sustainability

MDPI

Article

Evaluation Cloud Model of Spontaneous Combustion Fire Risk in Coal Mines by Fusing Interval Gray Number and DEMATEL

Kun Xu [1,2], Shuang Li [1,2,*], Jiao Liu [1,2], Cheng Lu [1,2], Guangzhe Xue [1,2], Zhengquan Xu [1,2] and Chao He [1,2]

[1] School of Economics and Management, China University of Mining and Technology, Xuzhou 221116, China
[2] Safety Science and Emergency Management Research Institute, China University of Mining and Technology, Xuzhou 221116, China
[*] Correspondence: lishuangchina@cumt.edu.cn

Abstract: Coal still occupies a key position in China's energy consumption structure, and ensuring safe production in coal mines is a key focus for ensuring energy security. Spontaneous combustion fires in coal mines are a serious threat to the sustainability of safe production in coal mines. In order to prevent coal mine fire risk scientifically and effectively and to assess the level of disaster risk effectively and rationally, a study was conducted on the risk of spontaneous combustion fires in underground coal mines. An evaluation cloud model of spontaneous combustion fire risk in coal mines integrating the interval gray number with the Decision-Making Trial and Evaluation Laboratory (DEMATEL) was established. Seventeen representative risk evaluation indicators were selected, and a coal mine spontaneous combustion fire risk evaluation index system was constructed based on four aspects: personnel, machinery, environment, and management. The interval gray number theory was introduced to improve the classical DEMATEL analysis method, which fully expresses the expert empirical knowledge and solves the problem of ambiguity and randomness in the semantic expression of expert evaluation. The relative importance of each indicator was determined by analyzing the influence relationships between risk evaluation indicators through the improved DEMATEL. A cloud model capable of transforming quantitative descriptions and qualitative concepts was used for comprehensive evaluation of risk, and based on the results of DEMATEL analysis, a comprehensive evaluation cloud model of coal mine spontaneous combustion fire risk was formed. Finally, the validity and practicality of the model were verified by using a mine in Shenmu City, Shaanxi Province, China as an example. This study provides a powerful tool to prevent spontaneous combustion fires in coal mines and makes a positive contribution to the sustainable development of coal mine safety management.

Keywords: coal mine; fire; risk evaluation; interval gray number; DEMATEL; cloud model

check for updates

Citation: Xu, K.; Li, S.; Liu, J.; Lu, C.; Xue, G.; Xu, Z.; He, C. Evaluation Cloud Model of Spontaneous Combustion Fire Risk in Coal Mines by Fusing Interval Gray Number and DEMATEL. *Sustainability* **2022**, *14*, 15585. https://doi.org/10.3390/su142315585

Academic Editor: Adam Smoliński

Received: 16 October 2022
Accepted: 17 November 2022
Published: 23 November 2022

1. Introduction

Coal still accounts for a large proportion of China's energy consumption structure, and coal mine spontaneous combustion fires threaten the sustainability of safe production in coal mines [1,2]. Large amounts of coal are frozen due to mine fires, disrupting rational mining deployments and causing serious economic and human casualty losses [3,4]. Scientific and effective risk evaluation of coal mine spontaneous combustion fires is the key to prevent spontaneous combustion fires in coal mines [5,6]. Therefore, it is necessary and practical to study comprehensive evaluation of the risk of spontaneous combustion fires in coal mines, which provides a positive contribution to the sustainable development of coal mine safety management.

In order to evaluate the risk of spontaneous combustion fires in coal mines in a more scientific and reasonable manner, it is first necessary to establish an evaluation index system that can fully characterize the overall risk level. Yu et al. proposed an evaluation system containing 11 indicators to analyze the main factors affecting the risk level in five aspects, including the fire-prone nature of coal, foal seam occurrence, mining technique, fire prevention and control measures [7]. Guo et al. established an evaluation index system containing five aspects, such as underground electromechanical equipment and fuel, coal spontaneous combustion tendency, coal structure failure, safety management, and fire control systems [8]. More scholars have constructed the corresponding evaluation index system from the perspectives of personnel, mechanical equipment, environment, and management [9–11]. In general, it shows that it is reasonable to analyze the evaluation indexes of coal mine spontaneous combustion fire risk from these four aspects.

Different risk evaluation indicators have different degrees of influence on the overall risk level of the evaluation object, i.e., there is variability in the importance of the indicators [12,13]. Therefore, how to reasonably determine the weights of each indicator in the index system is the second problem that needs to be solved [14,15]. Experts' empirical knowledge is still the key means to judge the importance of indicators, and the commonly used methods for determining indicator weights include hierarchical analysis, network hierarchy analysis, etc. [16–18]. However, such methods cannot fully characterize some fuzzy semantic expressions of experts' opinions. The interval gray number is derived from the gray theory proposed by Chinese scholar Deng Julong in 1982, which can effectively represent the evaluation behavior with certain fuzziness in the form of intervals and fully express the experts' judgments as a certainty index [19–21]. The DEMATEL model was proposed by American scholars in 1971 for making full use of expert knowledge in complex systems to accurately identify and analyze the relationships among various factors within the system [22,23]. The method has obvious advantages and important uses, but it also has the limitations of inadequate expression of experts' empirical knowledge and inaccurate expression of experts' fuzzy judgments. Therefore, introducing the interval gray number into the traditional DEMATEL model can effectively attenuate the limitations of the original method and improve the accuracy and credibility of the analysis model. Combining the interval gray number with the DEMATEL method, which is suitable for analyzing the influence relationships between factors in complex systems, can better represent the relative importance of each indicator in the index system.

