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Research Article

Cause Analysis of Coal Mine Gas Explosion Based on Bayesian Network

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As one of the types of coal mine disasters and accidents, gas explosion is an important resistance affecting coal mine safety production. How to effectively identify gas explosion, find out the causes of gas explosion accidents, and make timely prediction and rectification is an urgent problem in coal mine industry. In this paper, the cause model of coal mine gas explosion is constructed based on the Bayesian network, and the cause chain of gas explosion accident is established by SPSS correlation analysis. The main factors leading to gas explosion accidents are found by parameter learning, reverse reasoning, sensitivity analysis, and key cause path. The results show that the main causes of mine gas explosion are gas accumulation and fire source explosion. The main causes of gas accumulation are no wind or breeze caused by local ventilator problems. The generation of electric spark is the main cause of fire source explosion. Cable damage, short circuit, mechanical and electrical equipment explosion, illegal operations, and lack of safety skills are also important factors leading to gas explosion.

1. Introduction

As a big energy country in the world, China has 70% of the total energy resources, and the proportion of coal will not change greatly in the future for a long time [1]. In recent years, although the government has issued a series of policies to adjust the coal structure, shut down a large number of small and medium-sized mines with low production efficiency and poor production environment, and effectively reduce the occurrence of coal mine disasters and accidents, the objective factors of complex geological conditions and high difficulty of coal mining make coal mining enterprises still face various safety problems in the production process. Gas is a part of the underground coal retained in the carbonization process that generates gas. With the development of mining, the gas trapped in the coal seam is released. When the gas explosion limit is reached, oxygen and fire will produce gas explosion, which will cause serious damage to personnel and mines. It is similar to rockburst, which is one of the common disasters with great damage in mining engineering or deep engineering [2–4]. According to statistics, since the 14th Five-Year Plan, a total of 3069 coal mine accidents have occurred in China, including 991 gas explosion accidents. There were 22019 deaths caused by larger and above coal mine accidents, of which 9105 were caused by larger and above gas explosion accidents. Statistics show that the number of gas explosion accidents accounts for 25% of all accidents in the current period, and the number of deaths accounts for 36.7% of all deaths in the current period, as shown in Figure 1 [5, 6]. Gas explosion has the characteristics of wide distribution of hazard sources, highly concealable, strong suddenness, complex incentives, and relatively few occurrences, but causing serious casualties. Therefore, it is particularly necessary to study gas explosion accidents and analyze their causes, so as to provide the basis for risk assessment and accident prevention of gas explosion accidents.

The factors leading to gas explosion accidents are complex and diverse. Analysis and research on various factors and timely identification of hazards can effectively

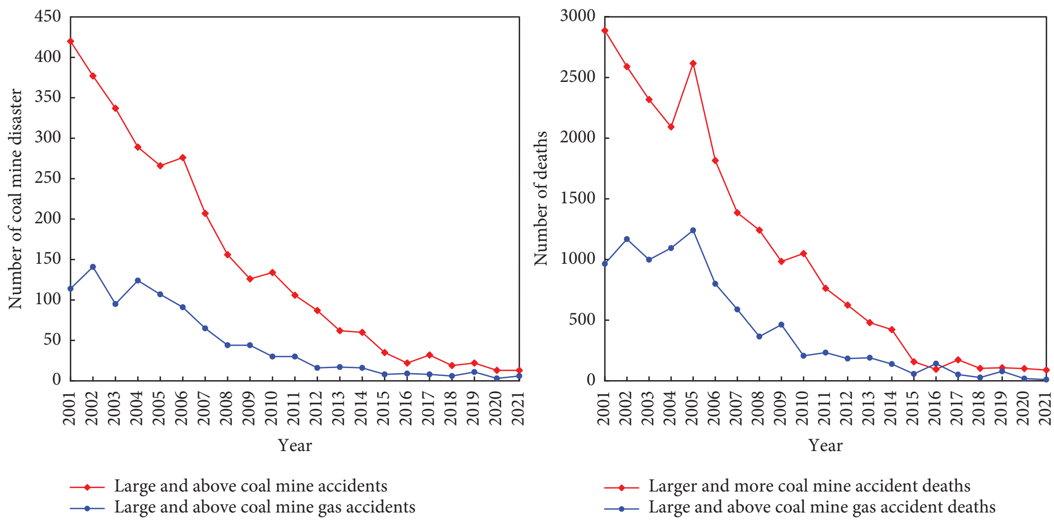

FIGURE 1: Larger and above coal mine accidents and coal mine gas explosion accidents in recent 20 years in China.

prevent and control the occurrence of coal mine gas explosion accidents. At present, international academic circles have achieved fruitful research results in clarifying the factors leading to coal mine gas explosion accidents and identifying potential hazards of gas explosion accidents. Cioca and Moraru [7] summarized the causes of gas explosion accidents from the aspects of methane-air mixing and ignition sources. Heinrich and William [8]found 88 percent of industrial accidents caused by human insecurity, 10 percent of mechanical equipment failures, and 2 percent of uncontrollable factors. Pual and Maiti [9]analyzed and studied the causes of gas explosion accidents by building a structural equation model of human behavior based on the specific behavior of people. Page [10] found that the management level of coal mine enterprises is the key factor to determine whether the coal mine gas explosion and accident occurred. Siu [11] believed that government departments should strengthen the supervision of coal mine production and standardize the management system of coal mine enterprises, which can effectively control the occurrence of coal mine gas explosion accidents. Zhang et al. [6] sorted out 126 cases of particularly significant gas explosion accidents in China from 1950 to 2015 and found that the necessary conditions for the gas explosion are gas accumulation and ignition fire source. The confusion of ventilation equipment management is the most common cause of gas accumulation, and illegal blasting is the main cause of ignition fire source. Nian et al. [12]used the GRA-ANP-FCE method to analyze the main influencing factors of coal mine gas explosion accidents and constructed the risk assessment index system of coal mine gas explosion based on the four dimensions of human-machine-equipment-management. It was found that human and management factors were the main control factors of gas explosion accidents. Zhang et al. [13] constructed the DEMATEL-ISM model and systematically identified the representative risk factors in gas explosion accidents. The results show that safety regulations and safety supervision should be the focus of gas explosion risk control. At present, the academic research on coal mine gas explosion is rich in content and diverse in research methods, but there are still shortcomings. In terms of accident case analysis, limited by factors such as accident characteristics and data sources, from the perspective of system engineering, the research results may have strong personal subjectivity and one-sided analysis.

