

Research Article

Research on Safety Subregion Partition Method and Characterization for Coal Mine Ventilation System

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The research analyzes and improves upon the concept of ventilation safety subregions in coal mines and proposes a partition method based on the breadth-first search algorithm for assessing the quality of the ventilation. This involves the analysis of the function of ventilation subregions and of ventilation gas-monitoring data. Then, using the so-called ventilation sensitivity matrix as the analysis method, we confirm the consistency of considering safety subregions, which are associated with air consumption places as the core concept and the objective positioning of the safety subregions within the ventilation analysis. This allows us to establish the validity and practicability of employing regional characteristic information of mine ventilation and gas concentrations in the mine's air. Finally, based on the characteristics of the ventilation subregions, ventilation air quantity network maps with safety subregions are proposed and their application is demonstrated. The advantages and characteristics of using these maps to replace ventilation network maps for ventilation analysis are demonstrated.

1. Introduction

China is the largest coal-producing and consuming country in the world. However, it also has one of the most serious records of coal mine disasters; with the rapid development of the nation's economy, the depths at which mining is required to take place in order to obtain coal are increasing. Hence, the continuous advancement of coal mining work leads to the structure of mine ventilation networks constantly changing and increasing in complexity. One aspect that arises is the demand for the effective management of mine ventilation and the continuous improvement of the coverage of ventilation systems.

The coal mine ventilation system is designed to supply air to various locations underground with the help of the main ventilation fans and ventilation structures to control toxic and harmful gases and dust in the production site within the regulatory limits. The fire safety of modern large-scale complex buildings is based on the delineated fire compartment [1], and coal mine ventilation systems also

have zoning characteristics. Zoning ventilation in coal mines is a widely used concept and can also be referred to as "independent ventilation" or "parallel ventilation." Zoning ventilation is a basic means of coal mine ventilation with many advantages: the operation is reliable, the disaster prevention and the disaster-resistant performance are strong [2, 3], the system structure is simple, the airflow is easy to adjust, the ventilation resistance is small [4–6], it can effectively control the problem of excessive wind speed in some airway [7, 8], and it is suitable for the ventilation needs of large mines with high dangerous gas levels and significant risks of spontaneous combustion [9–11].

The safety subregion, meaning the airway in one subregion area, shows a consistent ventilation effect to the airway in the other coal mine's ventilation system. The wind network area obtained is thus the safe division of the mine's ventilation system. The local characteristics of mine ventilation's have been widely recognized [12, 13], while researchers [14–16] have undertaken considerable work in the field of ventilation and gas disaster control based on safety subregions, examining the

correlation characteristics between local and global ventilation systems. The significance of security zoning has also been discussed in terms of safety subregion criteria. Wang et al. [17] proposed the concept of the influence zone and the dependent zone of any airway of a ventilation network and applied it to the analysis of air quantity compliance relationships between the airways. In a similar vein, Zhang [18] proposed a local loop recognition method based on matrix operations, while Huaming and Bin [19] proposed a circular wind path recognition method based on the depth-first search algorithm. Lixing [20] proposed a method of establishing a ventilation network graph generation tree using a depth-first search algorithm and applying it to wind network analysis.

In this work, the concept of safety subregions is proposed for the analysis and management of coal mine ventilation. First, an in-depth analysis of ventilation systems is carried out and the concept of safety subregion and watershed is used as the entry point for ventilation network partition by analyzing the local functional characteristics of the ventilation network. This allows a complex ventilation network to be divided into safety subregions, which can provide a simple observation angle and scientific basis for the classification of the ventilation analysis and have the potential of being applied to the ventilation design process. A partitioning algorithm for ventilation network safety subregions is then proposed and the ventilation correlation and influence law between subregions are analyzed.

2. Necessity of Partition Safety Subregion of Coal Mine Ventilation System

The capability of accurately analyzing mine ventilation systems directly affects our ability to anticipate and prevent ventilation safety problems [21–25]. At the same time, the topological structure of mine ventilation systems and the ventilation properties of mine shafts are constantly changing, resulting in changes in the associated risks within the system due to management lag or mistakes.

The ventilation parameters of each airway in a ventilation system have mutual influences, with both positive and negative correlations and differences in strengths and weaknesses [5, 26–30]. Due to the characteristics of the partition ventilation layout of the mining face, there are specific relationships between the local areas within the ventilation system. The airflow of the working face and its surrounding roadway tends to be consistent with the ventilation direction of the other working faces and their roadways. The trend of the influence of an airway on another local airway may also be the same. This phenomenon is the characteristic of the region or locality of the ventilation within the mine. This indicates that airways in the ventilation system can be grouped or partitioned according to the characteristics of their mutual influence. The resulting merging effectively simplifies the complex network concept and clarifies the ventilation impact characteristics between the various area within the system.

The safety subregion of the ventilation refers to the subregion of airways that are interconnected, have a high degree of safety commonality, and serve a certain process from the perspective of coal mine ventilation safety, based on the

influence relationship of wind flow and with reference to the mine operation layout, while retaining the actual correlation characteristics of the ventilation system. The process of partition within the ventilation safety subregion is the process of disaggregating the ventilation system into a collection of regions.

The safety subregion in the coal mine's ventilation system belongs to the basic area, based on the ventilation characteristics, and is composed of a collection of airways with a higher level of similarity in terms of the ventilation influence characteristics. There is a definite boundary between the safety subregions, and the wells in the zones are connected to each other. Of course, not all airways can synthesize groups and exhibit a highly uniform impact on other airways groups. Therefore, there is often a situation in a mine ventilation system where it is difficult for some airways to be classified into safe sections. Hence, these airways will be assigned a position outside of the safety zone. Some of the airways can form a group of airways consisting of only two or three airways. They will have uniform ventilation influence characteristics with respect to other safety subregions, and each airway in the group has uniform or similar functions. Such groupings can still be attributed to the concept of safe partitions.

