore layer no. 3	II	I	II

4.4. Analysis and Application of the Results

Based on the results of the weight analysis of ore self-ignition evaluation indicators using the interval-based analytic hierarchy process (AHP), the 30-day oxidation weight gain rate is the most critical factor for assessing ore self-ignition, followed by the self-heating point, and then the autoignition point. As shown in Figure 4, the distribution of the 30-day oxidation weight gain rate across different grades is fully consistent with the spontaneous combustion tendency grades of each ore layer, indicating that the 30-day oxidation weight gain rate has a significant influence on the assessment of ore spontaneous combustion tendency. Therefore, when preventing and controlling the spontaneous combustion of sulfide ores, special attention should be paid to the ore's oxidation weight gain rate, as well as the influence of self-heating points on spontaneous combustion. Ore layers with relatively high oxidation weight gain rates and low self-heating points should be prioritized for prevention.

Analysis using an improved zone approximation method indicates that the ore in the no. 1 underground pyrite seam generally tends to be prone to spontaneous combustion, while the ore layers no. 2 and no. 3 generally tend to be prone to self-heating. The finding that the ore in the no. 1 seam tends to be prone to spontaneous combustion is relatively reliable, whereas the finding that the ore layers no. 2 and no. 3 tend to be prone to self-heating is highly reliable. Based on a comprehensive evaluation of the spontaneous combustion tendency grade and reliability, the ore layers no. 1, no. 2, and no. 3 are classified as grade II, indicating that the consequences of spontaneous combustion would be relatively severe. For the ore layers no. 1, no. 2, and no. 3, relatively strict measures to prevent spontaneous combustion of ore can be adopted, such as pumping out mine pit water, enhancing monitoring of temperature and gas composition, and, if necessary, a water glass-based composite inhibitor can be sprayed locally. In addition, an improved interval approximation analysis was conducted on the evaluation indicators for each ore layer. For ore layer no. 1, the 30-day oxidation weight gain rate and self-heating point indicate a tendency toward easy spontaneous combustion; therefore, long-term, high-frequency, and regular monitoring of the 30-day oxidation weight gain rate and self-heating point is required to prevent and control spontaneous combustion of the ore. However, the autoignition point indicator for ore layer no. 1, as well as the evaluation indicators for ore layers no. 2 and no. 3, all indicate a tendency toward easy spontaneous heating; thus, general preventive measures such as irregular monitoring can be adopted. Ultimately, targeted and differentiated measures for preventing and controlling spontaneous combustion of the ore are implemented based on the overall analysis results of the ore layer and various indicators. After adopting these measures, the incidents of spontaneous combustion of the ore in this mine are reduced by more than 80%, fully demonstrating the accuracy of the evaluation results and the rationality of the measures.

5. Conclusions

(1) The comprehensive classification of sulfide ore spontaneous combustion tendency, based on the classification levels and reliability of spontaneous combustion tendency, innovates the classification standards for sulfide ore spontaneous combustion tendency. It enables a multidimensional analysis of sulfide ore spontaneous combustion tendency and provides a foundation and basis for a comprehensive and in-depth analysis of this phenomenon.

(2) By employing the interval-based analytic hierarchy process (AHP) to accommodate differences in experts' perceptions of the relative relationships among indicators, we analyzed the relative relationships of ore spontaneous combustion evaluation indicators. The results revealed that the 30-day oxidation weight gain rate has the most significant impact on ore spontaneous combustion, followed by the influence of self-heating points, while the influence of the autoignition point is the least significant. The method for calculating indicator weights better aligns with objective reality, and the resulting weights are more reliable, ensuring the accuracy of the analysis results regarding the spontaneous combustion tendency of the ore.

(3) Using improved interval approximation analysis, a comprehensive analysis of the spontaneous combustion tendency grades of sulfide ores is conducted in the form of interval numbers. Based on a case study of a certain underground pyrite mine, the analysis concluded that the ore in seam no. 1 is prone to spontaneous combustion, and this conclusion is relatively reliable, while the ore in seams no. 2 and No. 3 is prone to self-heating, and this conclusion is highly reliable. Combining the spontaneous combustion tendency analysis results of each evaluation indicator, targeted preventive measures against ore self-ignition are implemented for each ore layer and each indicator. The improved interval approximation analysis enables a comprehensive and in-depth analysis of the spontaneous combustion tendency of sulfide ores, providing guidance and assistance for the efficient and precise prevention and control of ore self-ignition hazards.