The Bayesian network is one of the most effective and representative theoretical models for expressing and reasoning uncertainty problems. The Bayesian network can not only analyze the correlation between various influencing factors in an event by means of prior probability and conditional probability, but also analyze the trend of event development by means of cause chain analysis, sensitivity analysis, and posterior probability calculation, so as to realize the functions of accident deduction and risk assessment [14]. At present, some scholars have integrated the Bayesian network model into the research field of coal mine production accidents. Li et al. [15] designed a combination model of AHP and BN to evaluate the risk of gas explosion accidents. Huang et al. [16] developed a grid-based gas explosion risk mapping method with Bayesian network. Li et al. [17] constructed the cause chain model of gas explosion accident based on the Bayesian network. In view of this, this study focuses on coal mine gas explosion accidents, in order to effectively identify the hazards of gas explosion accidents and to avoid the occurrence of gas explosion accidents from the source as the fundamental purpose, the cause mechanism model of coal mine gas explosion based on the Bayesian network is constructed, which provides certain decision support for coal mine enterprises to effectively prevent gas explosion accidents.

2. Data Investigation and Modeling Analysis

2.1. Bayesian Network Principle. Bayesian network is also known as belief network or causal probability network. As a commonly used machine learning technology, the Bayesian network is mainly based on probability theory and the Bayesian formula. By integrating probability theory and graph theory, the causal relationship between various factors in complex, fuzzy, and uncertain problems is intuitively and clearly displayed in a graphical way. Bayesian network mainly includes directed acyclic graph (DAG) and probability distribution table. DAG qualitatively describes the relationship between variables. The probability distribution table quantitatively expresses the relationship strength between variables [18, 19].

For event A, set all events that affect its occurrence as $V = (V_1, V_2, \cdots\cdots, V_n)$, the relevant Bayesian formula is

$$P(V_i|A) = \frac{P(A|V_i)P(V_i)}{P(A)} = \frac{P(A|V_i)P(V_i)}{\sum_{i=I}^{n} P(A|V_j)P(V_j)}, \quad (1)$$

where $P(V_i|A)$ is posterior probability, $P(V_i)$ is prior probability, and $P(A|V_i)$ is the probability of event A under the condition of event V_i, namely the conditional probability.

For the determined Bayesian network model, the joint probability distribution of nodes can be expressed as follows:

$$P(A) = \prod_{i=1}^{n} P(A_i|P_a(A_i)), \quad (2)$$

where $P_a(A_i)$ represents all parent nodes of node Ai.

Each node in the directed acyclic graph (DAG) of Bayesian networks represents a random variable, and the directed arc represents a direct causal relationship between one node and another. The parent node points to the child node, which represents the "result" caused by the "cause."

2.2. Cause Analysis of Gas Accumulation. The data of coal mine accident investigation reports from 2010 to 2021, in the official website of the China Coal Mine Safety Supervision Bureau, were investigated. After collection and collation, 65 larger and above coal mine gas explosion accidents were randomly selected. When the air volume of the working face or roadway is insufficient and local ventilator stops supplying air, it is easy to cause the gas concentration in the airflow to reach the explosion limit. According to the source of gas, the reasons for gas accumulation are divided into following six categories:

(1) Ventilation disorder: the unreasonable layout of mine ventilation system leads to the formation of series ventilation and circulating air, which leads to gas accumulation. There were 11 such accidents, accounting for 16.9%.

(2) Insufficient air volume: uninstalled main fan, small local fan air volume, random switch air doors, and other circumstances lead to insufficient air volume, resulting in gas accumulation. There were 10 such accidents, accounting for 15.4%.

(3) No breeze: the failure of the local ventilator, the random shutdown of the local ventilator, the damage of ventilation facilities, and the damage of air ducts lead to no wind and breeze, resulting in gas accumulation. There were 24 such accidents, accounting for 36.9%.

(4) Goafs and blind lane: gas accumulation in goaf, blind roadway, or other closed places. There were 8 such accidents, accounting for 12.3%.

(5) Gas accumulation in upper corner: insufficient air volume, inadequate gas drainage, or insufficient time cause gas accumulation in the upper corner. There were two such accidents, accounting for 3.1%.

(6) Geological changes: due to changes in geological conditions such as rockburst and gas outburst, abnormal gas emission or roof caving occurs. There were 10 such accidents, accounting for 15.4%.

Among the many reasons for gas accumulation, ventilation confusion, and no wind, insufficient airflow leads to gas accumulation in the upper corner. As long as the supervision is in place, there is enough time to take preventive measures, which can be completely avoided; geological changes, roof fall, and other reasons belong to the instantaneous gas accumulation. Once it occurs, it is difficult to take effective emergency measures due to the short time and only rely on the gas monitoring and monitoring system for gas overrun power cut.

