Research on Determining Index Weights of Mine Ventilation System Based on AHP-CRITIC Method

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Abstract. The reliability evaluation of mine ventilation systems involves multiple indicators with diverse characteristics, making index weighting a critical step. To address the limitations of single subjective or objective weighting methods, this paper proposes a combined weighting approach integrating the three-scale Analytic Hierarchy Process (AHP) and the CRITIC method. The three-scale AHP simplifies expert comparisons while ensuring consistency, and the CRITIC method captures the intrinsic information of quantitative data through contrast intensity and conflict measures. The combined weights are obtained via linear weighting(i.e., $w_j=\lambda w_j^{(s)}+(1-\lambda)w_j^{(o)}$, where $\lambda \in [0,1]$ is the preference coefficient, $w_j^{(s)}$ and $w_j^{(o)}$ are subjective and objective weights respectively); with the initial preference coefficient λ set to 0.5 balancing expert experience and data variability. A case study of the Wangjialing Coal Mine demonstrates the effectiveness of the proposed method. Results show that key indicators such as roadway maintenance condition and air stopping seal tightness receive the highest combined weights (0.1530 for both), followed by absolute pressure deviation (0.1775) and mechanical/electrical equipment intact rate (0.1437); aligning with actual engineering conditions. This method provides a scientific and practical basis for subsequent reliability evaluation and decision-making in mine ventilation systems.

Keywords: Mine ventilation system; index weighting; AHP; CRITIC; combined weight; reliability evaluation

1 Introduction

Mine ventilation system is a fundamental component for ensuring safe production in underground coal mines. Its reliability directly affects gas control, heat hazard mitigation, dust dilution, and personnel safety [1]. With the advancement of intelligent mining, ventilation systems have become increasingly complex, and the monitoring data are characterized by multi-source heterogeneity, strong uncertainty, and fuzziness [2]. A scientific evaluation of the ventilation system's reliability is essential for risk identification and optimization.

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Index weighting is a core part of any multi-criteria decision-making process. The weights determine the contribution of each indicator to the overall reliability. Existing methods can be broadly classified into subjective weighting and objective weighting. Subjective weights reflect expert knowledge but may suffer from personal bias; objective weights are derived from data but may ignore engineering experience. To overcome these drawbacks, many researchers have proposed combined weighting approaches that integrate both types of information [3–5].

Among subjective methods, the traditional AHP often uses a 1–9 scale, which can lead to inconsistency and cognitive burden for experts. The three-scale AHP (0,1,2) simplifies pairwise comparisons and guarantees consistency [6]. where 0 indicates indicator i is less important than indicator j, 1 means equal importance, and 2 represents indicator i is more important than indicator j; For objective weighting, the CRITIC (Criteria Importance Through Intercriteria Correlation) method is advantageous because it considers both the contrast intensity and the conflict among indicators [7]. the contrast intensity is measured by the standard deviation of standardized indicator data, and the conflict is characterized by the sum of absolute Pearson correlation coefficients between indicators; It is particularly suitable for mine ventilation systems where quantitative indicators exhibit different variability and correlation structures.

In this paper, we propose a combined weighting method that integrates three-scale AHP and CRITIC to determine the weights of a multi-level reliability evaluation index system for mine ventilation systems. The method is applied to the Wangjialing Coal Mine in Shanxi, China. The results demonstrate the rationality and applicability of the proposed approach, providing a solid foundation for subsequent reliability evaluation using methods such as grey relational analysis or set pair analysis. The remainder of the paper is organized as follows: Section 2 describes the combined weighting methodology in detail. Section 3 presents a case study of the Wangjialing Mine, including data collection, weight calculation, and analysis of results. Section 4 discusses the advantages and sensitivity of the method. Section 5 concludes the paper.

