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Article

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Research on the Safety Assessment Method of Coal Mine Gas

Situations Using G1-CRITIC Empowered Cloud Model

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Abstract: Scientifically evaluating the safety status of coal mine gas is crucial for effective gas risk management. This paper introduces the WSR theory to analyze the influencing factors of coal mine gas situations across the Wuli, Shili, and Renli dimensions. The G1 method and an improved CRITIC method are employed to calculate the subjective and objective weights of gas situation indicators, respectively. A distance function discrimination method is introduced to achieve comprehensive indicator weighting. Combining these methods with cloud model theory, a cloud model for coal mine gas situation safety assessment is constructed and validated through a case study. The results indicate that the assessment method based on the G1-CRITIC empowered cloud model effectively evaluates the gas safety status of the No. 3 coal seam in Wangzhuang Mine, with a safety level classified as Level II, consistent with the actual situation. This confirms the model's applicability for assessing coal mine gas safety situations.

Keywords: Coal Mine Gas Safety Status; WSR; Comprehensive Weighting; Cloud Model

0 Introduction

According to statistics, there are still over 1,500 high-gas mines, gas outburst mines, and mines managed based on outburst-prone coal seams in China. Gas mines continue to be a focal point in the country's coal mine safety situation and risk control. **Error! Reference source not found.**[1]. Therefore, developing a reasonable gas safety assessment method is crucial for ensuring coal mine safety and enhancing the effectiveness of gas risk management.

Regarding coal mine gas risk assessment, both domestic and international scholars

have conducted in-depth research and achieved significant results. The safety evaluation of coal mine gas is a critical aspect of ensuring the well-being of workers and the productivity of coal mines. Sun conducted research on coal mine gas safety evaluation based on the D-S Evidence Theory Data Fusion, emphasizing the importance of accurate assessment models. Additionally, Sun further enhanced the accuracy of gas safety evaluation through the development of a new model based on the adaptive weighted least squares support vector machine and improved Dempster–Shafer evidence theory[3]. Geologic data collection and assessment techniques play a vital role in enhancing safety in coal mining operations, as highlighted by Dyke[4]. Continuous improvement in data collection methods, geologic interpretations, and communication techniques is essential for predicting and mitigating adverse geologic conditions effectively[5][6]. Artificial intelligence has been increasingly utilized for coal mine gas risk assessment, as discussed by You[7]. By making coal mine risks known and controllable through technical means, the probability of accidents can be reduced, ensuring the safety and health of workers. In the context of gas concentration prediction, Song proposed a multi-parameter fusion prediction model based on a recurrent neural network to improve accuracy[8]. By optimizing hyperparameters and preventing overfitting, the model enhances the applicability of gas concentration prediction in coal mines[9][10]. Risk assessment of deep coal and gas outbursts is crucial for accident prevention, as demonstrated by Zhu[11]. Their proposed algorithm balances global and local search to improve stability, robustness, and model generalization, providing a new approach for risk prediction in coal mines. Furthermore, Jia emphasized the importance of comprehensive classification of coal mine gas explosion causes to identify the exact reasons behind accidents[12]. Understanding the root causes of accidents is essential for implementing targeted safety measures and policies. In conclusion, the evaluation of coal mine gas safety is a multifaceted process that involves advanced technologies, data fusion techniques, and comprehensive risk assessments. By continuously improving assessment models, data collection methods, and predictive models, the safety of coal mining operations can be significantly enhanced.

Although the aforementioned research has facilitated the assessment of coal mine

gas safety situations, several issues remain, including the cumbersome selection of assessment indicators, the substantial workload involved in calculating indicator weights, the lack of reflection on indicator interrelationships, and the ambiguity in gas safety situation grading. To address these issues, this study introduces the Wuli-Shili-Renli (WSR) method to develop a WSR-based indicator system for coal mine gas situation assessment. This approach effectively captures the fundamental patterns in gas situation development within the complex system of coal mines, adheres to the principles for managing gas situations, and considers the impact of human factors on gas safety. The G1 method is used for subjective weighting of gas safety indicators, while an improved CRITIC method is employed for objective weighting. A distance function discrimination method is introduced to achieve comprehensive weighting of gas safety situations. Finally, cloud model theory is integrated to facilitate the classification of coal mine gas safety situations.