2.3. Cause Analysis of Detonated Fire Source. The theoretical ignition temperature of gas is 650~750°C, but the underground environmental conditions are complex, there is a high temperature fire source, which may cause gas explosion. According to the causes of underground fire source, the ignition fire sources are divided into five categories:

(1) Electrical discharge: electric sparks may occur in the case of cable breakage and short circuit, open joint of line, explosion of junction box, live maintenance, explosion of mine lamp or mine lamp disassembly, spark of electric locomotive, and cable broken by falling stones. There were 34 gas explosion accidents caused by electric spark, accounting for 52.3%.

(2) Illegal explosion: fire may be caused by insufficient sealing mud, continuous blasting operation, and explosive deterioration. There were 13 gas explosion accidents caused by blasting flame, accounting for 20.0%.

(3) Naked fire: flames caused by smoking, mine lamp explosion, etc. There were three gas explosion accidents caused by open fire, accounting for 4.6%.

(4) Friction or impact sparks: in the process of mining equipment handling, sparks may occur in the collision between metal devices, the collision between rock and rock or between metal and roadway roof fall. There were 10 gas explosion accidents caused by friction or impact sparks, accounting for 15.4%.

(5) Coal spontaneous combustion: coal spontaneous combustion, fire area reburning, and other conditions are likely to produce spontaneous combustion sparks. There were five gas explosion accidents

caused by coal spontaneous combustion, accounting for 7.7%.

In coal mine production, friction, impact sparks, and other ways to detonate fire is difficult to avoid. Smoking, lighting sparks, live-line working, illegal explosion, and so on can be avoided. The completely avoidable ignition source is mainly caused by intentional violations by coal miners. Factors such as coal spontaneous combustion are not involved in this study.

2.4. Construction of Conceptual Model. According to the "triangle" theory of coal mine gas explosion, the occurrence of gas explosion accidents should have three conditions: ignition source, gas accumulation, and concentration of more than 5%, oxygen concentration not less than 12% [6]. The "Coal Mine Safety Regulations" published by the State Administration of Coal Mine Safety and the fault tree analysis theory in system engineering point out that most factors affecting coal mine safety production can be carried out from four aspects: personnel, equipment, environment, and management [20]. Based on the "triangle" theory of gas explosion, this paper sets network nodes from five dimensions of employee, equipment, environment, management, and others, as shown in Table 1.

The initial Bayesian network conceptual model of coal mine gas explosion is constructed by structural learning and parameter learning. Node T is "gas explosion," and other nodes are the relevant factors leading to coal mine gas explosion accidents. The connection between nodes is the causal relationship between relevant factors, as shown in Figure 2.

Table 1: Related variables.

Level 1 variable	Level 2 variable	Level 3 variable
Gas explosion T	Methane accumulation C	Employee H_1
		Equipment D_1
		Environment E_1
		Management M_1
		Others O
	Gas accumulation F	Employee H_2
		Equipment D_2
		Environment E_2
		Management M_2
		Material A
		Others O

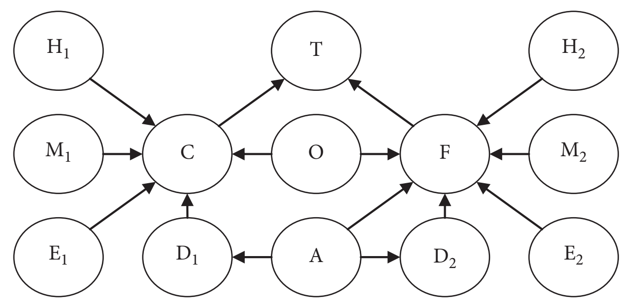

Figure 2: Initial model diagram of gas explosion.

3. Construction of the Bayesian Network Model for Gas Explosion

3.1. Selection of Node Variables. According to some typical cases of larger and above coal mine gas explosion accidents in recent 10 years in China, 47 keywords are extracted as Bayesian network branch nodes that directly or indirectly lead to gas explosion accidents. They are gas explosion (T), gas accumulation (C), fire source ignition (F), and electric sparks (S). Human factors are weak security awareness (H_1), gas leak detection (H_2), escape supervision (H_3), unlicensed employment (H_4), employee violation (H_5), illegal smoking (H_6), illegal explosion (H_7), illegal blasting (H_8), illegal welding (H_9), dismantling miner's lamp (H_{10}), and live work (H_{11}). Device factors are improper installation position of local ventilator (D_1), local ventilator series ventilation (D_2), insufficient air volume of local ventilator (D_3), local ventilator stops running (D_4), insufficient air volume of local ventilator (D_5), imperfect gas monitoring system (D_6), ventilation system damage (D_7), local ventilator open and stop at random (D_8), broken and exposed cable (D_9), coal drill explosion (D_{10}), junction box explosion (D_{11}), locomotive friction (D_{12}), explosion of electrical equipment (D_{13}), miner's lamp exploded (D_{14}), and electromechanical equipment short circuit (D_{15}). Environmental factors are gas accumulation in goaf (E_1), gas accumulation in upper corner (E_2), gas accumulation in blind lane (E_3), coal and gas outburst (E_4), abnormal gas emission (E_5), coal rock fall collision (E_6), and roof falling (E_7). Management factors are ventilation equipment management confusion (M_1), equipment management confusion (M_2), roof management confusion (M_3), security management confusion (M_4), insufficient safety education (M_5), organizing illegal production (M_6), gas monitoring and supervision chaos (M_7), lack of responsibility of safety production subjects (M_8), insufficient safety rules and regulations (M_9), and government regulation is not in place (M_{10}).

