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Screening of Evaluation Index and Construction of Evaluation Index System for Mine Ventilation System

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Abstract: The mine ventilation system is an indispensable component to improve coal mining efficiency and ensure the safety of production. Only by clearly grasping the comprehensive evaluation quality of the ventilation system can effective countermeasures be formulated. This paper establishes an evaluation index system for mine ventilation systems by combining a qualitative survey with quantitative research. Specifically, the primary indicators are screened through R-type clustering and the coefficient of variation method. The weight of each index is determined by the entropy weight method. Moreover, the technique for order preference by similarity to ideal solution (TOPSIS) method is used to evaluate the quality of the mine ventilation system. Finally, this evaluation system is used to evaluate the ventilation renovation project in the production mining area of the Sihe mine. The evaluation results verify the effectiveness of the establishment of the mine ventilation evaluation index system and of the evaluation methods.

Keywords: effectiveness evaluation; R clustering; coefficient of variation; optimization

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Citation: Bi, Q.-P.; Li, Y.-C.; Shen, C. Screening of Evaluation Index and Construction of Evaluation Index System for Mine Ventilation System. *Sustainability* **2021**, *13*, 11810. https://doi.org/10.3390/su132111810

Academic Editor: Alessandro Franco

Received: 26 September 2021
Accepted: 21 October 2021
Published: 26 October 2021

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1. Introduction

Coal has expanded globally as one of the foundational energy sources in the last few decades [1]. With the intention of sustainably using the limited coal resources, improving coal mining efficiency and mining safety are key influencing factors [2]. The premise of improving coal mining efficiency is to ensure the efficient operation of underground ventilation system. Moreover, most safety accidents in coal mines are related to underground ventilation systems [3]. A mine ventilation system is a complex dynamic regulation system which is accountable for transporting fresh air flow to underground roadways, meeting the respiratory requirements of staff, diluting harmful gases in roadways and eliminating toxic gases unrelated to production. Therefore, mine ventilation plays an essential role in safe production at the mine. The safety and stability of the mine ventilation system can be affected by many factors, such as design defects in the ventilation system, inadequate daily maintenance, and failure of the ventilation system to match the changes of excavation production in a timely fashion. Dramatic changes in any one of the internal or external factors can generate an enormous challenge to the safety and stability of the ventilation system and expand the risk of potential accidents. Hence, a universal evaluation system is needed in order to evaluate the quality of mine ventilation systems, which can propound scientific evaluation according to changes in the mine ventilation system [4].

The evaluation of mine ventilation systems primarily evaluates the quality of the ventilation system in three aspects: safety and reliability, economic rationality, and technical feasibility. The ventilation system corresponds to the actual demand by reasonably

arranging air flow routes and the air use position of the ventilation network. For mine ventilation systems, effective evaluation methods have been proposed to improve the accuracy and effectiveness of evaluation, which can be primarily summarized in three categories: the traditional evaluation method, combining a geographic information system (GIS) with other evaluation methods; the empirical evaluation method, based on several important indicators; and the comprehensive evaluation method, based on multiple index items [5].

Thanks to the efforts of researchers, more and more methods based on the comprehensive evaluation of multiple indicators have been proposed and extensively applied, including: fuzzy mathematics [6], technique for order preference by similarity to ideal solution (TOPSIS) [7], gray theory [8], discriminant analysis method [9], support vector machine method [10], neural network method [11], unascertained measure method [12] and multi-level fuzzy comprehensive evaluation method [13]. The comprehensive evaluation process based on multiple indicators is mainly composed of three parts: the establishment of an evaluation index system, the determination of index weight, and the selection of evaluation methods. Among these, determination of the weight of evaluation indicators is a significant part of the whole evaluation process. According to their different sources of original data and calculation processes when calculating the weight coefficient, weight determination methods are generally divided into three categories: the subjective weighting method, objective weighting method and combination weighting method [14]. The most reasonable weighting method should consider not only the objective law of indicator data, but also the central role of expert experience [15]. Zhang et al. used an improved analytic hierarchy process (AHP) and the entropy weight method to calculate the subjective and objective weight of the indexes for urban distribution networks [16]. Guo et al. proposed the AHP-ENTROPY weighting method combining subjective and objective weighting methods to obtain better index weights [17]. They achieved dynamic weighting of the indicators considering the dynamic changes of the index weights in different system scenarios.

After determining the reasonable index weight, the next crucial step is to select an evaluation method conforming to the actual situation. Zhao et al. proposed a performance evaluation method for smart meters based on grey correlation analysis [18]. Zhang et al. used a comprehensive evaluation method to realize the introduction of dimensional and multi-index quantitative analysis [19]. They used the comprehensive evaluation method to simplify the multi-level evaluation index, reduce the index hierarchy, and calculate the ideal solution. Shi presents the adoption of a fuzzy comprehensive evaluation model and group-decision AHP in evaluating the quality of construction projects [20]. This method could improve the validity and accuracy of the assessment, and it did not rely on the experience of experts. Jia et al. established an index system using the indicator importance sort algorithm [21]. This method was actually a combination method including expert experience and theoretical calculation.