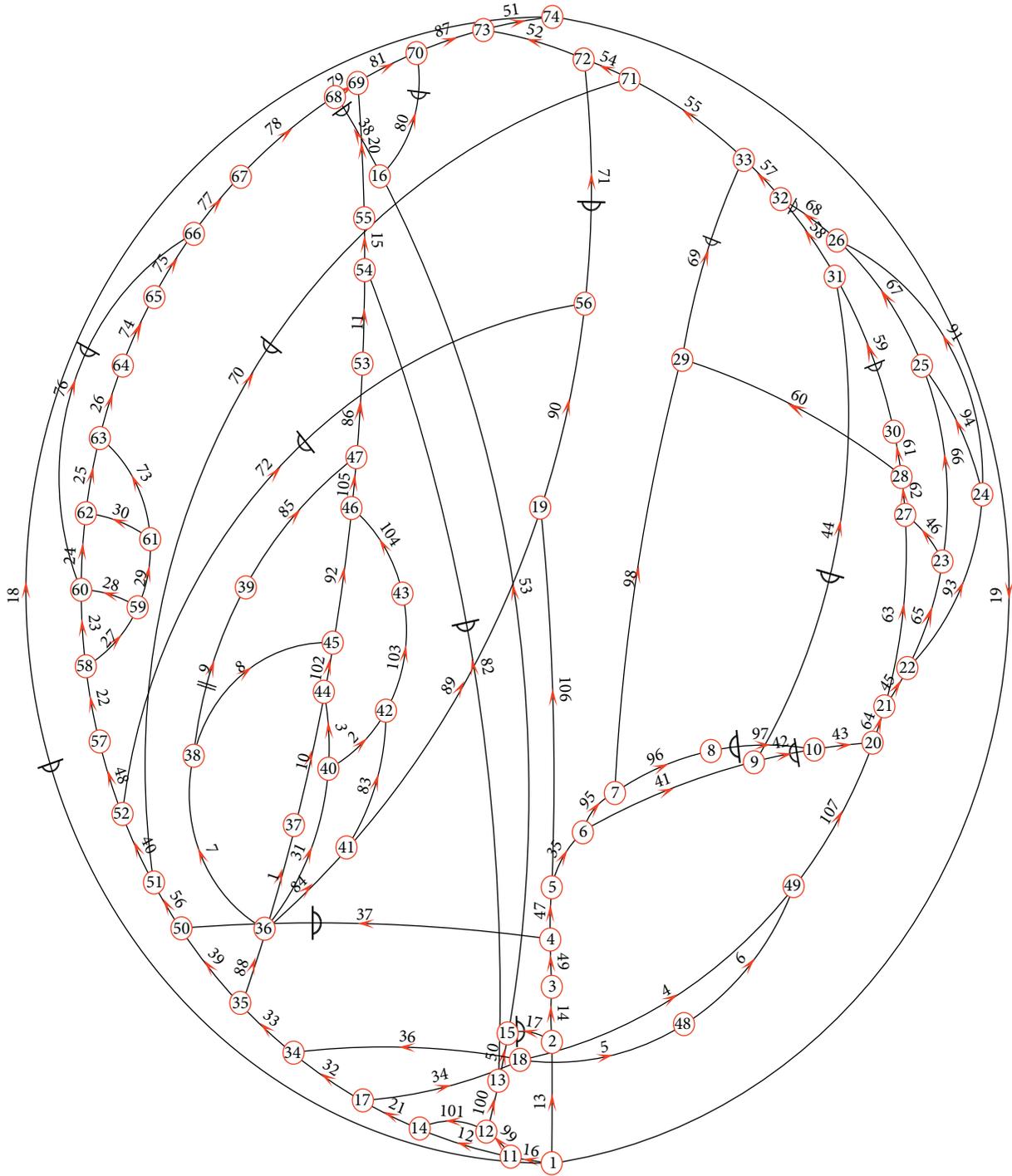
Dividing the ventilation network into safety subregions is conducive to the overall understanding of the ventilation network, as well as the sampling and analysis of air quantity and gases and gaining other information. This can lead to the timely identification of problems. For example, when the ventilation system is acting abnormally, it is easier to locate the problem quickly by identifying that there is a problem with a subregion, allowing a solution to be decided upon, based on the management's concept of safety subregion. Such a process is beneficial to the effective management and safety control of mines and helps to ensure the safe operation of the ventilation system.

In the following, an example will be presented of a mine in China, consisting of a main inclined shaft and an auxiliary inclined shaft. There are chambers off from the shafts, such as substations and drainage in the vicinity of the bottom yard. The whole mine has a fully mechanized working face and a spare mining working face, with a corresponding heading face. The ventilation system is made up of a total of 107 airways. The network solution data of the ventilation system shows that the total air quantity of the mine is $69.30 \text{ m}^3/\text{s}$, and the negative pressure of the main fan is 572.53 Pa. The ventilation network map of the mine is shown in Figure 1.

According to the ventilation network map, the fully mechanized mining face, the spare mining face, and the airways are served by independent ventilation, while the bottom hole substation and the pump house are on the same ventilation route. The correlation of the bottom airway is more complicated, and a more complex cross-linking pattern is formed in the inlet section of the mine.