3.2. Correlation Analysis between Variables. Analyze the correlation of various factors of gas explosion accidents and clarify the correlation between variables, which can provide objective reference for building a reasonable Bayesian network model later. Common correlation analysis methods include the Pearson correlation coefficient test and Spearman correlation coefficient test. Among them, the Pearson correlation coefficient test mainly applies to numerical variables, while the Spearman correlation coefficient test focuses on the correlation test between sequential variables [21, 22]. Since the variables constructed in this paper do not have the characteristics of numerical variables, Spearman correlation coefficient test is used to analyze the correlation of variables. In this paper, the statistical analysis software SPSS 25.0 is used to analyze the correlation between variables, and the correlation coefficient between variables is obtained, which provides data reference for the Bayesian network model constructed later. Due to the relatively large number of nodes involved, this paper selects some nodes with strong correlation, and the significance level is shown in Table 2. It can be seen from Table 2 that the correlation

Table 2: Main cause nodes of gas explosion.

Risk nodes	Correlation	Risk nodes	Sig.
T	←	C	0.869
	←	F	0.837
C	←	D_2	0.612
	←	D_3	0.511
	←	D_4	0.468
	←	D_8	0.417
	←	E_1	0.557
	←	E_2	0.530
	←	E_3	0.677
	←	E_5	0.632
	←	H_2	0.801
F	←	H_6	0.538
	←	H_7	0.612
	←	H_8	0.713
	←	S	0.652
M_1	⟶	D_1	0.563
	⟶	D_7	0.543
M_2	⟶	D_9	0.610
	⟶	D_{10}	0.701
	⟶	D_{11}	0.522
	⟶	D_{13}	0.612
	⟶	D_{14}	0.689
	⟶	D_{15}	0.522
S	←	H_5	0.685
	←	H_9	0.572
	←	H_{10}	0.483
	←	H_{11}	0.506
	←	E_9	0.522
	←	D_9	0.610
	←	D_{10}	0.701
	←	D_{11}	0.522
	←	D_{13}	0.612
	←	D_{14}	0.289
	←	D_{15}	0.322
H_1	⟶	H_5	0.685
	⟶	H_6	0.523
	⟶	H_7	0.642
	⟶	H_8	0.634
	⟶	H_9	0.472
	⟶	H_{10}	0.483
	⟶	H_{11}	0.506
M_{10}	⟶	M_4	0.537
	⟶	M_7	0.458
	⟶	M_8	0.512
	⟶	M_9	0.436
	⟶	D_6	0.702

strength between different nodes is different. Among them, variables C (gas accumulation) and F (ignition source) have the strongest correlation with gas explosion, reaching 0.869 and 0.837 at the level of 0.05 followed by H_1 (weak security awareness) and H_8 (illegal blasting).

3.3. The Complete Bayesian Network Model. The sample data of Table 2 are imported into the Bayesian network software GeNie 2.0 to construct the complete Bayesian network model of gas explosion. Structure learning algorithms in GeNie 2.0 software mainly include naive Bayes, greedy search algorithm, and Bayesian search algorithm. Combined with the data characteristics and algorithm characteristics after collection and processing, this paper uses greedy search Bayesian algorithm to learn Bayesian network structure. The processed data table is imported into GeNie 2.0 software, and the obtained Bayesian network model is shown in Figure 3. However, in the Bayesian network model of coal mine gas explosion constructed in this paper, there is a phenomenon that the causal relationship of some node variables is inconsistent with the objective facts. The main reason is that the greedy search Bayesian algorithm can only find one member of the equivalence class of the Bayesian network and cannot accurately judge the causal direction of the undirected edge, which leads to the limitation of the analysis results [18]. Therefore, it is necessary to adjust and optimize Bayesian networks based on objective facts.

3.4. Model Validation. After the establishment of the Bayesian network model, its effectiveness needs to be tested. In GeNie 2.0 software, the accuracy of each node can be obtained through cross validation, so as to verify the validity of the model. Table 3 is to select the accuracy of each node obtained by the K-fold cross-validation algorithm in cross validation. The specific operation method is to select the "Validate" button in the toolbar in GeNie 2.0, and the verification method is to select the "*K*-Fold Cross Validation," which realizes the calculation of the prediction accuracy of each node in the model. Due to the limited length of the article, this article intercepts the accuracy of some basic events. It can be seen from Table 3 that the maximum prediction accuracy of nodes can reach 0.99, and most nodes have prediction accuracy above 0.8. Overall, the Bayesian network model of coal mine gas explosion has high accuracy and can be used for cause analysis and reasoning.

4. Analysis of Bayesian Network Model for Gas Explosion

4.1. Bayesian Network Parameters Learning. Before starting Bayesian network parameter learning, it is necessary to know the conditional probability distribution of each initial risk node in advance. If the prior probability distribution and posterior probability distribution of each initial risk node are known, then the probability distribution of the parent node of each initial node can be calculated by the following formulas (3)–(5) [23, 24]:

$$B_{ei}(x) = P(x|e) = P(x|e_x^-, e_x^+) = \alpha P(e_x^-|x) p(x|e_x^+),\quad e = e_x^- \bigcup e_x^+, \tag{3}$$

$$\lambda(x) = P(e_x^-|x), \pi(x) = P(x|e_x^+), \tag{4}$$

$$B_{ei}(x) = \alpha\lambda(x)\pi(x), \tag{5}$$

where α is equal to the normalized factor, $\alpha = [P(e_x^-|e_x^+)]$, e_x^- is the sub-node of Bayesian network with x as the root