Unlike other evaluation occasions, an evaluation system for mine ventilation has such unique characteristics as multiple indicators, large amounts of statistical data, and many influencing factors. Jiang et al. used the unascertained measure theory and the uncertain information method to determine an evaluation system for mine ventilation. They applied this method to a lead–zinc mine ventilation system and achieved general results [22]. Cheng et al. proposed an integrated comprehensive method based on grey cluster analysis–fuzzy theory for selecting and evaluating the most suitable mine ventilation system [23]. Zhou et al. presented an approach to rank the alternatives by G1-coefficient of variation method. The result showed that this method could rank the alternative development face ventilation mode reasonably [24]. Yan et al. proposed a novel evaluation method based on cloud model clustering for the ventilation system of an underground metal mine [25]. The ventilation effectiveness could be properly classified as demonstrated by one case. Gao used the factor analysis method to screen the ventilation indicators and created the AHP-WRSR evaluation model by combining the analytic hierarchy process (AHP) and weight rank–sum ratio (WRSR) to optimize the scheme of a mine ventilation system [26].

However, qualitative methods such as expert consultation or literature summaries [27] are mostly used for the above index screening methods, and a quantitative screening process for indicators is lacking. Furthermore, some methods for quantitative screening of indicators have repeated indicators. These issues make it difficult for indicators to reflect satisfactory ventilation system information. Some of the above methods require the experience of experts, and if the experience of experts is unreliable, the obtained results will also be affected. Moreover, the above evaluation model is only focused on the evaluation of existing schemes, and no new schemes are considered. Facing complex systems such as multiple samples and multiple indicators, the above methods have the shortcoming of computational complexity and insufficient flexibility.

Aiming at the above problems, this paper studies the mine ventilation evaluation index system by combining qualitative research with quantitative research. Specifically, the primary evaluation index was determined through expert consultation and reference summary. Then, the primary index was screened through R-type clustering and the coefficient of variation method. Because the original data of the index were derived from the questionnaire and had a certain subjective willingness, this paper utilized the entropy weight method to determine the index weight. Finally, inspired by Li et al. [15], the TOPSIS method was employed for scheme evaluation.

The rest of this paper is organized as follows. Section 2 introduces the index screening method based on R-cluster and coefficient of variation. Section 3 establishes the evaluation index system for mine ventilation systems. Section 4 gives a case of mine ventilation optimization and lists the final optimization results and relevant analysis. Finally, the concluding remarks are summarized in Section 5.

2. Index Screening Based on R-Cluster and Coefficient of Variation

2.1. Repeated Index Clustering

Based on the evaluation data collected by the questionnaire, the indicators within the same guideline hierarchy are clustered by the R-type clustering method. Thereby, the data with strong correlations within the same criterion layer are apparently discovered. By screening indicators after R-cluster analysis, the problem of overlapping questionnaire evaluation indicators is effectively decreased. In this study, the minimum clustering criterion of deviation squares (MCCDS) was carried out to cluster indicators of the same criterion layer. Assuming that there are n indicators divided into p classes, the sum of the sums of the squared deviations of p classes is:

$$S = \sum_{i=1}^{p} \sum_{j=1}^{m_i} (X_i^j - \overline{X_i})'(X_i^j - \overline{X_i}) \ (i = 1, 2, \cdots, p) \tag{1}$$

where m_i represents the number of evaluation indicators in the ith category; X_i^j represents the value of the jth evaluation indicator in the ith category; and $\overline{X_i}$ represents the mean value of evaluation indicators of the ith class.

The distinct steps of R-type cluster analysis based on MCCDS are as follows:

- Step 1: Consider n evaluation index as n categories.
- Step 2: Any two of the n classes are combined into one class; the others remain unchanged. The total sum of the squared deviations of each scheme is calculated according to Equation (1). The combination scheme with the smallest sum of squares of the total deviation is a new classification. In addition, there is a total of $\mathrm{n} \times (\mathrm{n}+1)/2$ combination schemes.
- Step 3: Repeat step 2 until the preset number of clusters p is reached.

The number of clusters p is set according to expert experience, which has an outstanding influence on the selection of indicators. In order to decrease the influence of subjective arbitrariness, the classification results need to be tested for plausibility. The K–W nonparametric test was utilized in this paper. The classification is justified if the

significance level Sig for each category is >0.05. Otherwise, the cluster analysis needs to be continued until the detection requirements are met.

2.2. Selection of Maximum Information Index

The coefficient of variation is a statistic that measures the degree of dispersion of two or more groups of data. The smaller the coefficient of variation, the more centralized the dataset and the stronger the consistency. On the basis of R-type clustering, by comparing the magnitude of the coefficient of variation of the same category indicator, the indicator with the strongest consistency of the results, that is, the indicator with the smallest coefficient of variation value, is retained [28]. Through further screening of the coefficient of variation, the same category of indicators with weak consistency are removed. Thus, such processing not only preserves the typical indicators in the same category of indicators, but also avoids redundancy and overlap of the same category of indicators. The coefficient of variation of index i is calculated as follows:

$$CV_i = \frac{S_i}{E_i} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_{ij} - \overline{x}_j)^2}}{\overline{x_j}} \quad (2)$$

where CV_i represents the coefficient of variation of the i index; S_i represents the sample standard deviation of the i index; and E_i represents the mean value of the i index.

2.3. Information Contribution Degree of the Selected Index

The principle of judging the rationality of index screening results is that more original information can be reflected with fewer indicators. According to the method that the variance parameter can indicate the information content of the index, the following formula is utilized to calculate the degree of information contribution of the screened index [28]:

$$IC = \frac{\sum_{i=1}^{s} Varx_i}{\sum_{i=1}^{n} Varx_i} \quad (3)$$

where IC represents the information contribution degree of the selected index; $Varx_i$ represents the variance of the ith indicators; s represents number of indicators after screening; and n represents number of initial indicators.