3. Principles and Methods for Safety Subregion Partition

3.1. Principle of Partitioning Safety Subregions. A ventilation system may be divided into safety subregion for assessment, the main purpose of which is to lay the foundation for the following analyses:



- ⊙25 Represents network node; the number in it indicates the node number.
- ↔94 Represents airway in ventilation; the number above it indicates the airway number. The arrow on it indicates the direction of wind flow.
- ⊕ Represents trap door in a airway.

FIGURE 1: Ventilation network map of a mine.

- (1) Analyze the influence of the ventilation of an airway outside a specific safety subregion on that safety subregion.
- (2) Analyze the relationships and effects of ventilation aspects between safety subregions.
- (3) Analyze the influence of the ventilation parameters and relationships on the airways of a specific safety subregion.

The ventilation network map of the example mine is shown in Figure 1, where the circles represent the network node and the number inside the circle indicates the node number; the lines represent airways in ventilation, the numbers above them indicate the airway number, and the arrow on the lines indicates the direction of wind flow. The trap door in the ventilation system is represented in the figure by a straight line segment and a half-circle. The trap door can block the wind flow but allows people to pass through.

In order to effectively carry out the desired in-depth analysis, the safety subregions must be identified and complete. Only the internal structure of each safety subregion is complete, as is the ventilation information at the boundary, so that the ventilation analysis, calculations, and management can be carried out inside the subregion. Specifically, the airways in the safety subregion need to be connected to each other and have a complete structure, with the boundary of the safety subregion being clear and the information about it complete. Relatively independent ventilation performance analysis and control can only be achieved if the integrity of the safety subregion is guaranteed. At the same time, one must strive for a low degree of coupling between the subregions; that is, there are to be as few airways as possible at the subregion boundaries so that the impact between subregions are relatively simple, which facilitates analysis and pattern extraction in the region.

3.2. Safety Subregion Types for Mine Ventilation. Before the safety subregion is partitioned, the ventilation network of the coal mine is expressed as a directed graph:

$$G = \{V, E\}, \quad (1)$$

where E is the ventilation network airways set, expressed as

$$E = \{e_1, e_2, \dots, e_n\}, \quad (2)$$

where n represents the total number of airways e in the ventilation network, and

$$V = \{v_1, v_2, \dots, v_m\}, \quad (3)$$

is the set of network nodes v , where m represents the number of nodes, which are the intersections of the airways.

Each safety subregion consists of several airways identified by a subset of set E . Since the establishment of the safety subregion is centered on the air consumption places, some safety subregions can be identified by air consumption places. All k air consumption places in the ventilation system are expressed as e_1, e_2, \dots, e_n , which is a special airway.

When determining the range of a safety subregion, it is necessary to select an air consumption place in the mine and then carry out the downwind and reverse wind flow searches with respect to the air consumption place. For the downwind flow search airway set, an airway in the set which contains air completely or partially obtained from airway $E_{Use(i)} = \{e_j | r_{i,j} = 100\% r_{j,i} = 100\%\}$ is represented as set $E_{For(i)}$. For the reverse search airway set, an airway in the set from which air completely or partially flows into the airway $E_{Use(i)} = \{e_j | r_{i,j} = 100\% r_{j,i} = 100\%\}$ is represented as set $E_{Back(i)}$.

The method of partition the four types of safety subregion can be described as follows:

- (1) Air consumption subregions: air consumption subregions contain airways through which the majority of the air will pass to an air consumption place. This can be determined by comparing the air composition in the airways, which can be expressed by the matrix of the air quantity. Each element in the matrix represents the relationship of the air composition of the two airways: $r_{i,j}$ indicates the proportion of the air in airway e_i flowing into or from airway e_j . For example, when $r_{1,2} = 100\%$, it means that all the air in airway e_1 will flow into or away from airway e_2 :

$$R = \begin{bmatrix} 0 & r_{1,2} & \cdots & r_{1,n} \\ r_{2,1} & 0 & \cdots & r_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n,1} & r_{n,2} & \cdots & 0 \end{bmatrix}_{n \times n}. \quad (4)$$

The air consumption subregion is actually an extension of the air consumption place and is composed of the airways that are most closely related to the air consumption place. It is usually described by stating that the air of an airway in an air consumption subregion forms the majority of flow from or into the air consumption place. The judgment condition of an air consumption subregion is expressed as follows:

$$E_{CON(i)} = \{e_j | r_{i,j} > 60\% \parallel r_{j,i} > 60\%\}. \quad (5)$$

- (2) Intake airway subregion: after the establishment of the reverse search airway set, finding the common reverse search airways for all air consumption places will allow the intake airway subregion to be identified, as calculated by the following:

$$E_{In} = \bigcap_{i=1}^k E_{Back(i)}. \quad (6)$$

It should be noted that a complex ventilation network may have multiple downcast shafts, and an intake airway subregion may be established for each one.

- (3) Return airway subregion: the intersection of the downwind flow search airway set is the return airway subregion of the ventilation network and is calculated by the following:

$$E_{\text{Out}} = \bigcap_{i=1}^k E_{\text{For}(i)}. \quad (7)$$

Complex ventilation networks may have multiple main fans and upcast shafts, so there is a need to establish the return airway subregions for each upcast shaft.

- (4) Bypass subregion: the above types of regions are removed in the ventilation network, and the remaining airways are combined into a bypass subregion, expressed as follows:

$$E_{\text{Other}} = E - \bigcup_{i=1}^k E_{\text{CON}(i)} - E_{\text{In}} - E_{\text{Out}}. \quad (8)$$

The bypass subregion may not be a connected graph; it can be subdivided into multiple bypass subregions according to its connectivity.