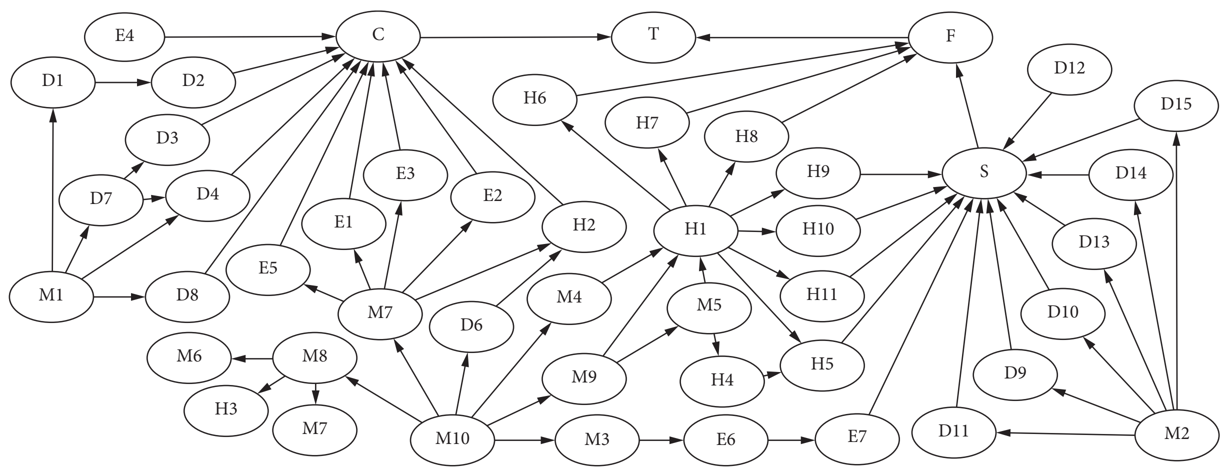

Figure 3: Complete Bayesian network model diagram.

node, e_x^+ is refers to the rest of node, $\pi(x)$ is refers to the prior probability distribution, and $\lambda(x)$ is refers to the posterior probability distribution.

Then the parent node at all levels is regarded as the child node of the next layer. According to the same method, the probability distribution of the next layer node can be calculated. In this way, the probability distribution of the highest-level node (top event) can be calculated. The above operation process reflects the "belief" (probability distribution) update and propagation function of each node in Bayesian network. The detailed results are shown in Figure 4.

4.2. Bayesian Network Backward Inference. Bayesian network inverse reasoning is to calculate the posterior probability of other node variables under the condition of known node variables (target variables) in the model. By comparing the posterior probability value of each node variable, the main factors that lead to the change of the target variable are found. Posterior probability analysis is the most involved problem in Bayesian network reasoning. On the one hand, the probability of result occurrence can be deduced under the premise of known reasons, namely predictive reasoning. On the other hand, we can also find out the most possible reasons for the occurrence of results when the state of results is known. The posterior probability represents the occurrence probability of basic events in the case of larger and above gas explosion accidents. By calculating the posterior probability value of basic events of gas explosion accidents, the probability of top events (gas explosion) is calculated by using GeNie 2.0 software. It is assumed that in the case of larger and above gas explosion accidents in the system, the posterior probability of each influencing factor is shown in Figure 5. The specific operation method is to select the "Set Evidence" function in GeNie 2.0 software, set the target node state "True" to 100%, select the relevant node to MAP, press the Update button starts the Annealed MAP algorithm, which finds the maximum a posterior probability assignment of states to the MAP Node, and obtain the posterior probability value of other nodes.

The posterior probability calculation results can roughly reflect the risk severity of each node. From the perspective of gas accumulation, the gas accumulation in goaf, the imperfection of gas monitoring and control system, the damage of ventilation system, and the high posterior probability of random start and stop of local ventilator should be regarded as the focus of mine gas ventilation management. From the perspective of ignition fire source, the posterior probability of electrical discharge, cable damage, roof falling, coal drill explosion, wiring box explosion, and mechanical equipment short circuit is higher, which should be the focus of mechanical equipment safety management. From the perspective of enterprise safety management, the posterior probability of nodes such as missed detection of gas, evasion of supervision, mechanical equipment management confusion, roof management confusion, safety management confusion, and safety production responsibility system is not implemented, and safety rules and regulations are not perfect and are higher. These factors need managers to pay enough attention.

4.3. Risk Nodes Sensitivity Analysis. Sensitivity analysis is done by investigating the effect of small changes in numerical parameters on the output parameters (e.g., posterior probabilities), which can help verify the probability parameters of Bayesian networks [25]. The sensitivity analysis button is called in the GeNie 2.0 software standard toolbar, and then the coloring of risk nodes will change, and the position of sensitive parameters will be displayed in the network diagram, as shown in Figure 6.

The results of sensitivity analysis show that the 17 red nodes, such as detonating fire source, gas leakage detection, imperfect gas monitoring system, damaged ventilation system, random start and stop of local ventilators, cable breakage and bareness, gas accumulation in goaf, and disordered safety management are the deepest color, which are highly sensitive nodes. Gas accumulation, electric sparks, and weak security awareness of these three nodes color is deeper, and they are sensitive nodes. Local ventilator open and stop at random, safety education and training is not in place, gas supervision confusion of these three nodes color is

Table 3: Precision table of risk nodes.

Risk nodes	Precision
H_1	0.67
H_2	0.55
H_3	0.95
H_4	0.80
H_5	0.70
H_6	0.95
H_7	0.94
H_8	0.95
H_9	0.98
H_{10}	0.60
H_{11}	0.95
D_1	0.95
D_2	0.96
D_3	0.90
D_4	0.88
D_6	0.87
D_7	0.96
D_8	0.87
D_9	0.91
D_{10}	0.92
D_{11}	0.98
D_{12}	0.97
D_{13}	0.92
D_{14}	0.95
D_{15}	0.90
E_1	0.91
E_2	0.99
E_3	0.99
E_4	0.97
E_5	0.96
E_6	0.95
E_7	0.94
E_8	0.95
E_9	0.98
E_{10}	0.60
M_1	0.45
M_2	0.75
M_3	0.93
M_4	0.65
M_5	0.48
M_6	0.55
M_7	0.85
M_8	0.60
M_9	0.88
M_{10}	0.64
C	0.83
S	0.75
T	0.80

shallow, and they are low sensitive nodes. The nodes with white color are almost insensitive nodes.