3. Construction of Evaluation Index System for Mine Ventilation System

3.1. Weight Calculation Based on the Entropy Method

The entropy method is an objective method for ascertaining the index weight based on the information entropy of the original index data. In information theory, the entropy is a measure of information irregularity. If a definite indicator contains more information, it indicates that the uncertainty situation is miniature and the corresponding entropy value is smaller. If a definite indicator contains less information, it indicates that the uncertainty situation is considerable and the corresponding entropy value is also large. Entropy values can not only characterize the degree of disorder of data information, but also indicate the degree of dispersion of the data. The main steps of the entropy method are as follows.

Firstly, the evaluation matrix is normalized. The raw data are normalized to map the data to the [0, 1] interval, eliminating the impact of dimensional unit restriction for comparison between different metrics. Generally speaking, there are three categories in an index set: interval index, negative effect index, and positive effect index. These indicators

have different tendencies and need to be consistent when there are many categories of indicators for an evaluation system. The normalized formula for the positive effect index is:

$$x_{ij} = \frac{v_{ij} - \min(v_{ij})}{\max(v_{ij}) - \min(v_{ij})} \tag{4}$$

The normalized formula for the negative effect index is:

$$x_{ij} = \frac{\max(v_{ij}) - v_{ij}}{\max(v_{ij}) - \min(v_{ij})} \tag{5}$$

where x_{ij} represents the value after normalization of the i sample of the j index; v_{ij} represents the original value of the i sample of the j index; $\max(v_{ij})$ represents the largest sample value among all samples for the j indicator; and $\min(v_{ij})$ represents the smallest sample value among all samples for the j indicator.

Secondly, the proportion of the i sample value under the j indicator is shown in the following equation, where p_{ij} represents the proportion of the i sample value under the j index:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{6}$$

Thirdly, the entropy of each indicator E_j is shown in the following equation:

$$E_j = -\frac{\sum_{i=1}^{m} p_{ij} Inp_{ij}}{Inm} \tag{7}$$

Fourthly, the indicator weight ω_j of the j indicator is shown in the following equation:

$$\omega_j = \frac{1 - E_j}{\sum_{j=1}^{n} (1 - E_j)} \tag{8}$$

The value of ω_j is between 0 and 1. The larger the ω_j value, the more significant the value of the j indicator.

3.2. Evaluation Model of TOPSIS

The correlation between the evaluation scheme and each indicator is difficult to indicate accurately in a definite mathematical expression. Therefore, the evaluation results obtained by linearly adding the index value and the weight are not scientific. In this paper, TOPSIS is utilized to evaluate multiple indexes. TOPSIS method is a systematic evaluation method fitting for multi-index and multi-scheme decision analysis. By calculating the weighted Euclidean distance between a scheme and the positive ideal solution, the closeness of the scheme to the positive ideal solution is obtained. The evaluation model is as follows.

Firstly, a weight normalization matrix is constructed. Assuming n evaluation schemes and m evaluation indicators for each scheme, the following characteristic matrix is obtained.

$$D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{9}$$

where x_{ij} represents the value of the j evaluation indicator in the i evaluation scheme. Then, the characteristic matrix is normalized to obtain the normalized matrix.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \tag{10}$$

Assuming that the weight of the indicator is ω, a weight normalization matrix in which the weight and normalization matrix are multiplied is determined.

$$p_{ij} = \omega_j r_{ij} (j = 1, 2, \cdots, m; i = 1, 2, \cdots, n) \tag{11}$$

Secondly, positive and negative ideal solutions are calculated.

$$Z^+ = (\max\{p_{11}, \cdots, p_{n1}\}, \max\{p_{12}, \cdots, p_{n2}\}, \cdots, \max\{p_{1m}, \cdots, p_{nm}\}) = (Z_1^+, \cdots, Z_m^+) \tag{12}$$

$$Z^- = (\max\{p_{11}, \cdots, p_{n1}\}, \max\{p_{12}, \cdots, p_{n2}\}, \cdots, \max\{p_{1m}, \cdots, p_{nm}\}) = (Z_1^-, \cdots, Z_m^-) \tag{13}$$

Thirdly, the closeness of each evaluation scheme to the optimal and worst solution is calculated.

$$D_i^+ = \sqrt{\sum_{j=1}^{m} (p_{ij} - Z_j^+)} \ (i = 1, 2, \cdots, n) \tag{14}$$

$$D_i^- = \sqrt{\sum_{j=1}^{m} (p_{ij} - Z_j^-)} \ (i = 1, 2, \cdots, n) \tag{15}$$

Fourthly, the closeness of the evaluation object to the positive ideal solution is calculated.

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \ (i = 1, 2, \cdots, n) \tag{16}$$

The value of C_i is between 0 and 1. The larger the C_i value, the more acceptable the i evaluation scheme.

4. Case Analysis

In the case of the Sihe Mine, the above evaluation system was used to evaluate the Sihe Mine renovation scheme, and the results of the assessment verified the rationality and effectiveness of the evaluation system. The Sihe mine has an independent east mine area (EMA) and west mine area. The EMA has fourteen ventilation shafts, including nine air-intake shafts (AIS) and five return air shafts (RAS). The No. 1 AIS and the No. 4 RAS serve Q1 area. The No. 3 AIS and the No. 5 RAS serve Q2 area. The No. 1 RAS, the No. 2 RAS and the No. 3 RAS serve Q3 area. The Q1 area, the Q2 area and the Q3 area all have independent AIS and RAS. In this case, the evaluation system for the mine ventilation system was studied primarily for Q3 area in EMA.

