



Evaluation of Emergency Management Capability in Coal Mines Based on Entropy Weight Method-DEMATEL-Cloud Model

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Abstract. To explore strategies for enhancing the emergency management capabilities of coal mining enterprises and facilitate the construction of their emergency response systems, this study establishes an evaluation index system for coal mine emergency management capabilities based on the four stages of emergency management (prevention, preparation, response, and recovery). A novel evaluation model integrating the Entropy Weight Method (EWM), Decision-Making Trial and Evaluation Laboratory (DEMATEL), and Cloud Model is proposed. First, the combined weights of evaluation indicators are determined using EWM and DEMATEL to balance objectivity and inter-factor influences. Subsequently, cloud model parameters are calculated, and cloud diagrams for both primary indicators and comprehensive evaluations are generated via MATLAB. The similarity degree between the comprehensive cloud and standard clouds is analyzed to determine the emergency capability level. Applied to a practical case, the results indicate that the evaluated coal mine's primary indicators are rated as "Good, " "Good, " "Qualified, " and "Poor, " with an overall "Qualified" rating, aligning with its actual conditions. Comparative validation with other methods confirms the model's feasibility and reliability, offering theoretical insights for improving coal mine emergency management.

Keywords: Coal mine; Entropy weight method; DEMATEL; Cloud model; Emergency management

1 Introduction

China is the world's largest producer and consumer of coal, and coal mine safety has always been a critical concern for the country [1]. According to data released by the National Bureau of Statistics, the coal mine fatality rate in China in 2023 was 0.094 deaths per million tons, an increase of 23.7% compared to the previous year, with 447

fatalities, a 79.35% rise from the previous year[2]. These statistics highlight the ongoing severity of safety issues in China's coal mining industry. Emergency management serves as the last line of defense in coal mine safety production[3], making it imperative to enhance the emergency management capabilities of coal mining enterprises.

Currently, numerous domestic scholars have conducted in-depth research on the emergency management capabilities of coal mining enterprises, yielding significant results. For instance, Wei Yinshang et al. [4] evaluated the vulnerability of coal mine emergency management systems by constructing an association function between evaluation indicators and vulnerability levels, using a multi-level extension evaluation method. Geng Xingyin et al. [5] employed structural equation modeling to analyze the main factors influencing the emergency management capabilities of coal mining enterprises and proposed corresponding countermeasures. Yang Fengfeng et al. [6] applied fuzzy analytic hierarchy process (AHP) to evaluate an emergency capability assessment system and divided the evolution of coal mine emergency capabilities into four stages using a logistic curve, providing a comprehensive analysis of a coal mine enterprise's emergency management capabilities.

Despite these advancements, the evaluation of coal mine emergency management capabilities in China still lacks systematic and practical methods and index systems. Existing methods, such as AHP and multi-level extension analysis, are often too subjective, making it difficult to accurately quantify the weights of evaluation indicators. Additionally, the selection of evaluation indicators varies widely among scholars, limiting their effectiveness in supporting decision-making for coal mine emergency management. To address these issues, this study builds an evaluation index system for coal mine emergency management capabilities based on the four stages of emergency management (prevention, preparation, response, and recovery). By combining the Entropy Weight Method (EWM) and DEMATEL, the study calculates the combined weights of evaluation indicators and employs the Cloud Model for comprehensive evaluation to determine the emergency capability level. Finally, the proposed model is applied to a practical case to evaluate the emergency management capabilities of a coal mine, providing theoretical and practical guidance for improving coal mine emergency management.

2 Construction of the Emergency Management Capability Index System for Coal Mines

Based on the PPRR (Prevention, Preparedness, Response, Recovery) emergency management theory[7], emergency management can be divided into four stages: prevention, preparation, response, and recovery. These stages are interconnected and form a cyclical system. Table 1 outlines the objectives and tasks of each stage in coal mine emergency management.