4.4. The Maximum Cause Chain Analysis of Accidents. GeNie 2.0 software provides the function of Bayesian network-based event maximum cause chain analysis. In this study, it can find out the key path leading to gas explosion accidents and provide reference for restricting the evolution of risk sources into accidents.

It can be seen from the results of the maximum cause chain analysis. Gas accumulation in goaf, coal and gas outburst, insufficient air volume of local ventilator, and other factors lead to the possibility of local gas accumulation. Electric sparks, illegal smoking, and illegal blasting are highly likely to lead to ignition. These factors together with the weak safety awareness of employees and enterprise safety management confusion formed the key cause chain of gas explosion accidents, as shown in Figure 7. Therefore, coal mine enterprises should strictly

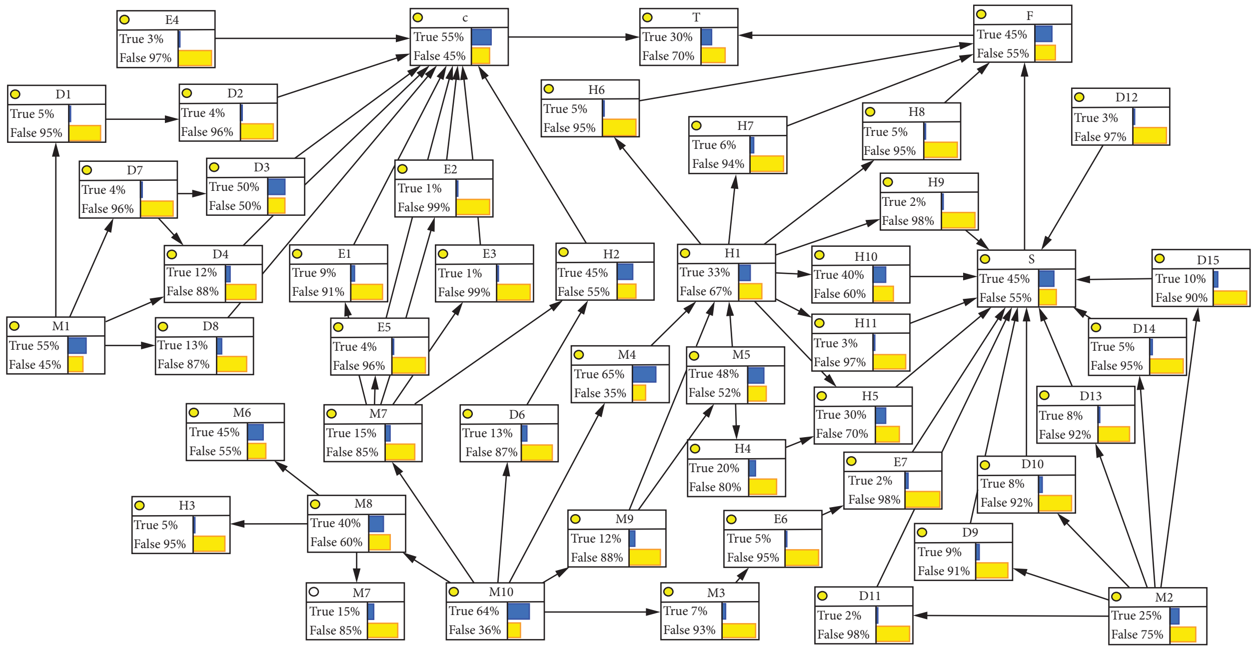

Figure 4: Conditional probability distribution graph of Bayesian network.

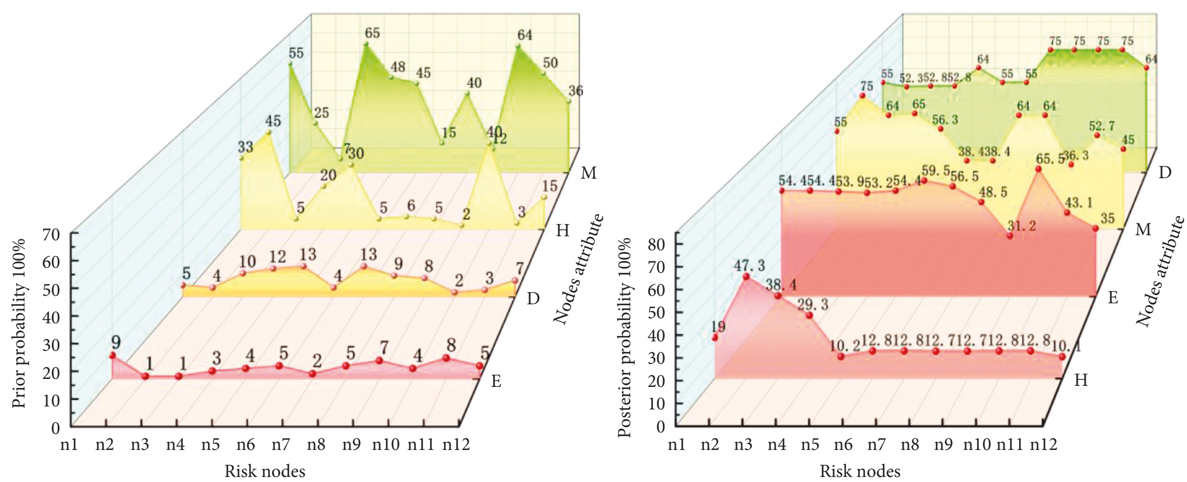

Figure 5: Prior probability and posterior probability graph.