1 WSR-Based Indicator System for Coal Mine Gas Situation Assessment

1.1 WSR Methodology

The Wuli-Shili-Renli (WSR) methodology is a systematic and dialectical approach to analyzing complex systems, proposed by Gu Jifa, a research fellow in systems science, and Zhu Zhuchang, PhD[13]. The methodology posits that complex systems are composed of three aspects: Wuli, Shili, and Renli—which are interdependent and mutually influential, comprising the operational structure and evolutionary mechanisms of complex systems. Wuli represents the basic patterns of an entity's development. Shili represents the principles for managing and coordinating situations. And Renli represents the influence of human factors on the development of objective entities. The WSR methodology addresses the questions of what an entity is, how to deal with it, and how best to deal with it, based on the three aspects. By dissecting complex systems through the WSR approach, one can effectively explore the essence of how they operate and propose comprehensive and systemic solutions to their problems through holistic cognition and stratified study.

1.2 WSR-Based Indicator System for Coal Mine Gas Situation Assessment

Gas safety situations in coal mines are the collective result of the coupling and interaction of multiple factors related to the mine itself and its operational processes. At its core, this involves the intersection and coupling of inherent risk factors associated with coal mine gas, gas accident prevention measures, and human execution factors[14]. Based on this analysis, an indicator system comprising Wuli, Shili, and Renli factors for coal mine gas situations has been established.

The Wuli factors of gas safety conditions are fundamental elements that constitute the gas situation in coal mines. Geological structure influences the occurrence of gas in coal mines; the depth of the coal seam determines the impact of geological stress on gas safety; higher gas pressure increases the danger of gas safety conditions; the coal's strength coefficient affects the interaction between the coal body and gas safety, with a higher strength coefficient correlating with safer gas conditions; and higher gas content in the coal seam makes the gas situation more hazardous[14]. Therefore, the Wuli factors of gas safety conditions comprise five elements: geological structure, coal seam depth, gas pressure, coal strength coefficient, and gas content in the coal seam.

The Shili factors of gas safety represent the principles followed by personnel in managing coal mine gas safety. The completeness of organizational structure indicates how well various organizational entities adhere to relevant regulations and procedures to ensure the effective execution of their respective tasks. A more complete organizational structure correlates with improved gas safety conditions. The effectiveness of the safety supervision mechanism reflects the ability to provide real-time monitoring of gas hazards, ensuring timeliness. A more robust safety supervision mechanism contributes to safer gas conditions. The safety investment fulfillment rate pertains to the safety investments made for gas safety, relative to the planned investments. A higher fulfillment rate corresponds to better gas safety conditions[15]. Therefore, the Shili factors of gas safety comprise three elements: organizational structure completeness, safety supervision mechanism effectiveness, and safety

investment fulfillment rate.

The Renli factors of gas safety conditions characterize the impact of human elements on gas safety. Better safety training leads to improved gas safety conditions; higher employee safety awareness contributes to a safer gas situation; and a more impeccable emergency management system enables personnel to respond to unexpected events more effectively and orderly, enhancing gas safety[16]. Therefore, the Renli factors of gas safety comprise three elements: safety training quality, employee safety awareness, and the completeness of the emergency management system.

1.3 Classification of Coal Mine Gas Safety Levels

Based on relevant literature research, the gas safety conditions in coal mines and their influencing factors are classified into four risk levels: I, II, III, and IV. These levels correspond to safety, relatively safe, relatively dangerous, and dangerous[17], respectively, as illustrated in Table 1.