The third problem to be faced is how to get the comprehensive risk evaluation level of the evaluation object by combining the weights of each index while considering different experts' evaluation opinions. In terms of comprehensive risk evaluation, scholars commonly use fuzzy comprehensive evaluation (FCE), TOPSIS, and machine learning evaluation methods. The FCE method is a mathematical method based on the ideas and methods of fuzzy mathematics, which enables comprehensive evaluation of fuzzy defined objects [24]. The TOPSIS method is an evaluation method that ranks a finite number of evaluation objects according to their proximity to an idealized target by detecting the distance between the evaluation object and the optimal solution and the worst solution [25]. The machine learning evaluation method mainly uses artificial intelligence algorithms such as artificial neural networks, support vector machines, and random forests to classify and evaluate evaluation objects with the support of large-scale data [26]. The above methods have the limitations of being more subjective, complicated to calculate, less sensitive, or having a larger sample data requirement [27–30]. The cloud model theory is intended to realize the transformation of quantitative evaluation data and qualitative expression by calculating the distribution of index data and forming a cloud map of converging cloud drops [31,32]. It is a composite uncertainty mathematical theory model based on probability statistics and fuzzy mathematics, which can fully reflect the evaluation opinions of several experts and take into account the randomness and fuzziness of the evaluation system while realizing the transformation between quantitative description and qualitative concepts [33–35].

This study involved constructing a coal mine spontaneous combustion fire risk evaluation index system, introducing gray theory to realize the quantitative transformation of experts' fuzzy evaluation opinions so as to determine the risk evaluation index weights, adopting cloud model theory to realize the transformation between quantitative evaluation data and qualitative evaluation levels, and finally forming a cloud model of coal mine spontaneous combustion fire risk evaluation integrating the interval gray number and

DEMATEL. The objective of this study is to help coal mines evaluate the level of spontaneous combustion fire risk accurately and effectively through the established evaluation index system and the proposed new coal mine spontaneous combustion fire risk evaluation model in order to advance safety control measures to prevent spontaneous combustion fire accidents and promote the sustainable development of coal mine safety and production capacity. The main contributions of this study are as follows:

(1) An evaluation index system that can comprehensively reflect the level of spontaneous combustion fire risk in coal mines was constructed from four aspects: personnel, mechanical equipment, environment, and management.

(2) The influence relationship between risk evaluation indicators was analyzed by fusing the interval gray number and DEMATEL, and the weights of the risk evaluation indicators were determined based on the centrality of the indicators.

(3) The effectiveness and practicality of the proposed evaluation model were verified by comparing different evaluation methods with a mine as a case study.

2. Materials and Method

2.1. Construction of Coal Mine Spontaneous Combustion Fire Risk Evaluation Index System

Spontaneous combustion fires in coal mines are a serious threat to safe production in coal mines, and the construction of a scientific and reasonable index system for evaluating the risk of spontaneous combustion fires in coal mines is of great significance to the evaluation and prevention of this type of disaster. In order to select a reasonable index that can fully reflect the level of spontaneous combustion fire risk in coal mines, this paper analyzed the main influencing factors affecting the risk of spontaneous combustion fires in coal mines from the perspective of the system in four aspects: personnel factors, equipment factors, environmental factors, and management factors. Combined with the research results of related literature [6,7,36,37], the indicators with high repetitiveness or meaninglessness were combined or deleted, and finally four first-order indicators as well as 17 s-order indicators were identified. The details are shown in Figure 1.

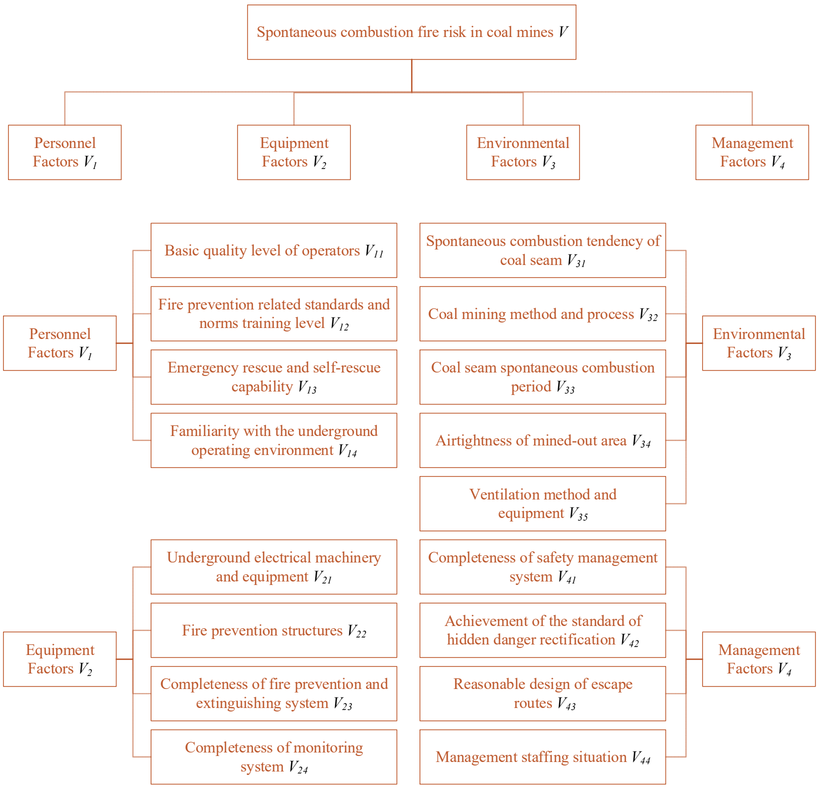

Figure 1. Coal mine spontaneous combustion fire risk evaluation index system.

2.2. Construction of the Evaluation Cloud Model of Coal Mine Spontaneous Combustion Fire Risk by Fusing Interval Gray Number and DEMATEL

2.2.1. DEMATEL Model Incorporating Interval Gray Number

(1) Construction of the interval gray number relationship matrix

Based on the fire risk evaluation index system established above, experts were invited to evaluate the interactions between different indicators based on their own experience. The experts compared the indicators two by two, and the semantic variables evaluated by the experts and the corresponding interval gray numbers are shown in Table 1.

Table 1. Optimization results of three algorithms on test functions.