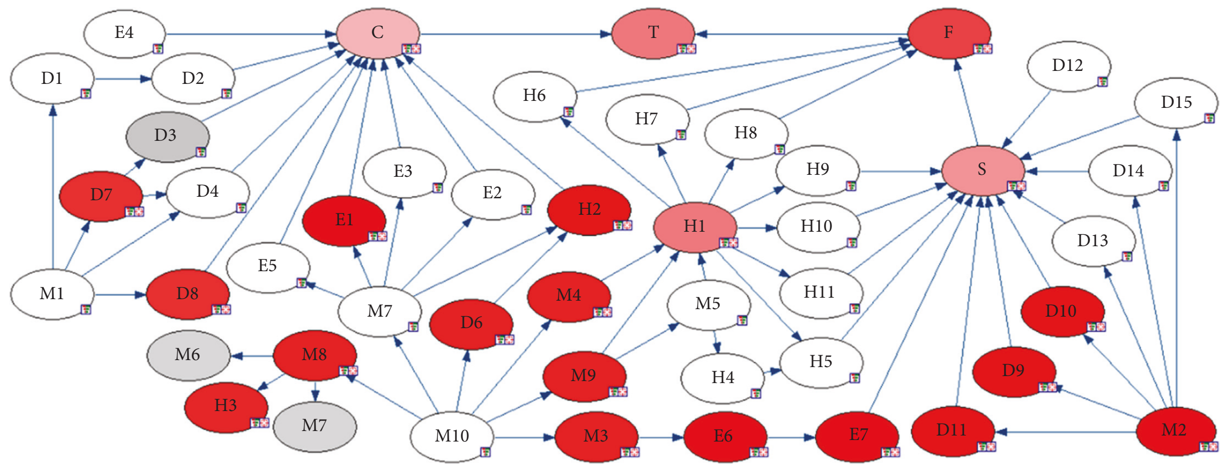

Figure 6: Sensitivity analysis of risk nodes.

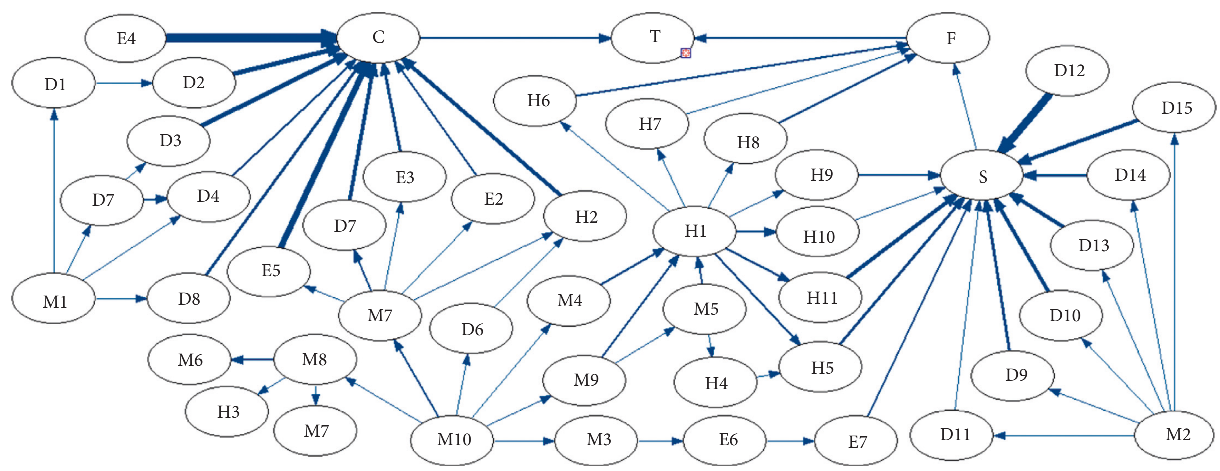

Figure 7: The maximum cause chain analysis of gas explosion.

implement the safety work guidelines, pay attention to underground ventilation management, fulfill the responsibility of safety management, implement daily safety inspection work, and put an end to employees' illegal command and illegal operation.

5. Conclusions

Many larger and above gas explosion cases show that the gas explosion accident is the result of the combined effect of gas accumulation and detonating fire source. In this study, from the above two directions, combined with the characteristics of gas explosion accidents, 47 keywords that directly or indirectly lead to accidents are extracted as the risk nodes of Bayesian networks. According to human factors, equipment factors, environmental factors, and management factors, these keywords are divided into four categories. The correlation analysis function of SPSS 25.0 software is used to determine the influence relationship between these nodes, and the directed arc is used to connect them to form the Bayesian network diagram of gas explosion. The following conclusions are drawn:

(1) The conditional probability distribution of each risk node is calculated by Bayesian network parameter learning. In the case of gas emission (E_1, E_2, and E_3) in the mining working face and insufficient air volume of the underground ventilator (D_3 and D_8), the possibility of coal seam gas accumulation will be greatly improved. Damage to materials and equipment (D_9, D_{10}) and miners' irregularities (H_9, H_{10}, H_{11}) can significantly increase the probability of ignition. Mismanagement (M_1, M_2, and $M7$) indirectly affects the probability of gas explosion.

(2) The posterior probability of the risk node indicates. The posterior probability of human factor (H_2), equipment factor (D_6), environmental factor (E_6), and management factor (M_2) in the four risk nodes is higher. Therefore, it is necessary to strengthen safety management, cultivate the safety awareness of gas inspectors, and improve the gas overrun alarm system.