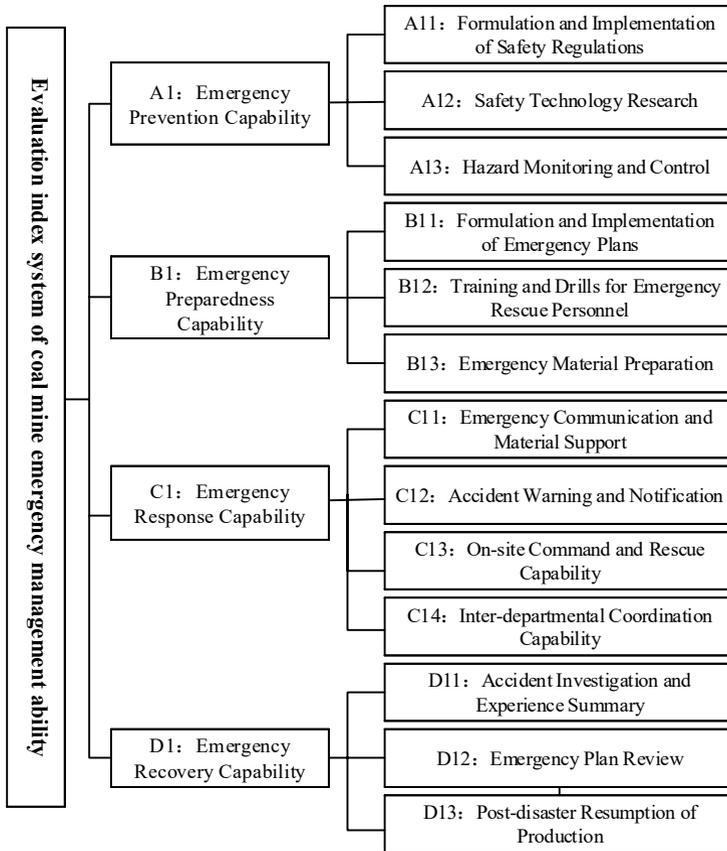


Fig. 1. Evaluation index system of coal mine emergency management ability

Table 1. Objectives and Tasks of Coal Mine Emergency Management Stages

Stage	Objective	Tasks
Prevention	Minimize accidents and disasters, reduce the probability of accidents, and ensure a safe production environment.	1. Identify and assess risks and hazards. 2. Establish safety management regulations. 3. Adopt advanced technologies and equipment. 4. Conduct safety training for employees.
Preparation	Prevent the escalation of accidents and ensure effective response.	1. Develop detailed emergency plans. 2. Conduct regular emergency drills. 3. Ensure adequate emergency resources, equipment, and personnel. 4. Establish an emergency command center.
Response	Take immediate actions to protect lives and property after an accident.	1. Report accidents and activate emergency plans promptly. 2. Organize and coordinate rescue operations. 3. Deploy professional rescue teams for search and rescue, firefighting, etc.
Recovery	Restore production and normal operations while learning from the incident.	1. Assess the accident site and develop recovery plans. 2. Provide psychological support to affected employees. 3. Analyze the accident and revise emergency plans and safety regulations. 4. Gradually resume production under safe conditions.

To comprehensively reflect the emergency management capabilities of coal mining enterprises, this study integrates systems engineering principles with existing research[8, 9, 10,11,12,13] to establish an evaluation index system. The system includes four primary indicators (emergency prevention capability, emergency preparedness capability, emergency response capability, and emergency recovery capability) and 13 secondary indicators, as shown in Figure 1.