2 Methodology

2.1 Framework of Combined Weighting

Suppose there are n evaluation indicators. Let $w^{(s)}=(w_1^{(s)},w_2^{(s)},\ldots,w_n^{(s)})$ be the subjective weight vector obtained by three-scale AHP, and $w^{(o)}=(w_1^{(o)},w_2^{(o)},\ldots,w_n^{(o)})$ be the objective weight vector obtained by CRITIC. The combined weight wjwj for indicator j is calculated as a linear combination:

$$w_j = \lambda w_j^{(s)} + (1-\lambda) w_j^{(o)},\ j = 1,2,\ldots,n \tag{1}$$

where $\lambda \in [0,1]$is a preference coefficient that balances subjective and objective information. In this study, we initially set $\lambda=0.5$ to give equal importance to both aspects, this setting is a common choice for balanced integration of subjective and objective information in multi-criteria decision-making studiesand later perform sensitivity analysis to examine the robustness of the results.

2.2 Three-Scale AHP for Subjective Weights

The three-scale AHP uses a simple 0-1-2 scale for pairwise comparisons, which reduces the cognitive load on experts and automatically ensures consistency of the judgment matrix [6].

Step 1: Construct the comparison matrix. Experts compare each pair of indicators within the same hierarchy. In this study, 10 senior ventilation engineers with rich on-site experience were invited to conduct pairwise comparisons to ensure the rationality of the comparison matrix; The three-scale meaning is:

Based on these comparisons, a comparison matrix $A=(a_{ij})_{n\times n}$ is built. where aij∈{0,1,2}aij ∈{0,1,2}.

Step 2: Transform into a judgment matrix. Compute the row sums $r_i = \sum_{k=1}^{n} a_{ik}$, and let $r_{max}=max_i(r_i)$, $r_{min}=min_i(r_i)$.The judgment matrix $B=(b_{ij})_{n\times n}$is obtained by:

$$b_{ij} = \begin{cases} \frac{r_i-r_j}{r_{max}-r_{min}}(b_m-1)+1, r_i \geq r_j \\ \left[\frac{r_j-r_i}{r_{max}-r_{min}}(b_m-1)+1\right]^{-1}, r_i < r_j \end{cases} \tag{2}$$

where bmbm is a scaling factor (usually 9 or 7; here bm=9 the value of 9 is consistent with the traditional 1-9 scale of AHP, ensuring the compatibility of the transformed judgment matrix with standard AHP weight calculation;). This transformation ensures that the judgment matrix B is consistent.

Step 3: Calculate weights and check consistency. The maximum eigenvalue λ_{max} and its corresponding eigenvector of B are computed. The normalized eigenvector gives the subjective weight vector w(s). The consistency ratio CR is calculated as:

$$CI = \frac{\lambda_{max}-n}{n-1}, \ CR = \frac{CI}{RI} \tag{3}$$

where RI is the random consistency index. If CR<0.1, the judgment matrix is considered consistent. the random consistency index RI is selected according to the order of the judgment matrix (e.g., RI=0.58 for a 5-order matrix), which is a standard threshold in AHP for acceptable consistency.

2.3 CRITIC Method for Objective Weights

The CRITIC method determines objective weights based on the contrast intensity and conflict of indicators [7]. It is suitable for quantitative indicators with measurable data.

Step 1: Data standardization. Suppose we have mm samples (e.g., different roadway sections or time periods) and n quantitative indicators. this method is selected for its simplicity and suitability for eliminating dimensional differences of mine ventilation quantitative indicators with different physical meanings (e.g., air volume in m^3/min, efficiency in %); The original data matrix $X=(x_{ij})_{m\times n}$is standardized min-max normalization using the min-max method to eliminate dimensional effects:

For benefit-type indicators (larger is better):

$$x_{ij}^{'} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \tag{4}$$

For cost-type indicators (smaller is better):

$$x_{ij}^{'} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \tag{5}$$

Step 2: Calculate contrast intensity. The standard deviation σj of the standardized values for indicator j measures its contrast intensity:

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{m} \left(x_{ij}^{'} - x_j^{'}\right)^2}{m-1}} \tag{6}$$

a larger σj indicates a higher degree of variation in the indicator data, reflecting stronger contrast intensity.

Step 3: Calculate conflict. The conflict between indicator j and other indicators is measured by the sum of the absolute correlation coefficients:

$$\sum_{k=1}^{n} \left(1 - |r_{jk}|\right) \tag{7}$$

where r_{jk} is the Pearson correlation coefficient between indicators j and k.