3.3. Partitioning Process Based on Breadth-First Search.

Based on the above content, this article proposes a method based on breadth-first search (an algorithm for traversing or searching tree or graph data structures) for safety subregion. It is put forward that air consumption places, such as a working face or excavation working face, should be taken as a root node. The partitioning of the ventilation network may then be realized by combining BFS and safety subregion formulas.

In order to perform ventilation partitioning, it is necessary to undertake a downwind and reverse wind search for each air consumption place. The breadth-first search algorithm is therefore used to search the ventilation network, from which the downwind flow search airway set and the reverse search airway set are established as the basis for building the safety subregions.

Taking the reverse wind search airway set construction, for example, a breadth-first search is performed on the ventilation network, as shown in Figure 2(a). First, the directed graph is reversed, as shown in Figure 2(b). In the reversed directed graph, if airway e_1 , in which start node is v_1 and end node is v_2 , is an air consumption place, then select node v_1 as the root node, illustrated as a circle with the number 1 in Figure 2. Then select all end nodes where the start node is v_1 as the first layer and marked as visited; only v_2 satisfies this condition in Figure 2 graph. After the first layer is established, random select node v_i in the first layer, searching for all the end nodes with starting node v_i , and if the node is an unvisited node, mark it as the next layer node; repeat the process to obtain the breadth-first search tree, as shown in Figure 2(c).

Then, the reverse search airway set EBack(1) of air consumption place e_1 is established with all the airways in the breadth-first search tree of e_1 . Combining the breadth-first search process with the safety subregion formula, a ventilation network partition method can be formed. The processing flow is shown in Figure 3.

4. Representation of Safety Subregions

4.1. Ventilation Network Map with Air Quantity Information.

Ventilation network maps are a very useful means of expressing the topology of a ventilation system to effectively

assist in its analysis based on graph theory. Due to the inherent complexity of a mine's ventilation system, the topology of a ventilation network is generally very complicated, as it is difficult to express the overall characteristics of the system. This may in fact lead to most mine ventilation technicians being discouraged due to its complicated and apparently disorderly nature. At the same time, the ventilation network map is only used to express the topology of the network, as the information provided is simplified and the management content of the ventilation parameters that are of most concern to technicians are not expressed, so it is subject to many restrictions in terms of its practical use. Technicians often use "simplified network maps" to characterize the structural characteristics of a ventilation system. At present, there is no standard for network simplification, and there is no standard technical procedure to be followed. Therefore, the simplification of the network map relies to a large extent on "experience," and the errors that may result from such a simplification are difficult to infer; hence, the application of ventilation network map is limited.

As mentioned above, for the series and parallel relationship in the ventilation system, airways can be combined into different safety subregions. These safety subregions are connected by airways like diagonal airways in the bypass subregion.

Under normal production conditions, the bypass subregion airways are mostly high-resistance and low-quantity airways, which need to be strictly managed to prevent short circuits in the ventilation, but they are less affected by their own high wind resistance in a ventilation analysis. Some airways in bypass subregions also have a large air quantity due to material and personal transportation; hence, they should not be ignored in the analysis.

Therefore, the ventilation main topologies structure can be seen as being formed by safety subregions with different air consumption places and airways in bypass subregion with large air quantities. However, traditional ventilation network maps cannot express this information clearly. Hence, a more intuitive expression of the overall structure of the ventilation system would be an improvement for ventilation analyses.

A new map, referred to as the ventilation air quantity network map, is therefore proposed. This map represents the increase and decrease of airflow between the airways in the ventilation network. It helps to more specifically express the intrinsic relationship between the elements of a ventilation network's structure. This new representation incorporates air quantity information into the ventilation network map, as shown in Figure 4.

The ventilation air quantity network map is arranged separately according to the safety subregion, and the linking airways between subregions are expressed by arrow line segments. Each square in the ventilation air quantity network map represents an airway whose lateral width corresponds to the air quantity of the airway. The airflow is from the lower to upper levels, from the lower lateral side of each airway, and flows out from the upper lateral side. The lateral sides between the airways correspond to the nodes between the airways in the ventilation network map, and the airflow flowing in each node is equal to the air quantity flowing out; that is, the sum of the lateral widths of the airways entering