Through the investigation, it can be seen that the required air volume in Q3 area is 29,800 m^3/min, the air supply volume is 47,460 m^3/min, and the air supply to demand ratio is 1.59. Wasting of air exists. The effective air volume in EMA is 38,907 m^3/min, and the effective air volume utilization rate is 81.98%. The effective air volume utilization rate is unsatisfactory. The common ventilation line of the three return wells in Q3 area is long, which leads to the disturbance phenomenon of fan operation and insufficient stability of fan operation. The total power consumption in Q3 area is 2066.85 kw. The average mining cost is undesirability. Thereby, there are two main means of renovation: (1) Close three RAS or transform them into AIS, and then reasonably arrange complete ventilation facilities and plan air flow routes; (2) Dismantle the buildings with ineffective regulation in the ventilation system and realize the simplification of the ventilation network. The optimized objects are the No. 1 RAS, the No. 2 RAS, the No. 3 RAS and Q4 area. The Q4

area belongs to the mining area, and some roadways are shared with other areas. Aiming at the problems existing in the above the Q3 area, six modification schemes are proposed in combination with the actual production conditions, as shown in Table 1.

Table 1. Reconstruction scheme of the Sihe mine ventilation system.

Scheme	Description	Modification Works
1	Close the No. 3 RAS, otherwise no change	Construction of closed wall on both sides of the No. 3 ventilation shaft bottom
2	Change the No. 3 RAS to AIS, otherwise no change	Dismantle fan and auxiliary devices in the No. 3 RAS; Add heating air room and other relevant facilities.
3	Close the No. 1 RAS, otherwise no change	Dismantle two closed walls in the No. 2 RAS; Open one wind bridge between the No. 1 RAS and the No. 2 RAS; Apply a closed wall on the north and south sides of the No. 1 RAS.
4	Change the No. 1 RAS to AIS, otherwise no change	Dismantle two closed walls between the No. 1 RAS and the No. 2 RAS; Apply one closed wall on the north and south sides of the bottom of the No. 1 RAS; Dismantle four closed walls between the general return wind roadway and the shunting yard in EMA.
5	Close the No. 1 RAS and modify the Q4 area, otherwise no change	Dismantle the air door between Lane 3015 and the North Transport on the basis of Scheme 3; Dismantle the air door between the east auxiliary tape roadway and the north tape roadway; Build one air door in the front of the second and third lanes of the No. 2 RAS, respectively.
6	Change the No. 1 RAS to AIS and modify the Q4 area, otherwise no change	Dismantle the air door between Lane 3015 and the North Transport on the basis of Scheme 4; Dismantle the air door between the east auxiliary tape roadway and the north tape roadway; Build one air door in the front of the second and third lanes of the No. 2 RAS, respectively.

4.1. Selection of Index Data

Whether the ventilation system optimization evaluation index system is reasonably established is directly associated to the selection of ventilation system optimization scheme. Therefore, the index system should reflect all the factors affecting the quality of the mine ventilation system scientifically, objectively and as comprehensively as possible. On the basis of following the purpose, scientificity, systematicness, operability and timeliness through literature retrieval combined with the opinions of experts in relevant fields, a mine ventilation system evaluation index system composed of five criterion layers and twenty indicators was preliminarily established, as shown in the Figure 1. Based on the selected twenty evaluation indicators, a questionnaire was designed using a Likert 7-level scale. On the scale, 1 point indicated that the index is extremely unimportant; 2 points indicated that the index is especially unimportant; 3 points indicated that the index is unimportant; 4 points indicated that the index is commonly important; 5 points indicated that the index is very important; 6 points indicated that the index is especially important, and 7 points indicated that the index is extremely important. Questionnaires were counted in an anonymous fashion. Respondents were front-line personnel with a professional title of associate engineer or above with experience in mine ventilation or systematic training or researchers with a master's degree or above. A total of 60 questionnaires were distributed and 53 valid questionnaires were returned.