Table 1 Grades classification on influencing factor of coal mine gas safety risk

Coal mine gas safety hazard U_i	Index level	Coal mine gas safety hazard level			
		I	II	III	IV
Wuli U_1	U_{11} Geological structure complexity	0~0.2	0.2~0.4	0.4~0.7	0.7~1.0
	U_{12} Depth of coal seam /m	≤ 400	400~600	600~800	≥ 800
	U_{13} Gas pressure / Mpa	0~0.66	0.66~0.74	0.74~3.0	≥ 3.0
	U_{14} Sturdiness coefficient of coal	≥ 3	2~3	1.5~2	≤ 1.5
	U_{15} Coal seam gas content / (m^3/t)	0~10	10~12	12~15	≥ 15
Shili U_2	U_{21} Organizational integrity	0.95~1.0	0.90~0.95	0.85~0.90	0~0.85
	U_{22} Safety supervision perfection	0.95~1.0	0.90~0.95	0.85~0.90	0~0.85
	U_{23} Safe investment rate	0.9~1.0	0.8~0.9	0.7~0.8	0~0.7
Renli U_3	U_{31} Safety training	0.9~1.0	0.8~0.9	0.7~0.8	0~0.7
	U_{32} Employee safety awareness	0.95~1.0	0.90~0.95	0.85~0.90	0~0.85
	U_{33} Perfection of emergency system	0.95~1.0	0.90~0.95	0.85~0.90	0~0.85

2 Determination of Comprehensive Weights Based on the G1-CRITIC

Method

2.1 Calculation of Subjective Weights Using the G1 Method

The G1 method is a subjective weighting technique[18] that, compared to other methods, offers advantages such as reduced computational effort and ease of use. The calculation process is as follows:

(1) Determination of Indicator Order Relationships: Assume that m experts are selected to evaluate n indicators within the coal mine gas safety assessment system. The order relationships among the indicators are determined based on the importance scores assigned by the experts.

$$H = \{H_1, H_2, \dots, H_n\} \quad (1)$$

(2) Calculation of the Ratio of Importance Between Adjacent Indicators

$$R_k = \frac{H_{k-1}}{H_k} (k = 1, 2, \dots, n) \quad (2)$$

(3) Calculation of Indicator Weights

$$W_n^G = \frac{1}{1 + \sum_{k=2}^n \left(\prod_{l=k}^n R_l \right)} \quad (3)$$

$$W_{k-1}^G = W_k^G \times R_k \quad (4)$$

2.2 Calculation of Objective Weights for Indicators Based on the Improved CRITIC Method

The improved CRITIC weighting method[18] is an objective approach that captures the interdependencies among indicators. The method uses the enhanced CRITIC information measure to reflect the information content of each indicator. It then employs the ratio of the enhanced CRITIC information measure of each assessment indicator to that of the least important indicator to determine the relative importance ratios. The calculation process is as follows:

(1) Calculation of Information Content of Indicators

$$C_k = \frac{\sigma_k}{u_k} \sum_{i=1}^m (1 - |t_{ik}|), k = 1, 2, \dots, m \quad (5)$$

In the formula, C_k represents the improved CRITIC information measure for the k -th indicator, σ_k denotes the standard deviation of the k -th indicator, μ_k is the mean of

the k -th indicator, and $\sum_{i=1}^m (1 - |t_{ik}|)$ represents the quantified value of the interaction between the k -th indicator and other indicators. t_{ik} denotes the correlation coefficient between the i -th and k -th assessment indicators.

(2) Determination of Indicator Weight W_k^{CK}

$$W_k^{CK} = \frac{C_k}{\sum_{i=1}^m C_i}, i = 1, 2, \dots, m \quad (6)$$

2.3 Determination of G1-CRITIC Comprehensive Weights

The distance function discriminant method is introduced to determine the weights of coal mine gas status assessment indicators based on G1-CRITIC. Respectively, α and β represent the weight coefficients of indicators W_k^G and W_k^{CK} . The distance function M and the comprehensive weight W_k satisfy the following conditions:

$$M = (W_k^G, W_k^{CK}) = \left[\frac{1}{2} \sum_{i=1}^n (W_k^G - W_k^{CK})^2 \right]^{\frac{1}{2}} \quad (7)$$

$$W_k = \alpha W_k^G + \beta W_k^{CK} \quad (8)$$

The distance function M and the weights α and β satisfy the following conditions:

$$M(W_k^G, W_k^{CK})^2 = (\alpha - \beta)^2 \quad (9)$$

$$\alpha + \beta = 1, \alpha > 0, \beta > 0 \quad (10)$$

3 Cloud Model for Safety Assessment of Mine Gas Conditions

Cloud models enable uncertain transformation of qualitative concepts and quantitative descriptions by establishing a mapping relationship between quantitative and qualitative concepts[19].