3 Entropy Weight Method-DEMATEL Combined Weighting Method

As an objective weighting method, the Entropy Weight Method (EWM) determines weights through data-driven analysis, eliminating subjective biases [14], yet it neglects interdependencies among factors. On the other hand, the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method is a structured modeling approach that uses matrices and graph theory to analyze the interrelationships and causal effects among factors[15]. However, DEMATEL is highly subjective. Therefore, combining these two methods can mitigate the impact of subjectivity on indicator weights. The specific steps of the EWM-DEMATEL combined weighting method are as follows:

(1) Construct the Single Indicator Evaluation Matrix

Assume there are m valuation objects and n evaluation indicators. The initial single indicator evaluation matrix $R = (r_{ij})_{m \times n}$ can be constructed, where r_{ij} represents the evaluation data of the i -th evaluation object on the j -th indicator.

(2) Calculate the Entropy Value and Weight of Each Indicator

The entropy value e_j and weight w_j of the j -th indicator are calculated using the following formulas:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m p_{ij} \ln p_{ij} \tag{1}$$

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^m r_{ij}} \tag{2}$$

$$w_j = \frac{1 - e_j}{n - \sum_{j=1}^n e_j} \tag{3}$$

Where p_{ij} is the weight of the j -th indicator for the i -th evaluation object, e_j is the entropy value of the j -th indicator, and w_j is the weight of the j -th indicator.

(3) Establish the Direct Influence Matrix

Experts are invited to score the degree of influence among indicators. To eliminate subjective differences among experts, the average of their scores is calculated to obtain the direct influence matrix $A = (a_{ij})_{n \times n}$, where a_{ij} represents the degree of influence of factor i on factor j.

(4) Calculate the Comprehensive Influence Matrix

First, normalize the direct influence matrix A using Equation (4) to obtain the normalized matrix N. Then, calculate the comprehensive influence matrix T using Equation (5):

$$N = \frac{A}{\max(\sum_{j=1}^n A_{ij})} \tag{4}$$

$$T = N(N - I)^{-1} \tag{5}$$

Where I is the identity matrix.

(5) Calculate Influence Degree, Affected Degree, Centrality, Cause Degree, and Weights

The influence degree D, affected degree C, centrality M, cause degree R, and weights W are calculated using the following formulas:

$$D_i = \sum_{j=1}^n t_{ij} \tag{6}$$

$$C_i = \sum_{j=1}^n t_{ji} \tag{7}$$

$$M_i = D_i + C_i \tag{8}$$

$$R_i = D_i - C_i \tag{9}$$

$$W_i = \frac{M_i}{\sum_{i=1}^n M_i} \tag{10}$$

Where t_{ij} is the element of the comprehensive influence matrix T, D_i represents the influence degree of factor i, C_i represents the affected degree of factor i, M_i represents the centrality of factor i, R_i represents the cause degree of factor ii, and W_i is the weight of factor i.

(6) Calculate the Combined Weights

To avoid significant errors caused by single weighting methods, the multiplicative synthesis method (Equation 11) is used to calculate the combined weights, reducing the bias in evaluation results:

$$W_{combined} = \sqrt{W_{EWM} \times W_{DEMATEL}} \tag{11}$$

4 Cloud Model Evaluation

The Cloud Model is a mathematical tool for transforming qualitative concepts into quantitative representations, effectively handling uncertainty and fuzziness[16]. It combines quantitative data with expert experience, providing a robust framework for evaluation[17]. The specific steps of the Cloud Model evaluation are as follows:

(1) Construct the Evaluation Language Set

Based on relevant literature[18,19,20]and expert opinions, the evaluation grades for coal mine emergency management capabilities are divided into five levels: Poor, Fair, Qualified, Good, and Excellent. The corresponding score ranges are, respectively.

(2) Establish the Standard Cloud Diagram

The standard cloud parameters for each evaluation grade are calculated using Equation (12), as shown in Table 2.

$$\begin{cases} Ex = \frac{C_{max} + C_{min}}{2} \\ En = \frac{C_{max} - C_{min}}{6} \\ He = k \end{cases} \tag{12}$$

Where Ex is the expectation, En is the entropy, He is the hyper-entropy, C_{max} and C_{min} are the upper and lower bounds of the evaluation grade, and k is a constant, typically set to 0.5.