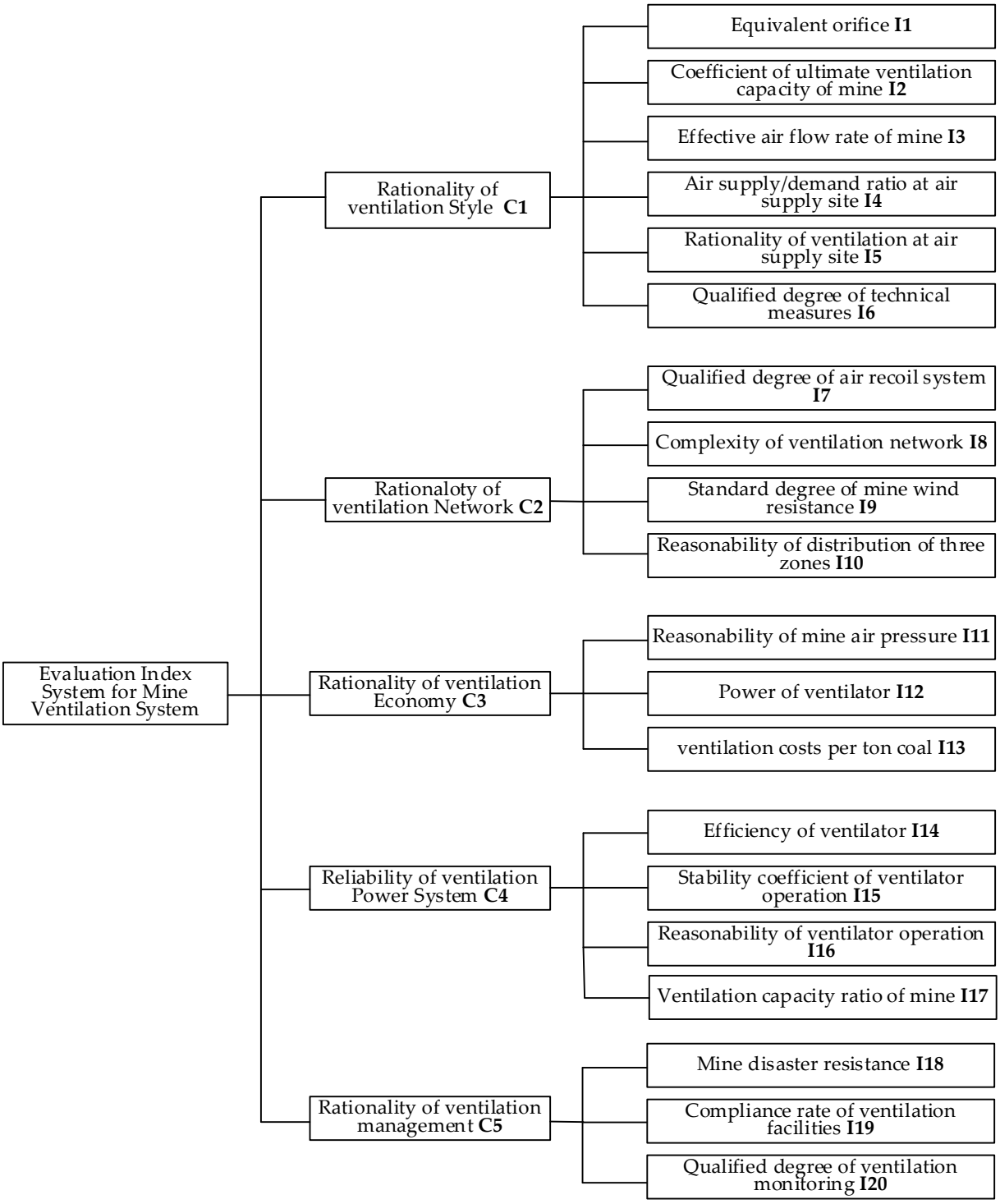

Figure 1. Primary model of evaluation index system.

4.2. Screening of Evaluation Index

Cluster analysis was performed on the 20 indicators using the method of R clustering, then the K–W test was performed on each class of indicators based on the clustering results. The results of the cluster analysis and K-W tests are shown in Table 2. Through the calculation of coefficient of variation, the index with the smallest coefficient of variation of the same class in each hierarchy of criteria was deleted. The C1 criterion layer removes the I6 index. The C3 criterion layer removes the I11 index. The C4 criterion layer removes the I17 index. The C5 criterion layer removes the I18 index. Furthermore, in the layer of the C2

criterion, the smallest coefficient of variation was the i10 index. The I10 index was an index to describe the distribution of mine resistance and the rationality of the ventilation system. It is generally believed that the distribution of three areas is reasonable. The closer the actual three-zone wind resistance distribution is to the ideal value, the better the ventilation effectiveness. The coefficient of variation of the I10 indicator was found to be greater than the other four indicators removed. Therefore, the I10 indicator was retained considering its importance. According to Equation (3), the information contribution degree of the selected index was calculated.

$$IC = \frac{\sum_{i=1}^{s} Varx_i}{\sum_{i=1}^{n} Varx_i} = \frac{21.74}{25.866} \times 100\% = 84.05\% \quad (17)$$

The results showed that 80% of the indicators after screening could reflect 84.05% of the original information. Gao [26] selected 16 indicators from the same 20 indicators by factor analysis. He used 80% of the screened indicators and only reflected 80.84% of the original data information. With the same 20 indicators, the screening indicator method we proposed could reflect more original data information. Apparently, our method improves approximately 4% on that used by Gao [26]. The validity of our index screening method was thus demonstrated.

Table 2. Index screening results of R clustering + coefficient of variation analysis.

Criterion Level	Index Code	Clustering Categories	Nonparametric Test	Coefficient of Variation	Retain or Delete
C1	I1	2	0.493	0.2315	Retain
	I2	2		0.1886	Retain
	I3	1	0.453	0.1783	Retain
	I4	1		0.1876	Retain
	I5	1		0.1876	Retain
	I6	1		0.1586	Delete
C2	I7	5	0.493	0.2559	Retain
	I10	5		0.2285	Retain
	I9	4	0.695	0.2583	Retain
	I8	4		0.2295	Retain
C3	I11	2	0.655	0.1723	Delete
	I13	2		0.1843	Retain
	I12	3		0.2392	Retain
C4	I14	3		0.2536	Retain
	I15	4		0.2289	Retain
	I16	5		0.2395	Retain
	I17	1		0.2014	Delete
C5	I18	2	1	0.1799	Delete
	I19	2		0.2048	Retain
	I20	3		0.2142	Retain

4.3. Indicator Calculation of Modification Scheme

Through the measurement of ventilation resistance and the investigation of fan performance in the Sihe Mine, the network construction and calculation of each scheme were

carried out with the assistance of network calculation software MVAD. Then, the data of the network solution was substituted into the corresponding indicator calculation formula [26,29] to obtain each index value of the optimization method. The original indicator parameters for each scheme are shown in Table 3.