Serial Number	Semantic Variable Interval	Semantic Expression	Relative Interval Gray Number Range
1	[0,1)	Extremely weak impact	[0,0]
2	[1,2)	Weak impact	[0,0.25]
3	[2,3)	Moderate impact	[0.25,0.5]
4	[3,4)	Strong impact	[0.5,0.75]
5	[4,5)	Very strong impact	[0.75,1]

(2) Construction of the direct influence matrix

The evaluation data of experts are transformed by the interval gray number to form the gray relation matrix, and then defuzzification is carried out on the expert survey data according to Table 1. The specific steps are as follows:

① Standardization of the upper and lower bounds of the interval gray number:

$$\underline{\oplus}\tilde{a}_{ij}^{k} = \frac{\underline{\oplus}a_{ij}^{k} - \min\underline{\oplus}a_{ij}^{k}}{\Delta_{\min}^{\max}} \tag{1}$$

$$\overline{\oplus}\tilde{a}_{ij}^{k} = \frac{\overline{\oplus}a_{ij}^{k} - \min\overline{\oplus}a_{ij}^{k}}{\Delta_{\min}^{\max}} \tag{2}$$

$$\Delta_{\min}^{\max} = \max\overline{\oplus}a_{ij}^{k} - \min\underline{\oplus}a_{ij}^{k} \tag{3}$$

where $\overline{\oplus}a_{ij}^{k}$ and $\underline{\oplus}a_{ij}^{k}$ denote the upper and lower bounds of the k-th expert's evaluation of the influence of factor i on factor j, respectively, after being transformed into the interval gray number, $\overline{\oplus}\tilde{a}_{ij}^{k}$ and $\underline{\oplus}\tilde{a}_{ij}^{k}$ denote the upper and lower bounds after normalization.

② Calculation of clear values:

$$b_{ij}^{k} = \frac{\underline{\oplus}\tilde{a}_{ij}^{k}\left(1 - \underline{\oplus}\tilde{a}_{ij}^{k}\right) + \left(\overline{\oplus}\tilde{a}_{ij}^{k} \cdot \overline{\oplus}\tilde{a}_{ij}^{k}\right)}{1 - \underline{\oplus}\tilde{a}_{ij}^{k} + \overline{\oplus}\tilde{a}_{ij}^{k}} \tag{4}$$

$$\mathrm{c}_{ij}^{k} = \min\underline{\oplus}a_{ij}^{k} + b_{ij}^{k}\Delta_{\min}^{\max} \tag{5}$$

③ Establishment of the direct influence matrix:

$$C = \frac{\sum_{1}^{k}\mathrm{c}_{ij}^{k}}{k} \tag{6}$$

(3) Construction of the comprehensive influence matrix

① Normalization of the direct influence matrix:

$$G = \frac{C}{\max_{i \le n}\sum_{j=1}^{n} C_{ij}} \tag{7}$$

② Establishment of the comprehensive influence matrix:

$$X = G(I - G)^{-1} \tag{8}$$

(4) Calculation of centrality and cause degree

① Calculation of influence degree and influenced degree of indicators:

$$\begin{cases} d_i = \sum\limits_{j=1}^{n} x_{ij} \\ r_i = \sum\limits_{i=1}^{n} x_{ij} \end{cases} \tag{9}$$

② Calculation of the centrality and the cause degree of each indicator:

$$\begin{cases} f_i = d_i + r_i \\ e_i = d_i - r_i \end{cases} \tag{10}$$

(5) Plotting the distribution of cause degree and centrality

The value of centrality indicates the importance of the indicator. If the value of cause degree is greater than zero, it means that the indicator influences other indicators as the cause, and if it is less than zero, it means that the indicator is influenced by other indicators. With the centrality as the horizontal coordinate and the cause degree as the vertical coordinate, the distribution of risk evaluation indexes by cause degree and centrality can be drawn.

(6) Calculation of the comprehensive weight of indicators

The centrality values calculated from the interval gray number DEMATEL model are normalized to obtain the corresponding weights of the evaluation indexes.

$$W_i = \frac{f_i}{\sum\limits_{1}^{n} f_i} \tag{11}$$

2.2.2. Cloud Model for Spontaneous Combustion Fire Risk Evaluation in Coal Mines

The cloud model was proposed by a Chinese scholar, Deyi Li, in 1993 [38,39]. It is a method that can represent the spatial state of a concept by numerical features and that can realize the mapping and conversion work between qualitative and quantitative representations, i.e., forward cloud generator and backward cloud generator. The cloud model can solve the problem of linguistic randomness and fuzziness in evaluation representation. Considering the above characteristics of expert empirical knowledge in coal mine spontaneous combustion fire risk evaluation, the cloud model was chosen to be used for the transformation assessment.

(1) According to the established index system, m experts are invited to score the n indicators, forming an evaluation matrix V with m rows and n columns, where V_{ij} represents the score of the i-th expert for the j-th indicator. $i = 1, 2, 3, \cdots, m$; $j = 1, 2, 3, \cdots, n$.

(2) The core of cloud model theory is to use the three values of expectation The core of cloud model theory is to use the three values of expectation (Ex), entropy (En), and super entropy (He) to describe the characteristics of clouds, reflecting the overall characteristics of qualitative problems. The numerical characteristics of clouds can generate cloud drops, which are accumulated and formed as clouds to realize the mapping between qualitative representation and quantitative description. The discourse domain (U) is divided into five corresponding subintervals according to the evaluation criteria level. The numerical characteristics of the standard cloud corresponding to the subintervals are calculated as follows:

$$Ex = \frac{x_{\max} + x_{\min}}{2} \tag{12}$$

$$En = \frac{x_{\max} - x_{\min}}{2\sqrt{2\ln 2}} \tag{13}$$

$$He = s \tag{14}$$

where $x_{\max}$ and $x_{\min}$ denote the upper and lower boundaries of the interval, respectively; s is a constant, and the larger the value, the greater the dispersion of the cloud droplets; here, the value is 0.5.