Table 2. Standard Cloud Parameters for Evaluation Grades

Evaluation Grade	Score Range	Standard Cloud Parameters
Poor	[0, 60)	(30, 10, 0.5)
Fair	[60, 70)	(65, 1.667, 0.5)
Qualified	[70, 80)	(75, 1.667, 0.5)
Good	[80, 90)	(85, 1.667, 0.5)
Excellent	[90, 100)	(95, 1.667, 0.5)

Using the backward cloud generator algorithm, the standard cloud diagram for coal mine emergency management capability evaluation is plotted using MATLAB

R2023a, as shown in Figure 2. To enhance accuracy and reduce randomness, the number of cloud drops is set to $D=1000$ based on the law of large numbers[21].

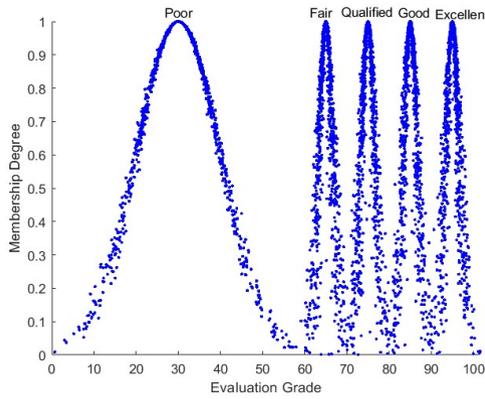


Fig. 2. Standard cloud map of coal mine emergency management capability evaluation

(3) Calculate Cloud Parameters for Indicators

Based on expert ratings, the cloud parameters for secondary indicators are calculated using the backward cloud generator algorithm. The combined weights $W_{combined}$ obtained from the EWM-DEMATEL method are used to calculate the cloud parameters for primary indicators using Equation (13):

$$\begin{cases} Ex = \sum_{i=1}^n W_i \cdot Ex_i \\ En = \sqrt{\sum_{i=1}^n (W_i \cdot En_i)^2} \\ He = \sqrt{\sum_{i=1}^n (W_i \cdot He_i)^2} \end{cases} \quad (13)$$

Where Ex_i , En_i , and He_i are the cloud parameters of the i -th secondary indicator, and W_i is its combined weight.

(4) Calculate Similarity Degree

To accurately determine the evaluation grade, the similarity degree between the comprehensive cloud and the standard clouds is calculated using Equation (14):

$$Similarity = \frac{\sum_{i=1}^D u_i}{D} \quad (14)$$

Where u_i is the certainty degree of the i -th cloud drop, and D is the total number of cloud drops.

5 Case Study

This study evaluates the emergency management capability of a coal mine under the China Energy Group using the proposed EWM-DEMATEL-Cloud Model. The coal mine is located in Otog Banner, Ordos City, and currently mines the 9-1 coal seam. It is a low-gas mine with no rock burst tendency in the coal seam and its roof and floor. The mine adopts a mixed development method with a main inclined shaft and an auxiliary vertical shaft.

5.1 Calculation of Combined Weights for Evaluation Indicators

To ensure the representativeness and reliability of expert opinions, the selection of experts adhered to the following criteria: Experts must hold senior positions in coal mine safety management or have published at least three peer-reviewed papers on emergency management; At least 10 years of field experience in coal mine safety operations or emergency response; The expert group included academic researchers (40%) and industry practitioners (60%) to balance theoretical and practical perspectives. To mitigate potential biases, the study implemented a double-blind scoring process where experts were unaware of each other's identities. Additionally, scores were normalized using Z-score standardization to reduce individual rating tendencies. Finally, the Kendall's W test was applied to assess inter-expert consistency ($W=0.82$, $p<0.05$), confirming sufficient agreement.