Author Contributions: Conceptualization, H.X. and D.Z.; methodology, H.Y. and Y.Z.; validation, L.Y.; writing—original draft preparation, H.X.; writing—review and editing, D.Z., H.Y. and L.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 52074116 (Daobing Zhang). The financial support is greatly appreciated.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the complexity of the data.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Yang, F.; Chen, B. Application of attribute interval recognition model to comprehensive assessment of spontaneous combustion tendency of sulfide ores. *China Saf. Sci. J.* **2012**, *22*, 70–75. [CrossRef]
2. Li, M.; Song, X.; Pan, W.; Li, Z. Inhibition mechanism and performance evaluation of solid inhibitor for sulfide ore. *J. Nat. Disasters* **2023**, *32*, 91–98. [CrossRef]
3. Wu, Q.; Li, X.; Weng, L.; Li, Q.; Zhu, Y.; Luo, R. Experimental investigation of the dynamic response of prestressed rockbolt by using an SHPB-based rockbolt test system. *Tunn. Undergr. Space Technol.* **2019**, *93*, 103088. [CrossRef]
4. Zhang, Y.; Guo, Q.; Zhang, Y.; Li, Y.; Sun, Y. Correlation analysis and prediction of coalspontaneous combustion risk based on correlation coefficient method. *China Saf. Sci. J.* **2024**, *34*, 125–132. [CrossRef]
5. Zhou, B.; Wu, A. Application of comprehensive fire prediction method in metal mines. *Nonferrous Mines* **1999**, 18–21.
6. Yang, F.; Wu, C.; Li, Z. Matter-element model and its application to comprehensive determination on spontaneous combustion tendency of sulfide ores. *J. Cent. South Univ.* **2011**, *42*, 3459–3464.

7. Huang, G.; Guo, H.; Luo, J.; Zhang, X.; Ding, H.; Tang, X. Spontaneous combustion tendency evaluation of sulfide ores based on AHP-TOPSIS evaluation model. *Min. Saf. Environ. Prot.* **2016**, *43*, 50–53.
8. Li, Z.; Wang, F.; Ma, S. Safety assessment of the spontaneous combustion tendency of sulfide ores based on AHP and SPA. *Sci. Technol. Rev.* **2009**, *27*, 69–73.
9. Jiang, A.; Zhang, D.; Wang, F.; Dong, Y.; Zhang, J.; Cai, W.; Yin, H.; Fu, R. Investigation into the causal mechanisms and deduction model for explosion risks in coal and gas tunnel construction. *J. Saf. Environ.* **2025**, *25*, 476–487. [CrossRef]
10. Jiang, F.; Jin, F.; Zhang, X.; Yang, H.; Wang, H.; Sheng, B. Economic benefit evaluation of coal mine safety input based on Choquet fuzzy integral. *China Saf. Sci. J.* **2024**, *34*, 76–82. [CrossRef]
11. Ma, C.; Jin, A.; Wang, Z.; Chen, S.; Zheng, Y. Integrating multi-source numerical simulation data with multi-criteria decision-makingfor stability assessment of open-pit mine slopes. *Chin. J. Eng.* **2026**, *48*, 1220–1231. [CrossRef]
12. Yuan, S.; Wang, J.; Zhang, W.; Han, C.; Wang, G.; Jia, D.; Liu, L.; Guo, H. Evaluation system of grouting effect of coal seam floor based on TOPSIS-RSR method with combination weighting. *J. Min. Strat. Control Eng.* **2024**, *6*, 033537. [CrossRef]
13. He, W.; Zeng, J.; Zhang, J.; Namaiti, A.; Shi, W.; Song, Y.; Tian, J. Dynamic urban flood risk assessment based on human activity patterns: An IFAHP-EWM-TOPSIS approach. *Sustain. Cities Soc.* **2025**, *133*, 106832. [CrossRef]
14. Pinheiro, B.C.; de Mello Sant'Ana, P.H. AHP-based decision making to selecting energy-efficient air conditioning equipaments in a commercial building. *Energy Build.* **2025**, *329*, 115281. [CrossRef]
15. He, Y.; Zhao, G.; Tang, Y.; Song, J.; Chen, Y. Available target evaluation of underground gas storage based on AHP-FCE methods. *Geoenergy Sci. Eng.* **2024**, *242*, 213255. [CrossRef]
16. Li, S.; Ma, B.; Wang, C. Research on risk assessment of prefabricated building construction based on Cov-AHP and cloud model. *J. Xi'an Univ. Technol.* **2024**, *40*, 429–437. [CrossRef]
17. Wu, Q.; Xie, C.; Xie, Y.; Zhao, Y.; Li, X.; Liu, J.; Weng, L. Extending application of asymmetric semi-circular bend specimen to investigate mixed mode I/II fracture behavior of granite. *J. Cent. South Univ.* **2022**, *29*, 1289–1304. [CrossRef]
18. Wang, X.; Shu, P.; Cao, L. Incremental-AHP-based weight assessment for risk factors of civil aircraft landing process. *China Saf. Sci. J.* **2010**, *20*, 112–115. [CrossRef]
19. Mao, Q. Weighted interval approximations of fuzzy numbers. *J. Jimei Univ.* **2019**, *24*, 231–233. [CrossRef]
20. Yang, Y.; Chen, G.; Wang, D. A security risk assessment method based on improved FTA-IAHP for train position system. *Electronics* **2022**, *11*, 2863. [CrossRef]
21. Tian, B.; Liu, C. Airport emergency capacity assessment model based on an interval-number analytic hierarchy process. *China Saf. Sci. J.* **2011**, *21*, 170–176. [CrossRef]
22. Li, X.; Wei, H.; Wang, J. Interval non-probabilistic reliability analysis of support structures for deep tunnel. *China Saf. Sci. J.* **2023**, *33*, 67–76. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.