3.1 Cloud model definition and its numerical characteristics

U is the theoretical domain corresponding to the values of coal mine gas safety indicators, C is the qualitative concept in coal mine gas safety indicators, x denotes cloud drops, and $u(x)$ is the affiliation degree of any cloud drop x to C in the theoretical

domain U , then

$$\mu: U \rightarrow [0,1], \forall x \in U, x \rightarrow \mu(x) \quad (11)$$

The cloud model is represented by expectation (Ex), entropy (En), and superentropy (He). Ex is the center of the cloud graph, En characterizes the reliability of Ex , and He characterizes the uncertainty of En . The distribution interval of cloud drops x is $[Ex-3En, Ex+3En]$.

3.2 Cloud Generator

The cloud generator is divided into forward and inverse cloud generators. The forward cloud generator mainly realizes the conversion from qualitative concept to quantitative, and the calculation steps are as follows:

- (1) With expectation En , variance He^2 , generate Gaussian random number $E'_{n_i} = NORM(En, He^2)$.
- (2) With the expected value of Ex , variance $E'^2_{n_i}$ Constructing Gaussian random numbers $x_i = NORM(En, E'^2_{n_i})$.
- (3) Calculation of the determination of the index:

$$\psi_i = \exp\left[-\frac{(x_i - Ex)^2}{2(En)^2}\right] \quad (12)$$

where ψ_i is the degree of determination of the index.

- (4) Cloud droplet interval construction, based on the above steps to form a cloud droplet (x_i, u_i) , and then repeat steps (1)~(3), until the formation of N cloud droplets.

3.3 Cloud numerical characteristics of coal mine gas safety indexes in mines

Referring to the related research results[20], the cloud number characteristics of coal mine gas safety hazard index in the mine can be calculated as follows,

$$\begin{cases} Ex = (F_{\min} + F_{\max}) / 2 \\ Ex = (F_{\max} - F_{\min}) / 6 \\ He = k \end{cases} \quad (13)$$

Where, $F_{\max}$ is the upper limit of the index value and $F_{\min}$ is the lower limit. k is

the degree of index fuzziness, which is taken as 0.05 here.

Based on the graded values of Table 1 indicators, the cloud numerical characteristics of the coal mine gas safety evaluation indicators are calculated by equation (14), and for variables with unilateral boundaries, their numerical characteristics are obtained in the form of boundary parameters[21], as shown in Table 2.

Table 2 Numerical characteristics of cloud model for index of coal mine gas safety

Index	Grade I (Ex, En, He)	Grade II(Ex, En, He)	Grade III(Ex, En, He)	Grade IV(Ex, En, He)
U_{11}	(0.10,0.03,0.05)	(0.30,0.03,0.05)	(0.55,0.05,0.05)	(0.85,0.05,0.05)
U_{12}	(400,66.67,0.05)	(500,33.33,0.05)	(700,33.33,0.05)	(800,33.33,0.05)
U_{13}	(0.33,0.11,0.05)	(0.70,0.01,0.05)	(1.87,0.38,0.05)	(3.00,0.38,0.05)
U_{14}	(3.00,0.17,0.05)	(2.50,0.17,0.05)	(1.75,0.083,0.05)	(1.50,0.25,0.05)
U_{15}	(5.00,1.67,0.05)	(11.00,1.00,0.05)	(13.50,0.50,0.05)	(15.00,0.50,0.05)
U_{21}	(0.975,0.008,0.05)	(0.925,0.008,0.05)	(0.875,0.008,0.05)	(0.425,0.142,0.05)
U_{22}	(0.975,0.008,0.05)	(0.925,0.008,0.05)	(0.875,0.008,0.05)	(0.425,0.142,0.05)
U_{23}	(0.95,0.017,0.05)	(0.85,0.017,0.05)	(0.75,0.017,0.05)	(0.35,0.117,0.05)
U_{31}	(0.95,0.017,0.05)	(0.85,0.017,0.05)	(0.75,0.017,0.05)	(0.35,0.117,0.05)
U_{32}	(0.975,0.008,0.05)	(0.925,0.008,0.05)	(0.875,0.008,0.05)	(0.425,0.142,0.05)
U_{33}	(0.975,0.008,0.05)	(0.925,0.008,0.05)	(0.875,0.008,0.05)	(0.425,0.142,0.05)

3.4 Comprehensive discriminative model construction

Based on the cloud numerical characteristics of the evaluation indexes of coal mine gas safety evaluation, the cloud diagram of evaluation indexes is generated and the determinacy of each index under different hazard levels is determined. Then the comprehensive rating of coal mine gas safety is calculated.

$$U = \sum_{j=1}^n \psi_k W_k \quad (14)$$

where ψ_k is the single indicator determinant and W_k is the optimal combination weight.