Table 3. Entropy Values and Weights of Evaluation Indicators

Indicator	Entropy Value	Weight
A11	0.976	0.056
A12	0.981	0.045
A13	0.921	0.190
B11	0.948	0.125
B12	0.948	0.123
B13	0.981	0.046
C11	0.980	0.047
C12	0.988	0.030
C13	0.977	0.056
C14	0.985	0.036
D11	0.985	0.035
D12	0.966	0.081
D13	0.946	0.130

10 experts (The group consisted of two full professors, two associate professors, and six senior executives in the coal mining sector.) were invited to rate the influence degree of factors affecting the coal mine's emergency management capability. The influence degree was rated on a scale of 1 to 5, representing "no influence" to "strong influence." The single indicator evaluation matrix was constructed, and the entropy

values and weights of the indicators were calculated using Equations (1)–(3), as shown in Table 3.

The initial direct influence matrix A was obtained by averaging the experts' scores. The comprehensive influence matrix T was calculated using Equations (4) and (5), and the DEMATEL results (influence degree, affected degree, centrality, cause degree, and weights) were derived using Equations (6)–(10), as shown in Table 4.

Table 4. DEMATEL Calculation Results

Factor	D	C	M	R	W	Attribute
A11	4.719	2.658	7.377	2.060	0.074	Cause
A12	3.829	3.057	6.886	0.772	0.069	Cause
A13	3.773	3.199	6.972	0.574	0.070	Cause
B11	4.674	4.651	9.324	0.023	0.094	Cause
B12	3.293	4.075	7.368	-0.782	0.074	Result
B13	3.472	4.068	7.540	-0.596	0.076	Result
C11	3.586	4.161	7.747	-0.575	0.078	Result
C12	3.617	4.115	7.732	-0.499	0.078	Result
C13	3.553	4.700	8.253	-1.147	0.083	Result
C14	3.390	4.023	7.413	-0.633	0.075	Result
D11	4.534	3.743	8.276	0.791	0.083	Cause
D12	3.881	3.888	7.769	-0.008	0.078	Result
D13	3.367	3.347	6.714	0.019	0.068	Cause

Table 5. Combined Weights of Evaluation Indicators

Indicator	EWM Weight	DEMATEL Weight	Combined Weight	Rank
A11	0.056	0.074	0.055	7
A12	0.045	0.069	0.041	10
A13	0.190	0.070	0.174	1
B11	0.125	0.094	0.154	2
B12	0.123	0.074	0.120	3
B13	0.046	0.076	0.046	9
C11	0.047	0.078	0.048	8
C12	0.030	0.078	0.030	13
C13	0.056	0.083	0.061	6
C14	0.036	0.075	0.035	12
D11	0.035	0.083	0.038	11
D12	0.081	0.078	0.083	5
D13	0.130	0.068	0.115	4

The combined weights were calculated using Equation (11), as shown in Table 5. The top three factors with the highest combined weights are hazard monitoring and

control (A13, 0.174), emergency plan formulation and implementation (B11, 0.154), and emergency personnel training and drills (B12, 0.120). These factors should be prioritized for improvement to enhance the coal mine's emergency management capability.

5.2 Cloud Model Comprehensive Evaluation

The aforementioned 10 experts were invited to provide comprehensive scores for each evaluation indicator of the coal mine's emergency management capability. Using MATLAB software, the cloud parameters for each indicator were calculated through the backward cloud generator, as shown in Table 6. By substituting the characteristic values of the cloud model for each indicator into Equation (13), the comprehensive cloud parameters were determined to be (78.065, 8.310, 1.252).