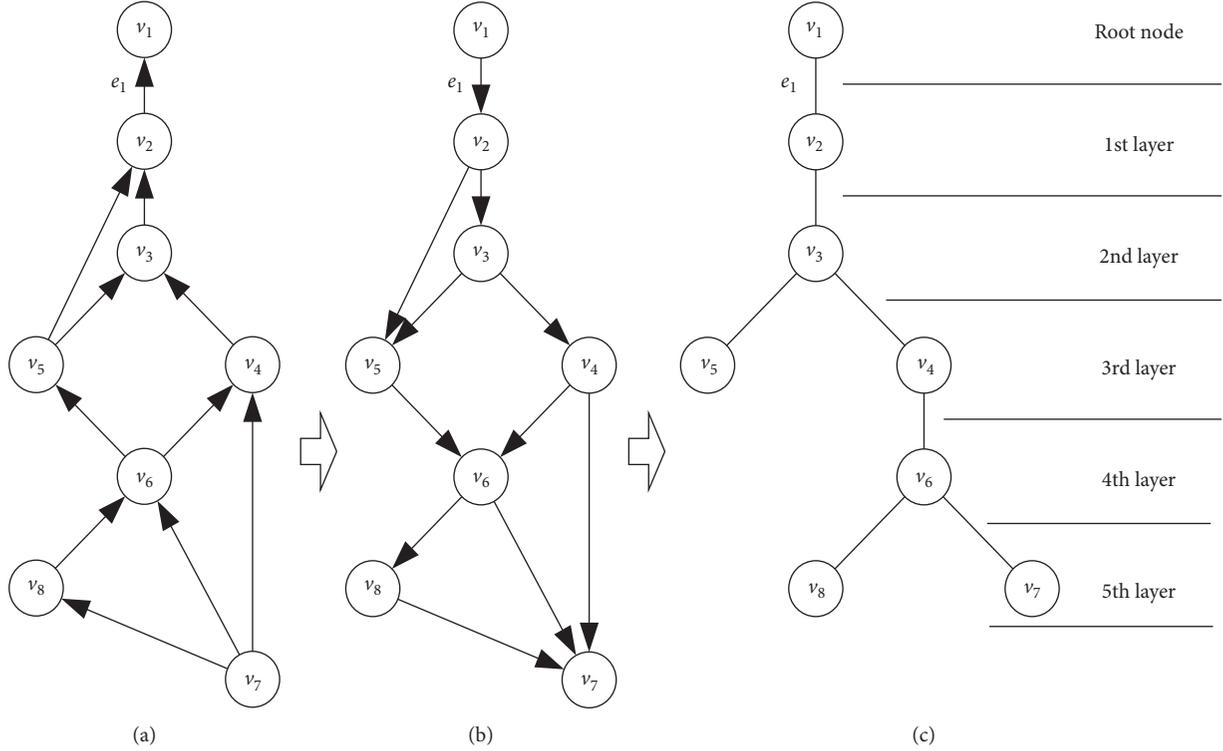


FIGURE 2: Constructing the reverse search airway set with breadth-first search algorithm. (a) Mine ventilation system expressed as a directed graph. (b) Directed graph reversal. (c) Breadth-first search process.

the wind is equal to the sum of the lateral widths of the airways of the node air outlets.

The big picture of the mine ventilation system can be clearly seen from the ventilation air quantity network map. Firstly, the distribution of the safety subregions is easy to see, as is the interaction of air quantity between the safety subregions. Finally, we can see the internal layout of the subregion.

Between subregions, there are linking airways that contain large quantities of air, described by arrow line segments, while the airways with lower amounts of air only show their outflow and access points to ensure the map is clear.

In terms of the structure, ventilation air quantity network maps are equivalent to traditional ventilation network maps, but with air quantity and subregion information. This leads to a concise and clearer picture of the ventilation system.

4.2. Ventilation Sensitivity Matrix. The ventilation sensitivity is the ratio of the air quantity of any airway to the wind resistance of each airway in the ventilation system, that is, the partial derivative of the air quantity of any airway in the system relative to the wind resistance of the other airways. When wind resistance R_j of airway e_j has a change ΔR_j , the airflow Q_i of any airway e_i in the network changes by ΔQ_i accordingly. At that time, when $|\Delta R_j| \rightarrow 0$, sensitivity d_{ij} is defined as follows:

$$d_{ij} = \lim_{|\Delta R_j| \rightarrow 0} \frac{\Delta Q_i}{\Delta R_j} = \frac{\partial \Delta Q_i}{\partial \Delta R_j}. \quad (9)$$

The definition of ventilation sensitivity [31] is, therefore, an implicit function derivation problem, based on the ventilation control equation, given by the following:

$$\left\{ \begin{array}{l} \sum_{i=1}^n \alpha_{ki} \frac{\partial Q_i}{\partial R_j} = 0, \\ \sum_{i=1}^n 2b_{li} R_i |Q_i| \frac{\partial Q_i}{\partial R_j} - \sum_{i=1}^n b_{li} \frac{\partial H_{zi}}{\partial R_j}, \\ b_{li} \frac{\partial H_{fl}}{\partial R_j} = 0, \quad (\text{if } R_j \neq R_i), \\ \sum_{i=1}^n 2b_{li} R_i |Q_i| \frac{\partial Q_i}{\partial R_j} - \sum_{i=1}^n b_{li} Q_i |Q_i|, \\ - \sum_{i=1}^n b_{li} \frac{\partial H_{zi}}{\partial R_j} - b_{li} \frac{\partial H_{fl}}{\partial R_j}, \quad (\text{if } R_j \neq R_i), \end{array} \right. \quad (i, j = 1, 2, \dots, n), (k = 1, 2, \dots, m), (l = 1, 2, \dots, c), \quad (10)$$

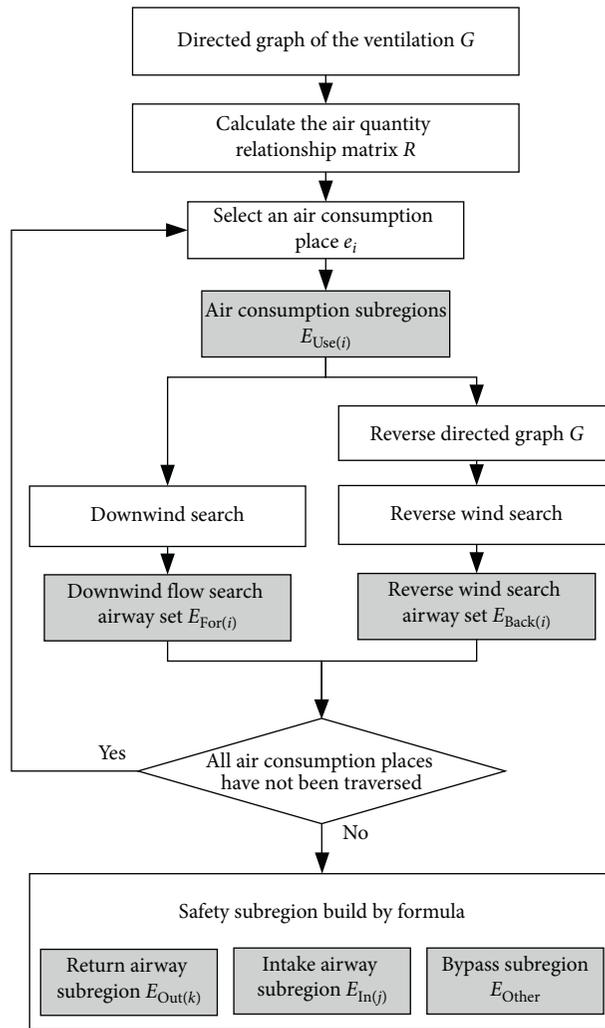


FIGURE 3: Safety subregion partition process.