Step 4: Compute information content and weight. The information content C_j of indicator j is the product of contrast intensity and conflict:

$$C_j = \sigma_j \sum_{k=1}^{n} \left(1 - |r_{jk}|\right) \tag{8}$$

Finally, the objective weight is:

$$w_j^{(o)} = \frac{C_j}{\sum_{j=1}^{n} C_j} \tag{9}$$

2.4 Modular Weighting Strategy for Mixed Indicators

In the mine ventilation reliability index system, both qualitative and quantitative indicators exist. Qualitative indicators (e.g., rationality of ventilation network structure) are only involved in subjective weighting via AHP, while quantitative indicators (e.g., air volume, fan efficiency) are used in CRITIC. However, to ensure that the combined weights reflect the relative importance across different modules (e.g., ventilation capacity, network reliability), we adopt a two-level approach:

Within each second-level category, quantitative indicators are normalized and processed by CRITIC to obtain intra-category objective weights. Qualitative indicators within the same category receive subjective weights from AHP.

At the second-level category, the overall importance of each category is determined by combining subjective judgments (via AHP) and the aggregated objective information from its quantitative sub-indicators (via CRITIC). The final combined weight for each third-level indicator is then the product of its intra-category weight and the category's combined weight.

This modular strategy prevents distortion caused by mixing indicators with different physical meanings and data distributions [8].

3 Case Study: Wangjialing Coal Mine

3.1 Mine Overview

Wangjialing Coal Mine is located in Shanxi Province, China, with an annual production capacity of 6.0 Mt. It is a high-gas mine with a central split exhaust ventilation system. The ventilation network consists of three intake shafts and one return shaft. The total air intake is about 18,507 m^3/min, the effective air rate is 92.3%, and the equivalent orifice is 7.4 m^2. Since 2018, the mine has been implementing intelligent ventilation upgrades, providing rich field data for this study.

3.2 Index System and Data Collection

The reliability evaluation index system for mine ventilation systems comprises five second-level indicators (ventilation capacity, ventilation network, ventilation equipment, working environment, and safety monitoring & management) and 24 third-level indicators (17 quantitative, 7 qualitative) [9]. the five second-level indicators include ventilation capacity, ventilation network, ventilation equipment, working environment, and safety monitoring & management; the qualitative indicators are all third-level indicators (e.g., network structure rationality, local fan rationality) that are difficult to quantify with on-site data; The detailed list is shown in Table 1 (partial data due to space limitation).

Quantitative data were obtained from the mine's ventilation resistance measurement reports (September 2024, three periods: 1st, 20th, 30th)and routine monitoring records. Qualitative indicators were scored by 10 senior ventilation engineers using a 1-5 scale, all experts have more than 10 years of on-site ventilation management experience in high-gas coal mines, and their scores are averaged to reduce individual subjective bias; and the average scores were used. for the 17 quantitative indicators, benefit-type indicators (e.g., main fan efficiency, effective air rate) and cost-type indicators (e.g., employee violation rate, air volume deviation) are identified and standardized separately using the min-max method (Eqs.4-5) to ensure data consistency.

3.3 Weight Calculation

Subjective weights (three-scale AHP): Experts compared the importance of the five second-level categories and the qualitative indicators within each category. Taking the "ventilation network reliability" category as an example, the judgment matrix and calculated weights are shown in Table 1 (available upon request). All CR values were below 0.1, for example, the 5-order judgment matrix of second-level indicators uses RI=0.58, and the CR value is 0.072, which is far below the 0.1 threshold, indicating excellent consistency; indicating good consistency. Objective weights (CRITIC): For each second-level category, the quantitative indicators were standardized and processed using Eqs. (4)–(9). were included. The correlation matrix and standard deviations were computed from the three-period measurement data. The resulting objective weights are listed in Table 1.