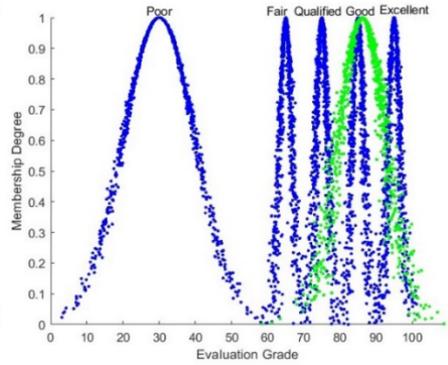
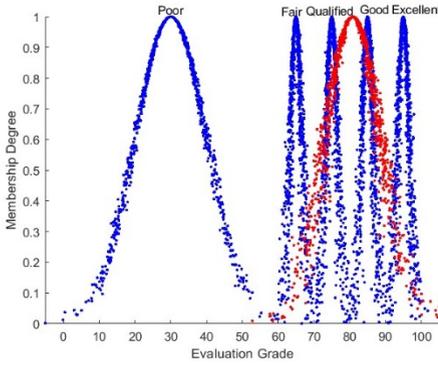
Table 6. Cloud Model Parameters of Primary and Secondary Evaluation Indicators

Evaluation Indicator	Cloud Parameters	Evaluation Indicator	Cloud Parameters
A1	(80.885, 7.802, 1.078)	A11	(69, 9.8611, 1.5717)
		A12	(66.5, 8.95, 1.2636)
		A13	(88, 7.5354, 1.0189)
B1	(86.192, 6.553, 1.046)	B11	(87, 6.0654, 1.0154)
		B12	(86, 7.5073, 1.0376)
		B13	(84, 5.5349, 1.4342)
C1	(75.254, 8.592, 1.497)	C11	(81, 6.0735, 1.1479)
		C12	(76, 8.4987, 1.616)
		C13	(76, 10.372, 1.4493)
		C14	(65.5, 7.9257, 2.2008)
D1	(65.940, 12.020, 1.721)	D11	(73.5, 9.2821, 1.4534)
		D12	(66.5, 10.9563, 1.8411)
		D13	(63, 12.8853, 1.6876)

Using MATLAB, the comprehensive cloud and the primary indicator clouds were plotted alongside the standard cloud in the same coordinate system. By comparing these clouds with the standard cloud, the rating and weak points of the coal mine's emergency management capability were determined, as illustrated in Figure 3.

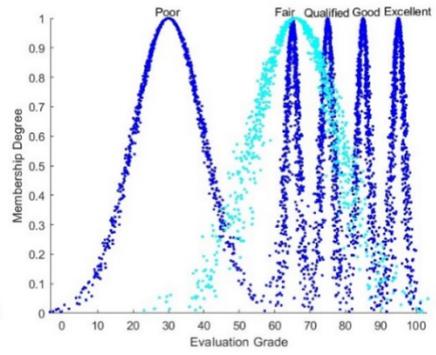
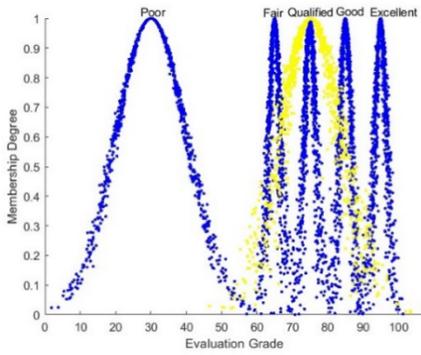
The similarity degrees between the comprehensive evaluation cloud and the standard clouds for each indicator level were calculated using Equation (14), as shown in Table 7. According to the maximum membership degree criterion, the level corresponding to the highest similarity degree represents the final emergency management capability rating of the coal mine.

To further validate the accuracy and effectiveness of the proposed comprehensive evaluation model in assessing coal mine emergency management capability, the model was compared with other commonly used methods, as presented in Table 8.