(3) Calculate the numerical characteristics of the evaluation cloud corresponding to the j-th index value.

$$Ex_j = \frac{1}{n}\sum_{i=1}^{n} V_{ij} \tag{15}$$

$$En_j = \sqrt{\frac{\pi}{2}}\frac{1}{n}\sum_{i=1}^{n}\left|V_{ij} - Ex_j\right| \tag{16}$$

$$S_j^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left[V_{ij} - Ex_j\right]^2 \tag{17}$$

$$He_j = \sqrt{S_j^2 - En_j^2} \tag{18}$$

where Ex_j, En_j, S_j^2 and He_j are the expectation, entropy, variance, and hyperentropy of the j-th indicator, respectively.

(4) Combining the index weights W_j, the numerical characteristics of the comprehensive evaluation cloud are calculated.

$$Ex = \frac{\sum_{j=1}^{n} W_j Ex_j}{\sum_{j=1}^{n} W_j} \tag{19}$$

$$En = \frac{\sum_{j=1}^{n} W_j^2 En_j}{\sum_{j=1}^{n} W_j^2} \tag{20}$$

$$He = \frac{\sum_{j=1}^{n} W_j^2 He_j}{\sum_{j=1}^{n} W_j^2} \tag{21}$$

2.3. Basic Information about the Case Mine Site

Coal spontaneous combustion fire is an important threat to coal mine safety. In this study, eight industry experts were invited to analyze and score the indicators of the established index system based on a coal mine located in Shenmu, Shaanxi Province, China.

2.3.1. Determine the Standard Cloud Feature Parameters

According to the project data material, combined with the knowledge of the coal mine and referring to relevant literature, the risk evaluation domain of coal mine spontaneous combustion fires is divided into five subintervals: low risk, relatively low risk, medium risk, relatively high risk, and high risk. The evaluation value range of the subintervals is shown in Table 2, and the characteristic parameters of the risk evaluation standard cloud of the project can be calculated according to as Formulas (12) to (14), and the standard cloud graph can be drawn using MATLAB programming; see Figure 2.

Table 2. The interval range of the discourse domain and the characteristic parameters of the standard clouds.

Evaluation Level	Range of Interval	Characteristic Parameters of Standard Clouds		
		Ex	***En***	***He***
low risk	[0,10)	5	4.25	0.5
relatively low risk	[10,25)	17.5	6.37	0.5
medium risk	[25,55)	40	12.74	0.5
relatively high risk	[55,90)	72.5	14.86	0.5
high risk	[90,100)	95	4.25	0.5

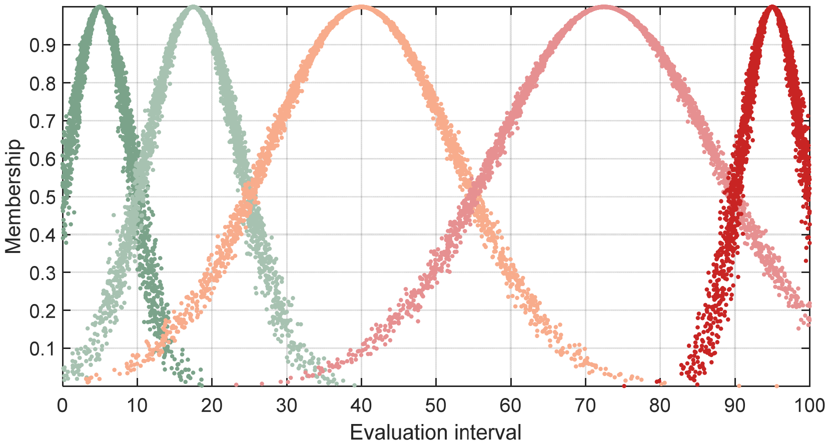

Figure 2. Standard cloud state diagram.

2.3.2. Basic Data for DEMATEL Analysis

Eight experts in the industry were invited to score the 17 risk evaluation indicators based on the project data information as well as their judgment of the situation. The specific scoring is shown in Table 3.

Table 3. Expert assessment scores for the case coal mine.

Indicators	Expert Evaluation Scores							
	No. 1	**No. 2**	**No. 3**	**No. 4**	**No. 5**	**No. 6**	**No. 7**	**No. 8**
V_{11}	8	12	13	2	8	2	9	10
V_{12}	15	22	12	19	13	16	21	11
V_{13}	9	4	10	2	10	16	9	16
V_{14}	26	26	23	22	29	23	28	24
V_{21}	23	21	16	25	23	27	17	26
V_{22}	20	26	26	24	22	17	16	14
V_{23}	8	6	2	9	9	6	1	10
V_{24}	15	14	16	21	11	15	21	14
V_{31}	50	54	46	43	56	47	49	53
V_{32}	20	21	19	24	14	13	25	15
V_{33}	30	35	29	29	34	28	30	35
V_{34}	26	25	25	19	22	20	24	25
V_{35}	10	7	14	13	7	9	5	4
V_{41}	9	12	8	5	15	11	11	7
V_{42}	8	2	10	6	6	7	13	4
V_{43}	7	5	7	7	1	7	2	11
V_{44}	8	13	6	5	14	13	7	10

3. Results

3.1. Determining the Comprehensive Weights of Indicators

3.1.1. Calculation of DEMATEL Analysis Data Based on Interval Gray Number

Eight experts in the industry evaluated the impact relationships between the 17 indicators based on their own experiences. The direct influence matrix of the indicators was established based on Formulas (1) to (6). The calculation results are shown in Table 4.

Table 4. Direct influence matrix *C*.