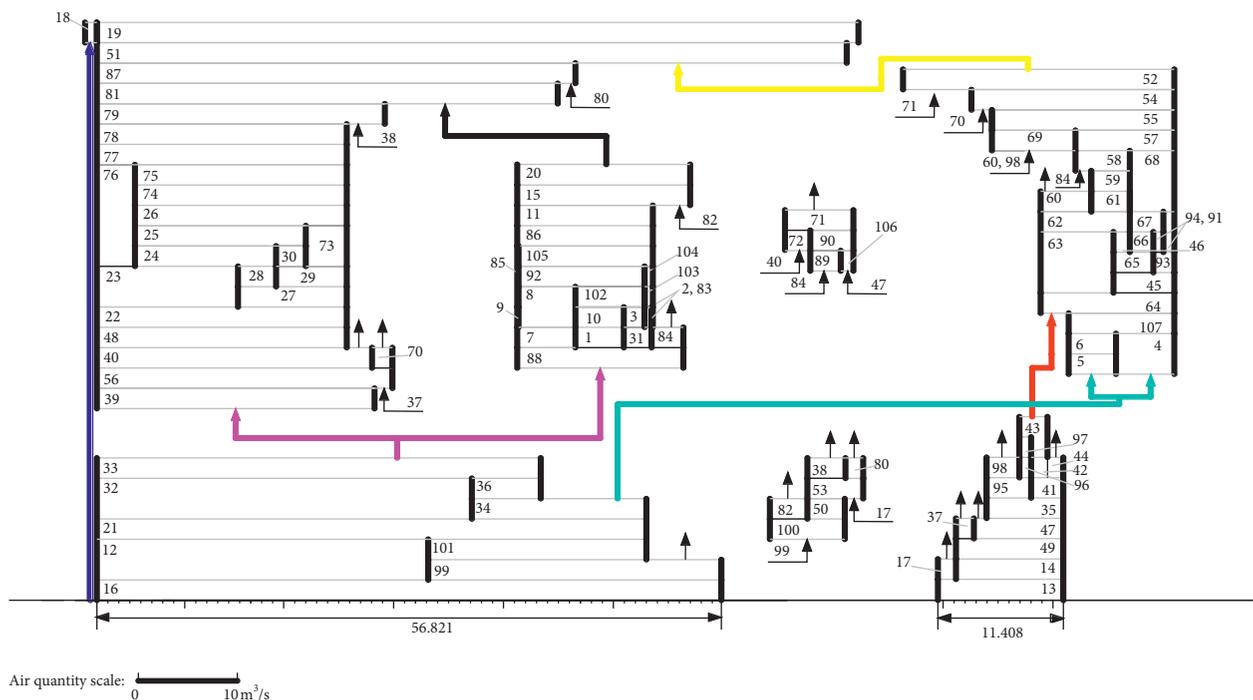


FIGURE 4: Ventilation air quantity network map.

where Q_i is airflow in airway e_i ; R_j is the constant of proportionality and is referred to as the resistance of airways e_j ; H_{z_i} is the elevation or potential head in airway e_i or known as natural ventilation pressure; H_{f_i} is pressure gain of a variable pressure fan, which means the pressure is generated by the fan in the independent l^{th} loop; $\partial H_{z_i}/\partial R_j$ is the reciprocal of the natural ventilating pressure on resistance R_j in airway e_i ; $\partial H_{f_i}/\partial R_j$ is the reciprocal of the total pressure generated by the fan to resistance R_j in the independent l^{th} loop; c is the number of the independent loops; m and n are the number of nodes and airways in the network, respectively; a_{ki} is the flow direction coefficient of airway e_i connected to node v_k in the network. When $a_{ki} = 1$, the air flows from airway e_i into node v_k and when $a_{ki} = 0$, the airflow is not into/out of node v_k . b_{li} is the direction of airflow in airway e_i in the independent l^{th} loop; specify the direction of the cotree branch as positive. When $b_{li} = 1$, it indicates that the airflow direction of airway e_i is positive; when $b_{li} = -1$, the airflow direction is negative; when $b_{li} = 0$, airway e_i is not in l^{th} loop.

The ventilation sensitivity indicates the tangential direction of the airway and resistance relation curve in the multidimensional space in the current position. Considering the definition of ventilation sensitivity, if the resistance of one airway increases and the air quantity of the other airways increases, the corresponding ventilation sensitivity is positive. On the contrary, if the resistance of one airway increases, the air quantity of the other airways will decrease; hence, the corresponding ventilation sensitivity is negative. It can be seen that if the ventilation sensitivity is positive, the two airways are in a generalized parallel state, while if the ventilation sensitivity is negative, the two airways are in a generalized-series position. The resistance of the airway increases and its air quantity always decreases; that is, the sensitivity to the airway itself is always negative.