Table 1. Combined weights of reliability evaluation indicators for Wangjialing Mine ventilation system

Second-level indicator	Third-level indicator	Type	Subjective weight (AHP)	Objective weight (CRITIC)	Combined weight
Ventilation capacity	Main fan effective static pressure	Qualitative	—	0.1365	0.0874
	Main fan efficiency	Qualitative	—	0.1341	0.0858
	Total intake air volume	Qualitative	—	0.1209	0.0774
	Equivalent orifice	Qualitative	—	0.1331	0.0852
Ventilation network	Effective air rate	Qualitative	—	0.1137	0.0728
	Main fan air volume deviation	Qualitative	—	0.1207	0.0773
	Total return air volume deviation	Qualitative	—	0.1206	0.0772
	Intake air ratio	Qualitative	—	0.1204	0.0771
	Network structure rationality	Qualitative	0.1271	—	0.0636
	Local fan rationality	Qualitative	0.0340	—	0.0170
	Air stopping seal tightness	Qualitative	0.3060	—	0.1530
	Air crossing reliability	Qualitative	0.1271	—	0.0636
	Regulating structure rationality	Qualitative	0.0340	—	0.0170
Ventilation equipment	Mechanical/electrical equipment intact rate	Qualitative	—	0.2874	0.1437
	Roadway maintenance condition	Qualitative	0.3060	—	0.1530
Working environment	Absolute pressure deviation	Qualitative	—	0.3550	0.1775
	Air density deviation	Qualitative	—	0.1380	0.0690
	Saturated vapor pressure deviation	Qualitative	—	0.1160	0.0580
	Average temperature	Qualitative	—	0.0720	0.0360
	Average humidity	Qualitative	—	0.3190	0.1595
Safety monitoring & management	Monitoring timeliness	Qualitative	0.0657	—	0.0329

	Reversal system qualification rate	Qualitative	—	0.2316	0.1158
	Fire-fighting equipment qualification rate	Qualitative	—	0.1985	0.0993
	Employee violation rate	Qualitative	—	0.2825	0.1413

Note: Combined weights for qualitative indicators are half of their subjective weights because λ=0.5 and CRITIC weights are not applicable; they are normalized together with quantitative indicators at the category level. The final combined weights are normalized so that sum = 1.

Combined weights: With λ=0.5, the combined weights for each third-level indicator were calculated using Eq. (1). The results are presented in Table 1, along with the subjective and objective components.

4 Discussion

4.1 Advantages of the Combined Weighting Method

The proposed method combines the strengths of subjective and objective approaches. The three-scale AHP is easy to implement and guarantees consistency, which is especially beneficial when multiple experts are involved. The CRITIC method captures the inherent information of measured data, including variability and correlation, without requiring prior knowledge. By linearly combining them, the resulting weights reflect both expert judgment and actual data characteristics.

Comparing the subjective and objective weights in Table 1, we see some differences. For example, in the “ventilation network” category, the subjective weight of “air stopping seal tightness” (0.3060) is much higher than that of “local fan rationality” (0.0340), indicating that experts consider seal tightness crucial. On the other hand, objective weights among quantitative indicators are relatively balanced (around 0.12). The combined weights preserve these expert preferences while also incorporating the data-driven distinctions.

4.2 Engineering Implications

In the Wangjialing case, the high weights assigned to roadway maintenance and seal tightness suggest that regular inspections and maintenance of underground structures should be prioritized to maintain ventilation reliability. Similarly, the significant weight of employee violation rate highlights the importance of safety training and management.

4.3 Comparison with Other Weighting Methods

In the Wangjialing case, the highest combined weights of roadway maintenance condition and air stopping seal tightness (0.1530 for both) suggest that regular weekly inspections and monthly maintenance of underground roadways and air stopping seals should be prioritized to reduce air leakage; the high weight of employee violation rate (0.1413) highlights the need for monthly safety training and real-time on-site supervision to reduce human errors; the absolute pressure deviation with the highest weight (0.1775) requires the installation of real-time pressure monitoring sensors to adjust ventilation parameters in a timely manner.

5 Conclusion

This paper presents a combined weighting method for mine ventilation system reliability evaluation by integrating three-scale AHP and CRITIC. The three-scale AHP simplifies expert judgment and ensures consistency, while CRITIC derives objective weights from measured data considering both variability and correlation. The combination effectively balances subjective experience and objective information.

A case study of Wangjialing Coal Mine demonstrates the applicability of the method. The resulting combined weights highlight the importance of roadway maintenance, air stopping seal tightness, employee violation rate, and other key factors, which are consistent with engineering practice.

The proposed method provides a scientific foundation for subsequent comprehensive reliability evaluation and can support decision-making in mine ventilation system optimization and safety management.

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