Indicators	V_{11}	V_{12}	V_{13}	V_{14}	$\cdots$	V_{41}	V_{42}	V_{43}	V_{44}
V_{11}	0.0000	0.1667	0.2969	0.4531	$\cdots$	0.2917	0.2969	0.0000	0.2083
V_{12}	0.2578	0.0000	0.8333	0.5000	$\cdots$	0.5469	0.6500	0.1406	0.4141
V_{13}	0.2917	0.3333	0.0000	0.4625	$\cdots$	0.2917	0.2083	0.5078	0.5000
V_{14}	0.2500	0.1667	0.6667	0.0000	$\cdots$	0.0000	0.0000	0.0000	0.0000
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
V_{41}	0.3333	0.5375	0.5859	0.2917	$\cdots$	0.0000	0.3359	0.4141	0.7422
V_{42}	0.0000	0.2500	0.5859	0.0000	$\cdots$	0.4141	0.0000	0.4531	0.2500
V_{43}	0.0000	0.0000	0.7031	0.0000	$\cdots$	0.2500	0.3750	0.0000	0.0000
V_{44}	0.2917	0.3359	0.7500	0.2917	$\cdots$	0.3333	0.5750	0.2917	0.0000

The comprehensive influence matrix is established according to Formulas (7) and (8), and then the influence degree, influenced degree, cause degree and centrality of each index are calculated according to Formulas (9) and (10). The calculation results are shown in Tables 5 and 6. Figure 3 shows the distribution of the cause degree and centrality of the evaluation indicators.

Table 5. Comprehensive influence matrix *X*.

Indicators	V_{11}	V_{12}	V_{13}	V_{14}	$\cdots$	V_{41}	V_{42}	V_{43}	V_{44}
V_{11}	0.0312	0.0639	0.0660	0.4531	$\cdots$	0.0482	0.0491	0.0163	0.0380
V_{12}	0.0214	0.1522	0.0819	0.5000	$\cdots$	0.0913	0.1030	0.0516	0.0757
V_{13}	0.0558	0.0604	0.0755	0.4625	$\cdots$	0.0641	0.0539	0.0951	0.0803
V_{14}	0.0269	0.0952	0.0103	0.0000	$\cdots$	0.0092	0.0085	0.0110	0.0097
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
V_{41}	0.0846	0.1421	0.0612	0.2917	$\cdots$	0.0355	0.0749	0.0919	0.1149
V_{42}	0.0449	0.1260	0.0181	0.0000	$\cdots$	0.0766	0.0257	0.0925	0.0517
V_{43}	0.0096	0.1029	0.0093	0.0000	$\cdots$	0.0413	0.0548	0.0155	0.0130
V_{44}	0.0590	0.1504	0.0576	0.2917	$\cdots$	0.0711	0.0966	0.0743	0.0256

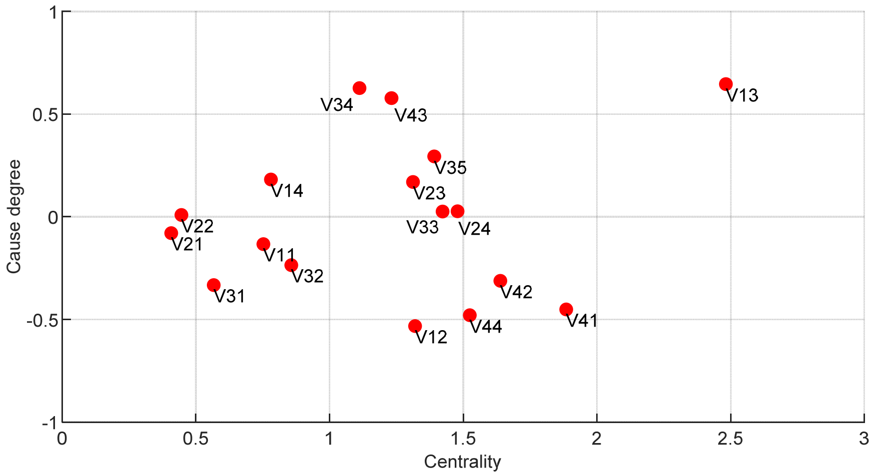

Figure 3. Distribution of evaluation indicators cause degree and centrality.

Table 6. Centrality and cause degree of indicators.

Indicators	Influence Degree d_i	Influenced Degree r_i	Centrality f_i	Cause Degree e_i
V_{11}	0.3097	0.4429	0.7526	−0.1332
V_{12}	0.3937	0.9263	1.3199	−0.5326
V_{13}	1.5641	0.9179	2.4820	0.6462
V_{14}	0.4810	0.2996	0.7805	0.1814
V_{21}	0.1639	0.2438	0.4077	−0.0798
V_{22}	0.2274	0.2185	0.4459	0.0089
V_{23}	0.7407	0.5713	1.3120	0.1694
V_{24}	0.7526	0.7259	1.4785	0.0267
V_{31}	0.1171	0.4498	0.5669	−0.3327
V_{32}	0.3106	0.5464	0.8570	−0.2357
V_{33}	0.7241	0.6984	1.4225	0.0258
V_{34}	0.8692	0.2427	1.1119	0.6264
V_{35}	0.8427	0.5487	1.3914	0.2940
V_{41}	0.7167	1.1682	1.8850	−0.4515
V_{42}	0.6635	0.9753	1.6388	−0.3118
V_{43}	0.9047	0.3268	1.2315	0.5779
V_{44}	0.5223	1.0019	1.5242	−0.4796

3.1.2. Calculation of the Comprehensive Weight of Indicators

Based on the analytical calculation results of the interval gray number DEMATEL, the comprehensive weights of the indicators are calculated based on the centrality of the indicators. The comprehensive weights of the indicators are calculated according to Formula (11). The calculation results are shown in Table 7.

Table 7. Calculation results of comprehensive weights of indicators.

Secondary Indicators	Weights	Tertiary Indicators	Weights
Personnel factors	0.2589	Basic quality level of operators	0.0365
		Fire prevention related standards and norms training level	0.0640
		Emergency rescue and self-rescue capability	0.1204
		Familiarity with the underground operating environment	0.0379
Equipment factor	0.1768	Underground electrical machinery and equipment	0.0198
		Fire prevention structures	0.0216
		Completeness of fire prevention and extinguishing system	0.0637
		Completeness of monitoring system	0.0717
Environmental factors	0.2596	Spontaneous combustion tendency of coal seam	0.0275
		Coal mining method and process	0.0416
		Coal seam spontaneous combustion period	0.0690
		Airtightness of mined-out area	0.0540
		Ventilation method and equipment	0.0675
Management factors	0.3047	Completeness of safety management system	0.0915
		Achievement of the standard of hidden danger rectification	0.0795
		Reasonable design of escape routes	0.0598
		Management staffing situation	0.0740

3.2. Determine the Affiliation State of the Comprehensive Evaluation Cloud

The cloud characteristic parameters of each index were calculated according to Formulas (15) to (18), and the calculation results are shown in Table 8.