The sensitivity matrix of the ventilation system can be obtained by sequentially arranging the ventilation sensitivity data, expressing the influence relationships between all the airways in the ventilation system. The partial sensitivity matrix of the mine ventilation system outlined above is shown in Figure 5.

The rows and columns of the ventilation sensitivity matrix are associated with a certain airway. Any data in the matrix, such as the data of the i -th row and the j -th column, express the change of the airflow of airway e_i to the change of airway e_j resistance. This is very useful for the analysis of complex ventilation systems.

Simple parallel and series airway arrangements are easy to identify in a ventilation system, but they are rare in real complex systems. Generalized-parallel and generalized-series states are relatively broad concepts and are often used to describe the degree of influencing between two airways, but they may not be easily judged by simple observations.

The positive and negative of the ventilation sensitivity can reflect the influence law between the relevant airways, providing accurate quantitative support for experience-based judgments. But in a real complex network, due to the topological structure, the positive correlation and the negative data distribution in the sensitivity matrix appear disorderly. It is difficult to grasp the overall structural

relationships. However, after safety subregion partitioning, sensitivity data can be ordered by subregions, allowing the overall structure to be seen more easily.

5. Ventilation Characteristics Analysis of Safety Subregion

One of the principles for partition ventilation safety subregions is that the airways in the same safety subregion have similar ventilation influence characteristics. The ventilation sensitivity data can, therefore, accurately represent this influence and thus can be effectively used to reveal the ventilation influence law between safety subregions.

5.1. Safety Subregion Partition and Expression. Considering the safety subregion partition method, the safety subregions of the example mine are shown in Table 1. The corresponding safety subregions are framed by thick red lines in the ventilation air quantity network map shown in Figure 5.

5.2. Characteristics Analysis with Ventilation Sensitivity Matrix. On the ventilation air quantity network map, the corresponding safety subregion is framed by thick lines; that is, the expression of the safety subregion on a ventilation air quantity network map with air volume scale is shown in Figure 5. It is clear from Figure 5 that the working face subregion, drivage subregion, and chamber subregion are in parallel, while the inlet and return intake airway subregions are in series with air consumption subregions.

In order to analyze the correlation characteristics between safety subregions, the airways of the example mine ventilation system are sorted according to their subregions. The recombination ventilation sensitivity matrix is referred to as the optimal permutation ventilation sensitivity matrix. In order to more clearly see the ventilation correlation characteristics between safety subregions, the sensitivity matrix table is further simplified into the form shown in Figure 6.

From the partial matrix, it can be seen that there are two air consumption subregions, one intake airway subregion and one return airway subregion. The ventilation relationship between the safety subregions is clearly and concisely expressed by the ventilation sensitivity data, and this feature has strong universality.

Due to the characteristics of the coal mine's layout, according to the partition method, when the safety subregion is divided by the air consumption place, the upstream and downstream relationships of the ventilation are implied, and the sensitivity matrix can be used to examine this relationship between the safety subregions.

Comparing the safety subregion ventilation air quantity network map with the optimal permutation ventilation sensitivity matrix, the two can be seen to correspond with each other. At the same time, it can be seen from the ventilation sensitivity matrix data that each airway in the same safety subregion exhibits a highly consistent ventilation effect on other safety subregions. That is to say, the