Table 3. Value of Evaluation Scheme.

Indicator	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5	Scheme 6
I1	12.25	12.53	14.15	14.8	13.79	14.44
I2	1.43	1.43	1.83	1.83	1.83	1.83
I3	0.85	0.851	0.893	0.882	0.857	0.862
I4	2.57	2.60	2.73	2.76	2.72	2.76
I5	95.2	95.2	91.9	93.5	98.4	100
I7	0.17	0.17	0.17	0.17	0.17	0.17
I8	5.27	5.28	5.27	5.28	5.27	5.28
I9	38.59	36.98	26.50	24.07	29.90	27.13
I10	0.000566	0.000373	0.002312	0.002601	0.002331	0.002818
I12	1343.3	1319.1	1194.4	1135.3	1239.9	1177.6
I13	1.638	1.622	1.633	1.633	1.637	1.616
I14	80.3	79.2	69.1	64.2	73.6	70.3
I15	0.785	0.818	0.715	0.852	0.754	0.85
I16	29.38	30.55	17.24	19.89	21.87	23.75
I19	1	1	1	1	1	1
I20	1	1	1	1	1	1

4.4. Evaluation Index Weight Assignment

From the questionnaires, according to Equations (4)–(8) the entropy weight of each indicator was calculated using the entropy method. The objective weight of each evaluation index was shown as Figure 2.

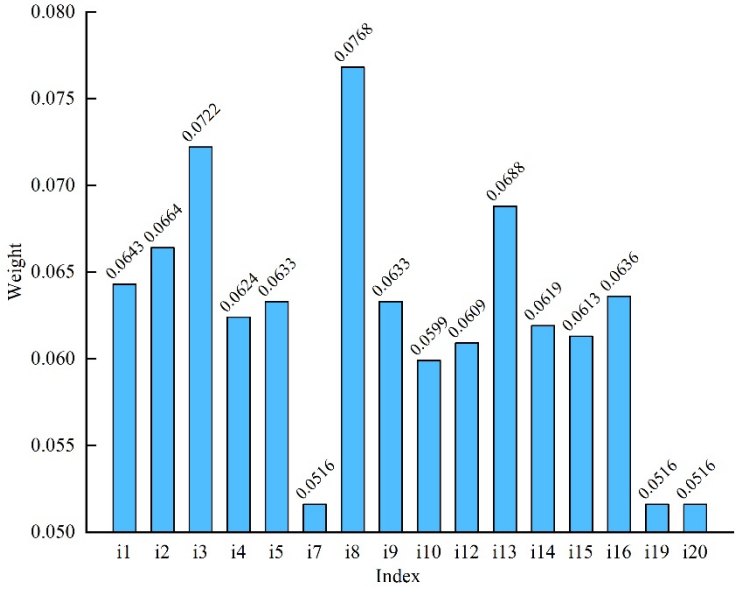

Figure 2. The results of index weight.

4.5. Result and Discussion

According to Equations (9)–(16), the comprehensive score of the scheme was calculated using the TOPSIS method. The comprehensive score of the scheme is shown as Figure 3. Based on the results, the scores were 4 and 6 for the significant quality scheme, 5 for the reference scheme, and 1, 2, and 3 for the unsatisfactory quality scheme. From the final composite score, Scheme 6 was the optimal scheme.

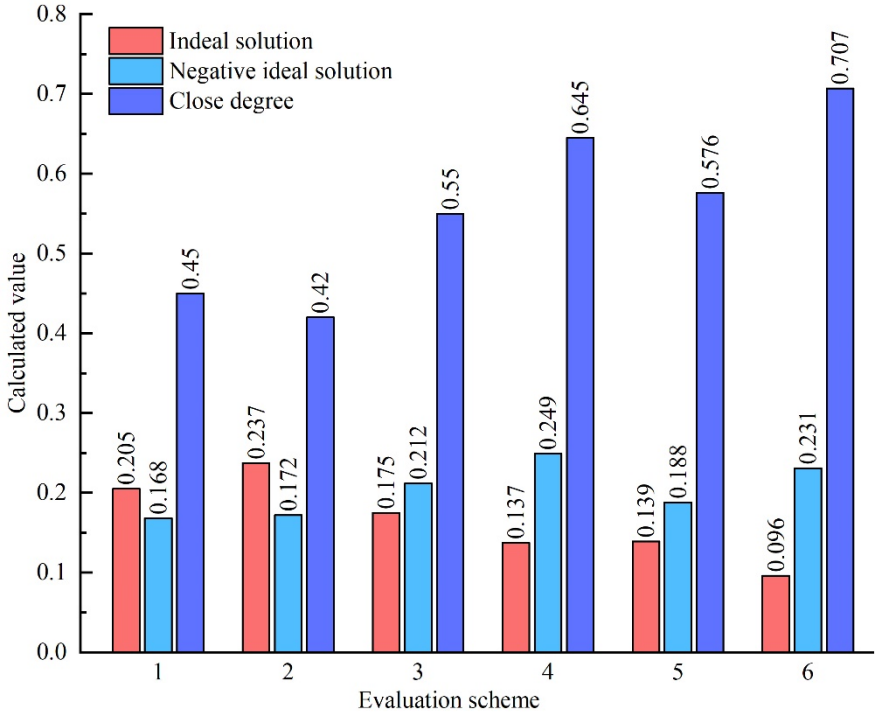

Figure 3. Comprehensive evaluation results.