Table 8. Expert scoring results and cloud feature parameters of each index.

Indicators	**Cloud Feature Parameters**		
	Ex	***En***	***He***
V_{11}	8.00	3.76	1.65
V_{12}	16.13	4.27	0.98
V_{13}	9.50	4.39	2.31
V_{14}	25.13	2.66	0.83
V_{21}	22.25	3.99	0.50
V_{22}	20.63	4.86	1.48
V_{23}	6.38	3.29	0.55
V_{24}	15.88	3.25	1.25
V_{31}	49.75	4.39	0.34
V_{32}	18.88	4.58	0.77
V_{33}	31.25	3.21	1.35
V_{34}	23.25	2.74	0.85
V_{35}	8.63	3.60	0.38
V_{41}	9.75	3.13	0.33
V_{42}	7.00	3.13	1.38
V_{43}	5.88	3.02	1.01
V_{44}	9.50	3.76	1.36

After the weighted calculation of Formulas (19) to (21), the final comprehensive evaluation cloud characteristic parameters can be obtained as (14.50, 3.61, 1.22), and the final generated comprehensive evaluation cloud diagram is shown in Figure 4. The risk level of spontaneous combustion fire in this mine is between low risk and relatively low risk, which is closer to relatively low risk.

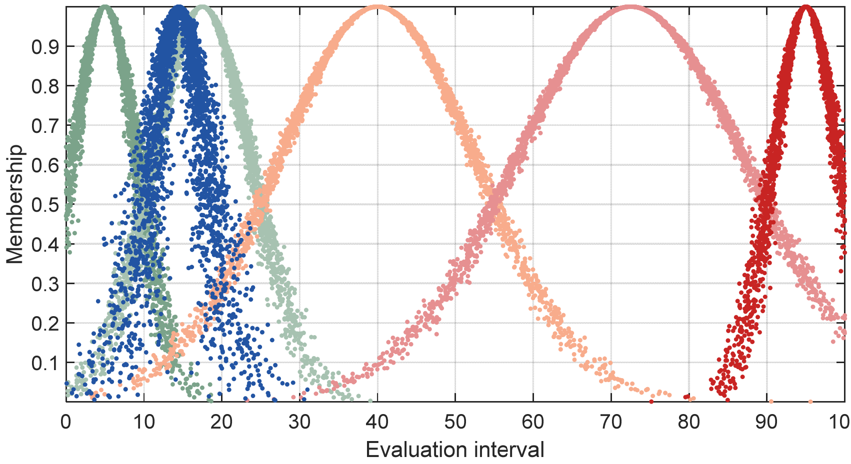

Figure 4. Comprehensive evaluation cloud diagram.

4. Discussion

4.1. Analysis of Impact Relationships among Indicators

From the analysis of the above calculation results, the degree of mutual influence between disaster-causing indicators is different, and the influence relationship between indicators can be quantified by the cause degree e_i. When the cause degree $e_i \geq 0$, the indicator i has a greater influence on other indicators and is called the cause indicator. When the cause degree $e_i \leq 0$, the indicator i is influenced by other indicators to a greater extent and is called the result indicator. From Figure 2, we can see that the cause degree of V_{13} (emergency rescue and self-rescue capability), V_{33} (natural fire period of coal seam), and V_{43} (reasonableness of escape route design) are higher, among which the cause degree of V_{13} is the highest, indicating that “emergency rescue and self-rescue capability” is the key to the change of the risk level of spontaneous combustion fire in coal mines. It is important to pay attention to strengthening relevant control measures from this perspective to reduce the overall risk level. Among the result indicators, V_{12} (level of training in fire prevention-related standards and regulations), V_{42} (compliance with standards for rectification of potential hazards), and V_{44} (availability of management personnel) have a low cause degree and are most likely to be influenced by other indicators. The centrality f_i reflects the overall importance of the indicator in the index system. As can be seen in Figure 2, V_{13} (emergency rescue and self-rescue capability), V_{41} (the degree of completeness of the safety management system), V_{42} (compliance with the standards for rectification of hidden hazards), and V_{44} (availability of management personnel) have the highest centrality, indicating that these four indicators are the four most important indicators of spontaneous combustion fire risk causation in coal mines.

4.2. Robustness Analysis of Evaluation Results under Different Evaluation Methods

The choice of evaluation method is very important in the evaluation process. Therefore, in order to verify the accuracy of the results, a fuzzy comprehensive evaluation method can be used to verify the evaluation results of the cloud model. The FCE method is based on the ideas and methods of fuzzy mathematics and is a mathematical method capable of comprehensive evaluation of objects that are difficult to define. In this study, the FCE method was used to evaluate the spontaneous combustion fire risk status of a coal mine, where the indicator weights follow the results of the improved DEMATEL calculation established in this study. The evaluation results were obtained based on the data of the experts' assessment of each indicator, calculated by the FCE method.

$$B = [0.306, 0.587, 0.081, 0.023, 0.003]$$

According to the principle of maximum affiliation, the calculated result is relatively low risk. It can be seen that the evaluation results obtained using the FCE method are consistent with the results obtained from the cloud model established in this study, indicating that the cloud model evaluation results are robust.

5. Conclusions

Accurate evaluation of spontaneous combustion fire risk in coal mines is the key to ensuring sustainable and safe production in coal mines. To fully characterize the mapping of expert knowledge in risk evaluation, this study fused the interval gray number with the DEMATEL method to analyze risk evaluation indicators, and constructed an affiliation cloud model based on the analysis results. The main conclusions of the study are three points as follows:

(1) Based on research of the literature and on expert consultation, a coal mine spontaneous combustion fire risk evaluation index system containing four secondary indicators and 17 tertiary indicators was constructed. In evaluating risk of an actual mine, the results show that the index system can reflect the level of spontaneous combustion fire risk in coal mines comprehensively and effectively.