(3) Through sensitivity analysis and maximum cause chain analysis of accidents. The risk nodes such as gas leak detection (H_2), ventilation system damage

(D_7), random opening and stopping of local ventilators (D_4), and goaf gas accumulation (E_1) have high sensitivity and are in the key path leading to gas explosion accidents. It can be considered that these factors are closely related to gas explosion accidents. In addition to the daily safety inspection work, coal mining enterprises need to pay attention to the training of staff safety awareness, improve safety rules and regulations, and increase safety investment in order to effectively prevent and control gas explosion accidents.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] J. E. Sinton, "Accuracy and reliability of China's energy statistics," *China Economic Review*, vol. 12, no. 4, pp. 373–383, 2001.

[2] G.-L. Feng, B.-R. Chen, Y.-X. Xiao, and Q. P.-X. H. W. Jiang, "Microseismic characteristics of rockburst development in deep TBM tunnels with alternating soft-hard strata and application to rockburst warning: a case study of the Neelum-Jhelum hydropower project," *Tunnelling and Underground Space Technology*, vol. 122, p. 104398, 2022.

[3] Y. Yu, D.-C. Zhao, G.-L. Feng, and D.-X. H.-S. Geng, "Energy evolution and acoustic emission characteristics of uniaxial compression failure of anchored layered sandstone," *Frontiers of Earth Science*, vol. 10, Article ID 841598, 2022.

[4] "A microseismic method for dynamic warning of rockburst development processes in tunnels," *Rock Mechanics and Rock Engineering*, vol. 48, no. 5, pp. 2061–2076, 2015.

[5] Y. Zhu, D. Wang, Z. Shao et al., "A statistical analysis of coalmine fires and explosions in China," *Process Safety and Environmental Protection*, vol. 121, pp. 357–366, 2019.

[6] J. Zhang, D. Cliff, K. Xu, and G. You, "Focusing on the patterns and characteristics of extraordinarily severe gas explosion accidents in Chinese coal mines," *Process Safety and Environmental Protection*, vol. 117, pp. 390–398, 2018.

[7] I.-L. Cioca and R. I. Moraru, "Explosion and/or fire risk assessment methodology: a common approach, structured for underground coalmine environments/Metoda szacowania ryzyka wybuchu i pożarów: podejście ogólne, dostosowane do środowiska kopalni podziemnej," *Archives of Mining Sciences*, vol. 57, no. 1, pp. 53–60, 2012.

[8] H. W. Heinrich, *Industrial Accident Prevention*, Industrial Accident Prevention. A Scientific Approach, Second Edition, 1941.

[9] P. S. Paul and J. Maiti, "The role of behavioral factors on safety management in underground mines," *Safety Science*, vol. 45, no. 4, pp. 449–471, 2007.

[10] K. Page, "Blood on the coal: the effect of organizational size and differentiation on coal mine accidents," *Journal of Safety Research*, vol. 40, no. 2, pp. 85–95, 2009.

[11] N. Siu, "Risk assessment for dynamic systems," *An overview*, vol. 31, 1994.

[12] Q. Nian, S. Shi, and R. Li, "Research and application of safety assessment method of gas explosion accident in coal mine based on GRA-ANP-FCE," *Procedia Engineering*, vol. 45, pp. 106–111, 2012.

[13] J. Zhang, Y. Zeng, G. Reniers, and J. Liu, "Analysis of the interaction mechanism of the risk factors of gas explosions in Chinese underground coal mines," *International Journal of Environmental Research and Public Health*, vol. 19, no. 2, p. 1002, 2022.

[14] B. G. Marcot and T. D. Penman, "Advances in Bayesian network modelling, Integration of modelling technologies," *Environmental Modelling & Software*, vol. 111, pp. 386–393, 2019.

[15] M. Li, H. Wang, D. Wang, Z. Shao, and S. He, "Risk assessment of gas explosion in coal mines based on fuzzy AHP and bayesian network," *Process Safety and Environmental Protection*, vol. 135, pp. 207–218, 2020.

[16] Y. Huang, G. Ma, and J. Li, "Grid-based risk mapping for gas explosion accidents by using Bayesian network method," *Journal of Loss Prevention in the Process Industries*, vol. 48, pp. 223–232, 2017.

[17] X. Li, X. Wang, and Y. Fang, "Cause-chain analysis of coal-mine gas explosion accident based on Bayesian network model," *Cluster Computing*, vol. 22, no. S1, pp. 1549–1557, 2019.

[18] M. Singh and M. Valtorta, "Construction of Bayesian network structures from data: a brief survey and an efficient algorithm," *International Journal of Approximate Reasoning*, vol. 12, no. 2, pp. 111–131, 1995.

[19] G. W. Brown, "Bayes' formula," *American Journal of Diseases of Children*, vol. 135, no. 12, p. 1125, 1981.

[20] S.-S. Chen, J.-H. Xu, and Y. Fan, "Evaluating the effect of coal mine safety supervision system policy in China's coal mining industry: a two-phase analysis," *Resources Policy*, vol. 46, pp. 12–21, 2015.

[21] E. Isaac, "Test for significance of pearson's correlation coefficient," *Administration and personnel development in adult and community education, a module*, vol. 13, 2018.

[22] E. S. Pearson, "The test of significance for the correlation coefficient," *Journal of the American Statistical Association*, vol. 26, no. 174, pp. 128–134, 1931.

[23] G. F. Cooper, "A diagnostic method that uses causal knowledge and linear programming in the application of Bayes' formula," *Computer Methods and Programs in Biomedicine*, vol. 22, no. 2, pp. 222–237, 1986.

[24] C. Walters and D. Ludwig, "Calculation of Bayes posterior probability distributions for key population parameters," *Canadian Journal of Fisheries and Aquatic Sciences*, vol. 51, no. 3, pp. 713–722, 1994.

[25] E. Castillo, J. M. Gutierrez, and A. S. Hadi, "Sensitivity analysis in discrete Bayesian networks," *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, vol. 27, no. 4, pp. 412–423, 1997.