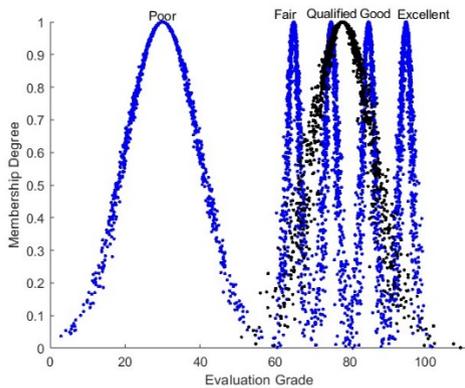
(a)A1: Emergency Prevention Capability

(b)B1: Emergency Preparedness Capability



(c)C1: Emergency Response Capability

(d) D1: Emergency Recovery Capability



(e) Comprehensive Emergency Management Capability

Fig. 3. Cloud map of primary indexes and comprehensive evaluation

Table 7. Results of Similarity Calculation

Evaluation Indicator	Poor	Fair	Qualified	Good	Excellent
Comprehensive Emergency Management Capability	0.0012	0.0579	0.1894	0.1312	0.0270
Emergency Prevention Capability	0.0004	0.0264	0.1637	0.1740	0.0465
Emergency Preparedness Capability	0.0002	0.002	0.0579	0.2425	0.1079
Emergency Response Capability	0.0039	0.0902	0.2120	0.1000	0.0195
Emergency Recovery Capability	0.0454	0.1347	0.1049	0.0397	0.0059

Table 8. Comparison of Results under Different Evaluation Models

Evaluation Model	Evaluation Result	p-value
DEMATEL-ANP-Cloud Model	Qualified	0.12
Entropy Weight-Cloud Model	Qualified	0.09
Improved CRITIC-Cloud Model	Qualified	0.15
Fuzzy TOPSIS	Qualified	0.21
Grey Relational Analysis	Qualified	0.18

5.3 Analysis of Evaluation Results

According to Figure 3 and Table 7, the comprehensive evaluation cloud of the coal mine's emergency management capability lies between "Qualified" and "Good," with the highest similarity to the "Qualified" standard cloud. Based on the maximum membership degree principle, the comprehensive evaluation result of the coal mine's emergency management capability is "Qualified." This result is consistent with the actual production situation of the coal mine, indicating that the model's evaluation aligns well with the mine's emergency capabilities. Similarly, the evaluation results for the primary indicators of the coal mine's emergency management capability are "Good," "Good," "Qualified," and "Fair," respectively.

To validate the robustness of the model, a sensitivity analysis was conducted by perturbing the combined weights of evaluation indicators ($\pm 10\%$) and recalculating similarity degrees. Based on the calculation results the "Qualified" level exhibited minimal fluctuations ($\Delta < 0.03$) under weight perturbations, confirming the model's insensitivity to parameter uncertainties.

The unanimous 'Qualified' ratings across all models reflect agreement in qualitative outcomes, confirming the validity of the original model. Moreover, the absence of significant differences ($p > 0.05$) in quantitative similarity scores between the original model and comparative methods underscores its robustness. This demonstrates that the entropy weight method-DEMATEL-cloud model approach for comprehensive evaluation of coal mine emergency management capability is both scientific and applicable. Furthermore, it validates the reliability of the evaluation results.

6 Conclusion

(1) An evaluation index system for coal mine emergency management capability was established, incorporating four primary indicators (emergency prevention, preparedness, response, and recovery) and 13 secondary indicators based on the PPRR theory and existing research. This system provides a comprehensive framework for assessing and improving emergency management in coal mines.

(2) A novel evaluation model integrating the Entropy Weight Method (EWM), DEMATEL, and Cloud Model was proposed. The combined weights of indicators were calculated using EWM and DEMATEL to balance objectivity and inter-factor influences, while the Cloud Model was employed to handle uncertainty and fuzziness in the evaluation process. This approach ensures a more accurate and reliable assessment of emergency management capabilities.

(3) The model was applied to a practical case study, and the evaluation results aligned with the actual production situation of the coal mine, demonstrating the model's validity and reliability. The sensitivity analysis further confirmed the model's robustness, as variations in input parameters had minimal impact on the final evaluation results.

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