(2) In order to accurately characterize the results of experts' assessment of the influence relationships among the indicators, the interval gray number representation method was incorporated into DEMATEL to analyze the influence relationships among the indicators. The results show that "emergency rescue and self-rescue capability" has the highest cause degree and is the key indicator for the change in the level of risk of spontaneous combustion fires in coal mines. The three indicators of "emergency rescue and self-rescue capability", "completeness of safety management system", and "achievement of the standard of hidden danger rectification" have the highest centrality, or highest relative importance, and should be given priority attention in the establishment of appropriate prevention and control measures.

(3) Based on the index centrality calculated by the improved DEMATEL method analysis, the weights of each index in the index system were calculated and a cloud model of

coal mine spontaneous combustion fire risk evaluation was constructed. By examining a mine in Shenmu City, Shaanxi Province, China as a case, the final risk level of spontaneous combustion fire in the mine was determined to be relatively low risk from the analysis of the constructed cloud model. The robustness analysis of the obtained evaluation results was carried out using different evaluation methods. The results showed that the constructed model is valid and practical.

In this study, the interval gray number was used to improve the DEMATEL method to determine the weights of evaluation indicators. This weight determination method fully expresses the judgment of experts regarding risk factors based on their years of experience in the field, but the method also has the limitation of being more subjective. The next step is to establish a more scientific and reasonable weight determination method from the perspective of the objectivity of the index data and then combine the cloud model to visualize and analyze the evaluation results.

Author Contributions: Conceptualization, K.X.; methodology, K.X. and J.L.; software, K.X. and C.L.; investigation, G.X., Z.X. and C.H.; writing—original draft preparation, K.X.; writing—review and editing, K.X. and S.L.; visualization, K.X.; supervision, S.L.; funding acquisition, S.L. and K.X. 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 (71972176), Major projects of Jiangsu Social Science Foundation of China (21ZD006), Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX22_2681), and Graduate Innovation Program of China University of Mining and Technology (2022WLKXJ018).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

References

1. Zhang, D.; Cen, X.; Wang, W.; Deng, J.; Wen, H.; Xiao, Y.; Shu, C. The graded warning method of coal spontaneous combustion in Tangjiahui Mine. *Fuel* **2021**, *288*, 119635. [CrossRef]
2. Li, S.; Xu, K.; Xue, G.; Liu, J.; Xu, Z. Prediction of coal spontaneous combustion temperature based on improved grey wolf optimizer algorithm and support vector regression. *Fuel* **2022**, *324*, 124670. [CrossRef]
3. Zhou, B.; Wu, J.; Wang, J.; Wu, Y. Surface-based radon detection to identify spontaneous combustion areas in small abandoned coal mine gobs: Case study of a small coal mine in China. *Process. Saf. Environ.* **2018**, *119*, 223–232. [CrossRef]
4. Lu, Y.; Qin, B. Identification and control of spontaneous combustion of coal pillars: A case study in the Qianyingzi Mine, China. *Nat. Hazards* **2015**, *75*, 2683–2697. [CrossRef]
5. Kong, B.; Li, Z.; Yang, Y.; Liu, Z.; Yan, D. A review on the mechanism, risk evaluation, and prevention of coal spontaneous combustion in China. *Environ. Sci. Pollut. R* **2017**, *24*, 23453–23470. [CrossRef] [PubMed]
6. Li, H.; Guo, G.; Zheng, N. New Evaluation Methods for Coal Loss Due to Underground Coal Fires. *Combust. Sci. Technol.* **2021**, *193*, 1022–1041. [CrossRef]
7. Yu, S.; Liu, X. Study on Multi-Indicator Quantitative Risk Evaluation Methods for Different Periods of Coal Spontaneous Combustion in Coal Mines. *Combust. Sci. Technol.* **2022**. [CrossRef]
8. Guo, Z.; Wu, Y. The Application of Unascertained Measure Model to Synthetic Evaluation for Underground Fire Risk of Bofang Coal Mine. In Proceedings of the 2009 Wase International Conference on Information Engineering, ICIE 2009, Taiyuan, China, 10–11 July 2009; Volume I, p. 599.
9. Lin, X.; Chen, G.; Du, X. Establishment of Accident Risk Early-Warning Macroscopic Model on Ventilation, Gas, Dust and Fire in Coal Mine. *Procedia Eng.* **2012**, *45*, 53–58. [CrossRef]
10. Li, S.; You, M.; Li, D.; Liu, J. Identifying coal mine safety production risk factors by employing text mining and Bayesian network techniques. *Process. Saf. Environ.* **2022**, *162*, 1067–1081. [CrossRef]
11. Fa, Z.; Li, X.; Qiu, Z.; Liu, Q.; Zhai, Z. From correlation to causality: Path analysis of accident-causing factors in coal mines from the perspective of human, machinery, environment and management. *Resour. Policy* **2021**, *73*, 102157. [CrossRef]
12. Zhang, G.; Wang, E.; Zhang, C.; Li, Z.; Wang, D. A comprehensive risk assessment method for coal and gas outburst in underground coal mines based on variable weight theory and uncertainty analysis. *Process. Saf. Environ.* **2022**, *167*, 97–111. [CrossRef]