The ventilation tasks undertaken by the No. 1 RAS, the No. 2 RAS and the No. 3 RAS belong to a ventilation network and they are interrelated. Combined operation of multiple fans is the main feature of the Sihe ventilation system. Moreover, the ventilation network under the multiple fans is very complex, and system optimization using artificial network calculation can hardly be realized, and thus cannot meet the needs of safe production. Therefore, on the basis of establishing a ventilation network model by computer technology, the renovation scheme of the Sihe coal mine was simulated. The results after simulation for the schemes are shown in Table 4.

Table 4. The relevant parameters of the schemes calculated by simulation software.

Scheme		1	2	3	4	5	6
No. 3 RAS	Negative Pressure (Pa)	\	\	1795.7	1712.0	1719.6	1633.1
	Service Rating (KW)	\	\	463.8	449.9	451.2	436.2
	Air volume (m^3/s)	\	\	258.3	262.8	262.4	267
No. 1 RAS	Negative Pressure (Pa)	1780.2	1742	\	\	\	\
	Service Rating (KW)	428.1	425	\	\	\	\
	Air volume (m^3/s)	240.5	244	\	\	\	\
No. 2 RAS	Negative Pressure (Pa)	2250.8	2184.9	1740.9	1596.1	1910.3	1762.7
	Service Rating (KW)	915.2	894.1	742.3	689.2	802.1	741.4
	Air volume (m^3/s)	406.6	409.2	426.4	431.8	419.9	425.5
Total Power (KW)		1343.3	1319.1	1194.4	1135.3	1239.9	1177.6
Effective Air Flow Rate of Mine (%)		85%	85.1%	89.3%	88.2%	85.7%	86.2%
Distribution of Three Zones		0.000566	0.000373	0.002312	0.002601	0.002331	0.002818
Equivalent Orifice		12.25	12.53	14.15	14.80	13.79	14.44

There are three production areas, Q1, Q2 and Q3, in the EMA area, and mine excavation coal production is expected to increase. The No. 3 RAS only serves two roadways,

Dongjiao and Donggui. Changing the use of the No. 3 RAS will cause insufficient air volume in the Dongjiao, which affects the yield of Q3 area. After changing the No. 1 RAS to AIS the system was safer, the inlet branch of the system network increased, the negative pressure of the system decreased, and the air volume of the system increased. Scheme 4 (3308.1 Pa) and Scheme 6 (3395.8 Pa) both had less negative pressure than the others (Scheme 1: 4031 Pa; Scheme 2: 3926.9 Pa; Scheme 3: 3536.6 Pa; Scheme 5: 3629.9 Pa). Scheme 4 (694.6 m^3/s) and Scheme 6 (692.5 m^3/s) both had larger air volume than the others (Scheme 1: 647.1 m^3/s; Scheme 2: 653.2 m^3/s; Scheme 3: 684.7 m^3/s; Scheme 5: 682.3 m^3/s). Hence, Scheme 4; Scheme 6 were superior to the other schemes. Moreover, From the perspective of engineering quantity, Scheme 6 had less construction quantity than Scheme 4, which could save a lot of manpower and financial resources. Compared with Scheme 4, Scheme 6 was more intensive, and considering that the remaining roadway in Q4 Area could be used as a material bank for Q1 and Q2 areas, Scheme 6 was preferred. Compared with Scheme 5, Scheme 6 was far superior in terms of system power consumption (1177.6 vs. 1239.9), effective air flow rate of mine (86.2% vs. 85.7%) and equivalent orifice (14.44 vs. 13.79). Therefore, scheme 5 was omitted. Scheme 6 was the optimal scheme, i.e., change the No. 1 RAS to AIS and modify the Q4 area.

In response to the shortcomings of the Q3 area, we used scheme 6 to modify the ventilation system; the measured parameters are shown in Table 5. Compared with the parameters of scheme 6 in Table 4, the negative pressure of the No. 3 RAS was 1633.1 Pa, and the measured actual negative pressure was 2030 Pa, which essentially met the actual requirements. The negative pressure of the No. 2 RAS was 1762.7 Pa, and the actual negative pressure measured was 2436 Pa, which also essentially met the actual requirements. The simulation results were on the whole not much different from the actual requirements.

Table 5. Parameters of ventilation system before and after renovation.

Items		Before Renovation			After Renovation		
		No. 1 RAS	No. 2 RAS	No. 3 RAS	No. 1 RAS	No. 2 RAS	No. 3 RAS
Air Supply/Demand	Demand Airflow (m^3/min)	10,800	10,800	7200	None	8000	6800
	Supplying Airflow (m^3/min)	14,460	22,860	10,140	None	20,068	11,318
	Supply/Demand Ratio	1.34:1	2.12:1	1.41:1	None	2.51:1	1.67:1
Rationality of Resistance	Percentage of Inlet Section Resistance	18.1%	33.14%	41.41%	None	18.62%	67.01%
	Percentage of Return Section Resistance	33.2%	33.19%	58.59%	None	35.68%	32.99%
	Percentage of Using Section Resistance	48.7%	33.67%	0%	None	45.70%	0%
Rationality of Economic	Exhaust Air Rate (m^3/min)	14,460	22,860	9900	None	25,218	11,318
	Negative Pressure (Pa)	2080	3120	2330	None	2436	2030

In response to the shortcomings in the Q3 area, we analyzed the ventilation system before and after renovation for the rationality of ventilation system resistance, air volume supply and demand, resistance distribution in the three areas, and economic rationality.