3 Case study

A case study is conducted using the No. 3 coal seam of Wangzhuang Mine, Shanxi Lu'an Group, to validate the coal mine gas condition safety assessment method based

on the G1-improved CRITIC-weighted cloud model. Wangzhuang Mine, located in Changzhi City, Shanxi Province, has a rated production capacity of 7.10 Mt/a and is classified as a high-gas mine. The geological structure of Wangzhuang Mine is relatively simple, with a coal seam depth of approximately 740 meters. Gas pressure is measured at 0.08 MPa, the coal firmness coefficient is 0.45, and the gas content in the coal seam is 8.20 m³/t. Other indicators are assessed based on expert evaluation.

Qualitative and quantitative index values are determined through expert experience. Based on the principle of the G1 method for determining weights, industry experts are consulted to analyze the sequence relationships and importance of each indicator. According to formulas (1) to (4), subjective weights are calculated, and based on formulas (5) to (6), objective weights for indicators are determined using the improved CRITIC method. Finally, combining formulas (7) to (10), the comprehensive weights of the indicators are determined. The weights of indicators for the safety assessment of coal mine gas conditions are shown in Table 3.

Table 3 Weights of the Coal Mine Gas Condition Assessment Indicator System

Secondary index	Three-level index	G1		CRITIC		Combined weight	
		Secondary index	Three-level index	Secondary index	Three-level index	Secondary index	Three-level index
Wuli U_1	U_{11}	0.417	0.086	0.386	0.091	0.406	0.088
	U_{12}		0.094		0.086		0.092
	U_{13}		0.103		0.096		0.101
	U_{14}		0.086		0.088		0.088
	U_{15}		0.098		0.104		0.102
Shili U_2	U_{21}	0.281	0.088	0.296	0.084	0.289	0.084
	U_{22}		0.082		0.086		0.082
	U_{23}		0.095		0.088		0.092
Renli U_3	U_{31}	0.302	0.093	0.318	0.095	0.305	0.094
	U_{32}		0.091		0.094		0.092
	U_{33}		0.084		0.088		0.085

Based on the cloud digital characteristics of coal mine gas condition safety indicators from Table 2, the risk level certainty of each indicator is calculated using Formula (12). Then, by combining the comprehensive weights of the coal mine gas

condition safety indicators from Table 3, the overall certainty of the hazard assessment model is calculated using Formula (14) to determine the safety level of the No. 3 coal seam at Wangzhuang Mine. The calculation results show that the safety level certainty of the No. 3 coal seam at Wangzhuang Mine is $P(I)=0.088$, $P(II)=0.132$, $P(III)=0.106$, and $P(IV)=0.075$. According to the principle of maximum certainty, the gas safety risk level of the No. 3 coal seam at Wangzhuang Mine is classified as Level II, which is consistent with the actual conditions of the mine.

4 Conclusions

By introducing the WSR methodology, a set of influencing factors for coal mine gas conditions was constructed across three dimensions: Wuli, Shili, and Renli. Based on relevant research, a grading criterion for these influencing factors was established. A method for determining indicator weights was proposed, which combines the G1 method for subjective weights, the improved CRITIC method for objective weights, and the distance function method for comprehensive weights. Additionally, a cloud model for coal mine gas condition safety assessment was developed using cloud model theory. This model was validated through an engineering case study of the No. 3 coal seam at Wangzhuang Mine, Shanxi Lu'an Group, where the gas condition level was determined to be Level II, consistent with the actual conditions observed at the mine.

Author contributions

Wenke Zhang contributed to the idea of research, performed the data analysis and wrote the manuscript.

Data availability statement

All data generated or analysed during this study are included in this published article.

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