13. You, M.; Li, S.; Li, D.; Xu, S. Applications of artificial intelligence for coal mine gas risk assessment. *Safety Sci.* **2021**, *143*, 105420. [CrossRef]
14. Chen, L.; Huang, Y.; Bai, R.; Chen, A. Regional disaster risk evaluation of China based on the universal risk model. *Nat. Hazards* **2017**, *89*, 647–660. [CrossRef]
15. Zheng, L. Research on Project Risk Management of Power Engineering Based on Fuzzy Comprehensive Evaluation Method. *Autom. Control. Mechatron. Eng. II* **2013**, *415*, 287–293. [CrossRef]
16. Zhao, H.; Guo, S. Risk Evaluation on UHV Power Transmission Construction Project Based on AHP and FCE Method. *Math. Probl. Eng.* **2014**, *2014*, 687568. [CrossRef]
17. Long, L.; Li, Z. An assessment model of monitoring risk in deep excavation based on fuzzy theory. *Indoor Built. Environ.* **2020**, *29*, 221–229. [CrossRef]
18. Wu, L.; Bai, H.; Yuan, C.; Xu, C. Fanpce technique for risk assessment on subway station construction. *J. Civ. Eng. Manag.* **2019**, *25*, 599–616. [CrossRef]
19. Lv, C.; Wu, Z.; Liu, Z.; Shi, L. The multi-level comprehensive safety evaluation for chemical production instalment based on the method that combines grey-clustering and EAHP. *Int. J. Disast. Risk. Res.* **2017**, *21*, 243–250. [CrossRef]
20. Ye, J.; Dang, Y. A novel grey fixed weight cluster model based on interval grey numbers. *Grey Syst.* **2017**, *7*, 156–167. [CrossRef]
21. Li, L.; Li, X. Analysis on the related factors of China's technological innovation ability using greyness relational degree. *Grey Syst.* **2022**, *12*, 651–671. [CrossRef]
22. Chai, Q.; Li, H.; Tian, W.; Zhang, Y. Critical Success Factors for Safety Program Implementation of Regeneration of Abandoned Industrial Building Projects in China: A Fuzzy DEMATEL Approach. *Sustainability* **2022**, *14*, 1550. [CrossRef]
23. Mirhosseini, S.A.; Kiani Mavi, R.; Kiani Mavi, N.; Abbasnejad, B.; Rayani, F. Interrelations among Leadership Competencies of BIM Leaders: A Fuzzy DEMATEL-ANP Approach. *Sustainability* **2020**, *12*, 7830. [CrossRef]
24. Ren, X.; Jiang, Q.; Jiang, J.; He, Z.; Ouyang, B.; Peng, B. Evaluation of cabin energy consumption based on combination weighting and grey fuzzy comprehensive model. *Eurasip J. Adv. Sig. Pr.* **2022**, *2022*, 36. [CrossRef]
25. Alkan, N.; Kahraman, C. Circular intuitionistic fuzzy TOPSIS method: Pandemic hospital location selection. *J. Intell. Fuzzy Syst.* **2022**, *42*, 295–316. [CrossRef]
26. Zhou, Y.; Qin, X.; Li, C.; Zhou, J. An Intelligent Site Selection Model for Hydrogen Refueling Stations Based on Fuzzy Comprehensive Evaluation and Artificial Neural Network—A Case Study of Shanghai. *Energies* **2022**, *15*, 1098. [CrossRef]
27. Bao, X.; Man, J.; Wang, Q. Comprehensive Evaluation of Risks in Green building Based on the Fuzzy Comprehensive Evaluation. In *Applied Mechanics and Materials*; Trans Tech Publications Ltd.: Bäch SZ, Switzerland, 2013; Volume 368–370, pp. 1154–1157.
28. Zhang, Y.; Wang, R.; Huang, P.; Wang, X.; Wang, S. Risk evaluation of large-scale seawater desalination projects based on an integrated fuzzy comprehensive evaluation and analytic hierarchy process method. *Desalination* **2020**, *478*, 114286. [CrossRef]
29. Liu, Z.; Jiang, Z.; Xu, C.; Cai, G.; Zhan, J. Assessment of provincial waterlogging risk based on entropy weight TOPSIS-PCA method. *Nat. Hazards* **2021**, *108*, 1545–1567. [CrossRef]
30. Xu, Y.; Zhang, J.; Hua, Y.; Wang, L. Dynamic Credit Risk Evaluation Method for E-Commerce Sellers Based on a Hybrid Artificial Intelligence Model. *Sustainability* **2019**, *11*, 5521. [CrossRef]
31. Lee, P.; Zhao, Y.; Lo, T.; Long, D. A multi-period comprehensive evaluation method of construction safety risk based on cloud model. *J. Intell. Fuzzy Syst.* **2019**, *37*, 5203–5215. [CrossRef]
32. Wang, W.; Liu, X.; Ma, Y.; Liu, S. A New Approach for Occupational Risk Evaluation of Natural Gas Pipeline Construction with Extended Cumulative Prospect Theory. *Int. J. Fuzzy Syst.* **2021**, *23*, 158–181. [CrossRef]
33. Yao, X.; Deng, H.; Zhang, T.; Qin, Y. Multistage fuzzy comprehensive evaluation of landslide hazards based on a cloud model. *PLoS ONE* **2019**, *14*, e0224312. [CrossRef] [PubMed]
34. Tian, Y.; Chen, L.; Huang, L.; Mou, J. Featured risk evaluation of nautical navigational environment using a risk cloud model. *J. Mar. Eng. Technol.* **2020**, *19*, 115–129. [CrossRef]
35. Ma, Z.; Zhang, S. Risk-Based Multi-Attribute Decision-Making for Normal Cloud Model Considering Pre-Evaluation Information. *IEEE Access* **2020**, *8*, 153891–153904. [CrossRef]
36. Zhou, A.; Jing, G.; Zhang, Y. Study on Spontaneous Combustion in Goaf Based on Fuzzy Comprehensive Evaluation. *Prog. Saf. Sci. Technol.* **2008**, *7*, 224–228.
37. Singh, R.N.; Shonhardt, J.A.; Terezopoulos, N. A new dimension to studies of spontaneous combustion of coal. *Miner. Resour. Eng.* **2002**, *11*, 147–163. [CrossRef]
38. Zhao, M.; Zhang, C.; Chen, S.; Jiang, H. Safety Assessment of Channel Seepage by Using Monitoring Data and Detection Information. *Sustainability* **2022**, *14*, 8378. [CrossRef]
39. Cai, S.; Wei, W.; Chen, D.; Ju, J.; Zhang, Y.; Liu, W.; Zheng, Z. Security Risk Intelligent Assessment of Power Distribution Internet of Things via Entropy-Weight Method and Cloud Model. *Sensors* **2022**, *22*, 4663. [CrossRef]