1. After renovation of the ventilation system, the Q3 area was equipped with ventilation tasks by the No. 3 RAS and the No. 2 RAS. The return air volume of the No. 3 RAS was 11,318 m^3/min. The operating negative pressure was 2030 Pa, and the equivalent orifice was 4.87 m^2. The return air volume of the No. 2 RAS was 25,218 m^3/min. The operating negative pressure was 2436 Pa, and the equivalent orifice 8.98 m^2. Both the No. 2 RAS and the No. 3 RAS belong to ventilated easy mines. Moreover, according to the "Technical Conditions of Ventilation for Coal Mine Worker Mining" [30], the relationship between resistance and air volume of the mine ventilation system in the production mine was specified. The return air volume of the No. 3 RAS was 11,318 m^3/min, and its ventilation resistance value should be less than 2940 Pa; the actual pressure was 2030 Pa. The return air volume of the No. 2 RAS was 25,218 m^3/min, and its ventilation resistance value should be less than 3920 Pa; the actual pressure was 2436 Pa. Thus, the ventilation system of the Sihe Coal Mine conforms to the provisions of "Technical Conditions of Ventilation for Coal Mine Worker Mining" after renovation. Considering the air demand of the long-distance tunneling roadway in the northern EMA, the Supply/Demand Ratio of the No. 3 RAS and the No. 2 RAS was increased in order to avoid inadequate air volume and excessive waste of air volume.
2. In addition, after renovation of the ventilation system, the ventilation resistance of the inlet section, using section, and return section of the No. 2 RAS revealed a situation of low resistance in the inlet section, high resistance in the return section and moderate resistance in the using section. The average 100 m resistance (36.15 Pa) of the total ventilation route was low, indicating that the distribution of system resistance was reasonable and the ventilation system was reasonable. Since the No. 3 RAS was only used to eliminate gas, the inlet air route was long and the return air route was the length of the wellbore. The resistance in the inlet and return areas showed the special situation of the high inlet section and low return section. After renovation of the ventilation system, the effective air volume of the mine was 29,910 m^3/min. The total air inlet volume of the mine was 33,532 m^3/min, and the effective air volume was 89.2%, which met the requirements of the regulation and effectively utilized the air volume. Moreover, the equivalent orifice was 13.7 m^2, which was an easy ventilation system.
3. Before renovation of the ventilation system, the exhaust volume of the fan in the No. 1 RAS was 14,460 m^3/min. The negative pressure was 2080 Pa. The operating power was 501.3 kW, and the average daily power consumption was 12,031.2 kWh. After changing the No. 1 RAS to AIS, at least USD 679,000 per year would be saved in power consumption for fan operation. In addition, it could also save the maintenance cost of fan and auxiliary facilities and labor costs for about ten personnel, including post and maintenance personnel. In general, about USD 773,000 in various costs would be saved each year.
4. There was a large disturbance intensity between the No. 1 RAS fan and the No. 3 RAS fan before renovation, which was calculated to be 33.85% in excess of the fan disturbance cut-off value [31]. After renovation, the resistance in the common section between the No. 1 RAS and the No. 3 RAS was 251.48 Pa and the disturbance intensity of the fan was 11.9%, which fulfilled the relevant requirements.

5. Conclusions

Based on analysis of the shortcomings of the existing mine ventilation evaluation systems, a mine ventilation evaluation system combining qualitative and quantitative analysis was herein proposed. Through theoretical analysis and case discussion, the following conclusions can be summarized:

i. The 20 evaluation indexes of mine ventilation were selected through expert consultation and reference summary. Then the primary index was screened through R-clustering and the coefficient of variation method. The results showed that 80%

of the indicators after screening could reflect 84.05% of the original information. Apparently, our method is improved by approximately 4% compared with Gao [26].

ii. Because the original data of the index was derived from a questionnaire and had a specific subjective willingness, this paper utilized the entropy weight method to determine index weight. This method decreased the influence of subjective factors on the weight of indicators as much as possible, so that the weight of indicators was more acceptable and the evaluation results were more scientific.

iii. Aiming at the properties of enormous sample data, a complex indicator system and the possibility of future ventilation evaluation system expansion, the TOPSIS method was utilized to evaluate the mine ventilation evaluation system. The ventilation evaluation system was applied to the Sihe mine. The ventilation simulation results showed that Scheme 4; Scheme 6 had lower negative pressure and higher air volume compared to other schemes. Compared with Scheme 4, Scheme 6 was more time-saving and labor-saving in the renovation project. Compared with Scheme 5, Scheme 6 had great advantages in terms of system power consumption, effective air volume rate, and equivalent orifice. The actual test results were essentially consistent with the simulation results of Scheme 6. The correctness of the optimized scheme is verified by simulation results and practical renovation.

The evaluation system method proposed in this paper provides a novel solution for multi-index and multi-quantity optimization decision-making for mine ventilation evaluation systems.

Author Contributions: Q.-P.B., Y.-C.L. and C.S. contributed equally to the research design and preparation of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing not applicable.

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

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