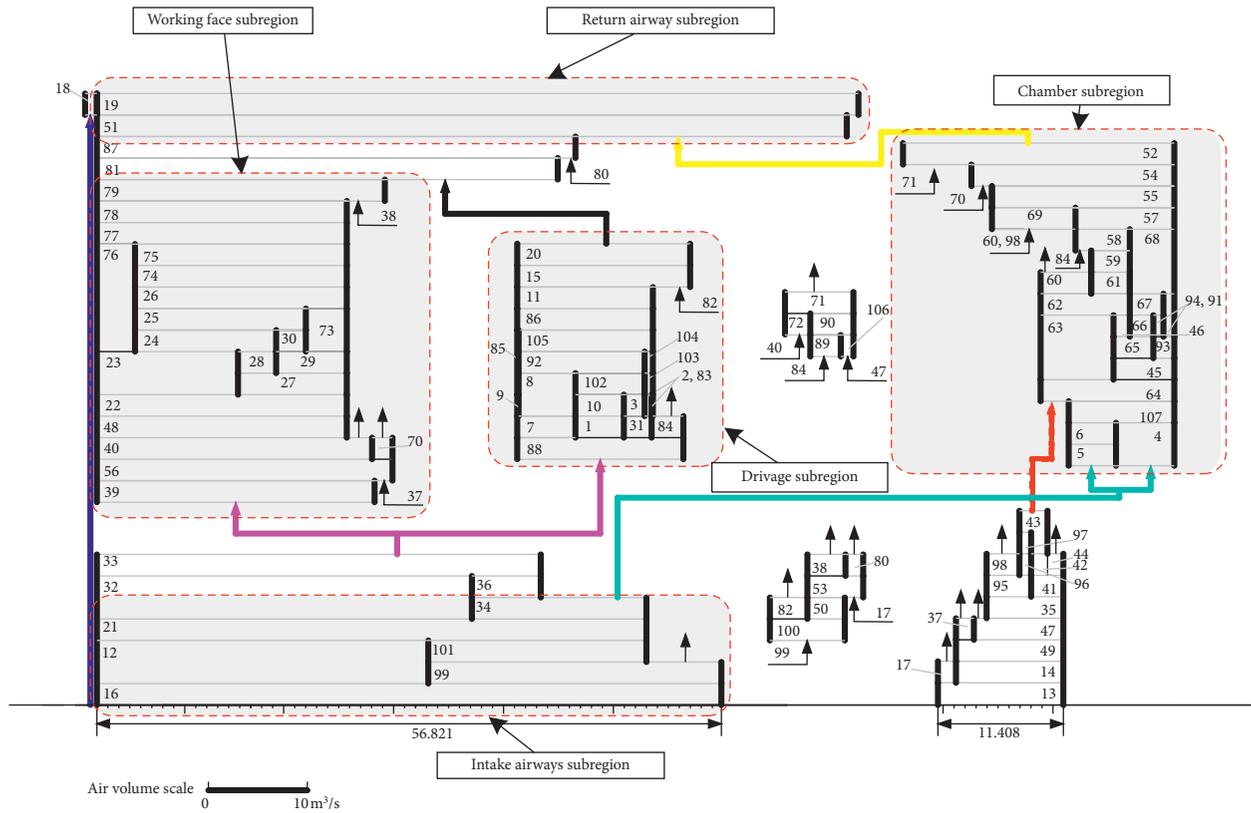


FIGURE 5: Safety subregion for a ventilation air quantity network map.

TABLE 1: Safety subregion of the example mine.

Safety subregion	Included airways	Type of safety subregion
Working face subregion	24, 25, 26, 74, 75, 73, 76, 77, 78, 79, 27, 28, 29, 22, 48, 40, 56, 39, 70	
Drivage subregion	2, 3, 103, 10, 104, 8, 9, 92, 102, 105, 85, 86, 11, 15, 20, 88, 1, 7, 31	Air consumption subregion
Chamber subregion	52, 54, 55, 57, 68, 58, 59, 61, 60, 62, 63, 69, 107, 4, 64, 45, 5, 6	
Intake airway subregion	16, 21, 12, 32, 99, 101, 34	Intake airway subregion
Return airway subregion	51, 19, 81, 87	Return airway subregion
Bypass subregion	71, 72, 90, 89, 84, 47, 38, 99, 17, 98, 97, 43	Bypass subregion

corresponding ventilation area has the ventilation characteristics while serving the connotation of the specific mining operation, so it can provide an important basis for the comprehensive analysis of the ventilation gas monitoring and effectively guide the ventilation safety technicians to interpret the ventilation system.

Generally speaking, from the intake area to the return area of the mine, there is a strong regional aspect, and each region shows consistent positive or negative correlation characteristics, for example, ventilation effects between the airways 10, 102, 7, and 8 in drivage subregion to airways 24, 25, 26, and 27 in the working face subregion.

Ventilation effects between airways may or may not be consistent within the same subregion. If the airways in the

safety subregion are in a simple series or parallel state, the mutual influence will be the same. With the increase of the structural complexity of the ventilation network, the influence of airways on each other will become more complicated.

The basic characteristics of the coal mine ventilation system ensure a clear parallel relationship between the safety subregions with the air consumption location as the center. The complex connecting airways, such as the angular connection airway, are difficult to be included in the safety subregion, which are mostly bypass airway between safety subregions and are auxiliary tunnels with high resistance and low air quantity, which do not have a substantial impact on the application of safety subregion concept.

No.	81	87	19	51	1	10	102	7	8	11	86	105	24	25	26	74	75	73	76	12	16	21	32	
81	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
87	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
51	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	-	-	-	-	-	-	-	+	+	-	-	-	+	+	+	+	+	+	+	-	-	-	-	-
10	-	-	-	-	-	-	-	+	+	-	-	-	+	+	+	+	+	+	+	-	-	-	-	-
102	-	-	-	-	-	-	-	+	+	-	-	-	+	+	+	+	+	+	+	-	-	-	-	-
7	-	-	-	-	+	+	+	-	-	-	-	-	+	+	+	+	+	+	+	-	-	-	-	-
8	-	-	-	-	+	+	+	-	-	-	-	-	+	+	+	+	+	+	+	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+	-	-	-	-	-
86	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+	-	-	-	-	-
105	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+	-	-	-	-	-
24	-	-	-	-	+	+	+	+	+	+	+	+	-	-	-	-	-	-	+	+	-	-	-	-
25	-	-	-	-	+	+	+	+	+	+	+	+	-	-	-	-	-	-	+	+	-	-	-	-
26	-	-	-	-	+	+	+	+	+	+	+	+	-	-	-	-	-	-	+	-	-	-	-	-
74	-	-	-	-	+	+	+	+	+	+	+	+	-	-	-	-	-	-	+	-	-	-	-	-
75	-	-	-	-	+	+	+	+	+	+	+	+	-	-	-	-	-	-	+	-	-	-	-	-
73	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-
76	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
32	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

FIGURE 6: Distribution of positive and negative data for the optimal permutation ventilation sensitivity matrix.

6. Conclusions

- (1) The concept of safety subregions of ventilation networks is investigated, and a partition principle and method are proposed based on the breadth-first search algorithm.
- (2) A ventilation air quantity network map for safety subregions is proposed. As an innovative application based on the ventilation system, it effectively expands the information transfer efficiency and application range of ventilation analysis.
- (3) Based on the ventilation sensitivity matrix, the characteristics of ventilation correlations between safety subregions were determined, providing new ideas and entry points for the in-depth analysis of ventilation and gas-monitoring data.

Clarifying and specifying the ventilation network safety subregions help clarify the granularity of ventilation analysis and management. That is, the granularity will not be too large for managers to fully grasp the situation or too small to control critical factors. It is, therefore, a convenient means for technical and management personnel to effectively grasp

the correlation characteristics between regions and to form a more systematic comprehension of ventilation systems in coal mines.

Data Availability

The data are available and explained in this article; readers can access the data supporting the conclusions of this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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