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An Impacting Factors Analysis of Unsafe Acts in Coal Mine Gas Explosion Accidents Based on HFACS-ISM-BN

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Abstract: With the development of intelligent coal mine construction, China's coal production safety has been greatly improved, but coal mine gas explosion accidents still cannot be completely avoided and the unsafe acts of miners are an important cause of the accidents. Therefore, this study firstly collected 100 coal mine gas explosion cases in China, improved the framework of human factors analysis and classification system (HFACS) and used it to identify the causes of miners' unsafe acts in detail. A hierarchy of the impacting factors is established. Then, combining with the interpretive structural model (ISM), the correlation between the impacting factors among different levels, especially among non-adjacent levels, is qualitatively analyzed through expert judgment. Then, the correlation among the contributing factors was quantitatively tested by chi-square test and odds ratio (OR) analysis. On this basis, a Bayesian network (BN) is constructed for the impacting factors of miners' unsafe acts. The results show that the probability of coal mine gas explosion accident is 20% and 52%, respectively. Among the leading factors, the government's insufficient crackdown on illegal activities had the greatest impact on miners' violations, with a sensitive value of 13.2%. This study can provide reference for evaluating the unsafe acts of miners in coal mine gas explosion accidents by the probabilistic method.

Keywords: coal mine gas explosion; unsafe acts; HFACS; interpretive structural model; Bayesian network

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1. Introduction

In the past decade, the intelligent construction of coal mines in China, the world's largest coal producer, has injected new vitality into its coal industry [1]. However, the complexity of intelligent equipment operation procedures and the vicious working environment of miners have increased the risk of coal mining [2]. With the depletion of shallow coal mining, the mining depth gradually deepens, and the geological conditions become more complex, which increases the amount of gas emission, and the risk of gas accidents, especially the risk of methane gas explosion accident in coal seam, also increases [3]. On the one hand, gas explosion is one of the most serious coal mines disasters [4]. Since 2015, coal mine gas explosions have killed more than 300 people, more than half of China's total coal mine fatalities. Zhang et al. [5] have counted 1399 coal mine accidents since the beginning of this century, and concluded that gas explosion is the largest single accident that caused the largest number of casualties. On the other hand, despite decades of development, human factors are still an important cause of coal mine accidents. Chen et al. [6] analyzed major coal mine accidents in China from 1980 to 2000, and concluded that human factors accounted for 97.67% of the accidents. Li et al. [7] examined 287 articles on unsafe acts among miners from 2000 to 2016, and found that human factors accounted for more than 90 percent of accidents. Therefore, it is necessary to study the causes of miners' unsafe acts in coal mine gas explosion accidents.

HFACS framework is considered to be a powerful tool for human factor analysis of accidents [8]. Although the HFACS framework is widely used in chemical [9], navigation [10], and construction [11,12] fields, it still has limitations in analyzing the unsafe acts of miners. First, in the establishment of hierarchy, analysis results will be different due to subjective factors such as statistical methods of data. For example, Patterson et al. [13] collected more than 500 coal mine accidents cases in Australia in the first decade of the 21st century. Through the analysis of HFACS framework, the results show that human factors account for less than 10% of the accident factors. Lenné et al. [14] also collected nearly 300 major coal mine accidents that occurred in Australia in the first decade of the 21st century. Based on the HFACS framework analysis, they concluded that human factors accounted for more than 60% of the accidents. Therefore, testing is needed to reduce subjective influence during the establishment of HFACS framework. Secondly, HFACS framework is a qualitative method, while HFACS framework is static in the evaluation of accident factors, and cannot well express the diversity of data and uncertainty of accident process in the evaluation of data [15]. Therefore, appropriate tools to quantify HFACS framework are needed to make up for the deficiencies of HFACS framework. Ghasemi et al. [16] adopted the method of quantifying HFACS framework with Bayesian networks to quantitatively identify the impact factors of gas leakage accidents and screen out the key factors. Ma et al. [17] adopted the method of combining Bayesian network and HFACS framework to identify the key root events of fire and explosion accidents in university laboratories, so as solving the inconvenience caused by the static nature of traditional HFACS framework in accident analysis. The above scholars have verified the feasibility of Bayesian network quantization HFACS framework. Thirdly, for coal mine gas explosion accident, the factors leading to the accident are highly coupled [18]. When the traditional HFACS framework is applied to the analysis of the unsafe acts of miners, after the establishment of the hierarchy structure, the correlation of factors of adjacent levels can only be analyzed according to the hierarchy order, and it is difficult to express the coupling of gas explosion accident causes well. Interpretive structural model (ISM) can determine the relationship between the factors that cause problems in complex environment, first build the adjacency matrix through expert experience, and extract the structural model after calculation, which can improve the accuracy of correlation analysis of HFACS framework to a certain extent. However, the construction processed of ISM relies too much on the qualitative judgment of expert experience, and the quantitative analysis is insufficient, which has a certain subjectivity [19].

To solve the above problems, this study collected 100 typical cases of gas explosion accidents in China in recent decades, and improved the applicability of HFACS framework to coal mine gas explosion accidents in China based on existing studies. With the help of the improved HFACS framework, the causes of miners' unsafe acts are identified in detail from the level of government negligence, organizational influence, prerequisite of unsafe acts, and unsafe acts. In order to reduce the subjectivity of the traditional HFACS framework, the reliability of the improved HFACS framework is tested by using the rater reliability. Then, through the ISM method, experts are invited to establish the adjacency matrix of the factors causing the unsafe acts of miners, and the hierarchical structure model is extracted after calculation, so as to better reflect the highly coupling of coal mine gas explosion accident causes. Using chi-square test and odds ratio analysis, the correlation of each pair of factors is tested quantitatively, and the Bayesian network model is constructed. Finally, frequency statistics of 100 accident cases were carried out based on the improved HFACS framework, the probability of each node in the Bayesian network was calculated, and the induction path of unsafe acts was obtained through reverse reasoning by importing GeNIe software (developed by the decision systems laboratory at the University of Pittsburgh, version 2.3 of GeNIe), and the sensitive factors of unsafe acts were obtained through sensitivity analysis.

2. Materials and Methods

The first step of this study is to improve the HFACS to obtain the accident factors of miners' unsafe acts in coal mine gas explosion accidents in China. The second step is to construct BN network qualitatively through ISM method, and then verify BN structure quantitatively through inspection. Finally, the induced path and sensitive node of miners' unsafe acts in coal mine gas explosion were analyzed by GeNIe software (developed by the decision systems laboratory at the University of Pittsburgh, version 2.3 of GeNIe). The process is shown in Figure 1.

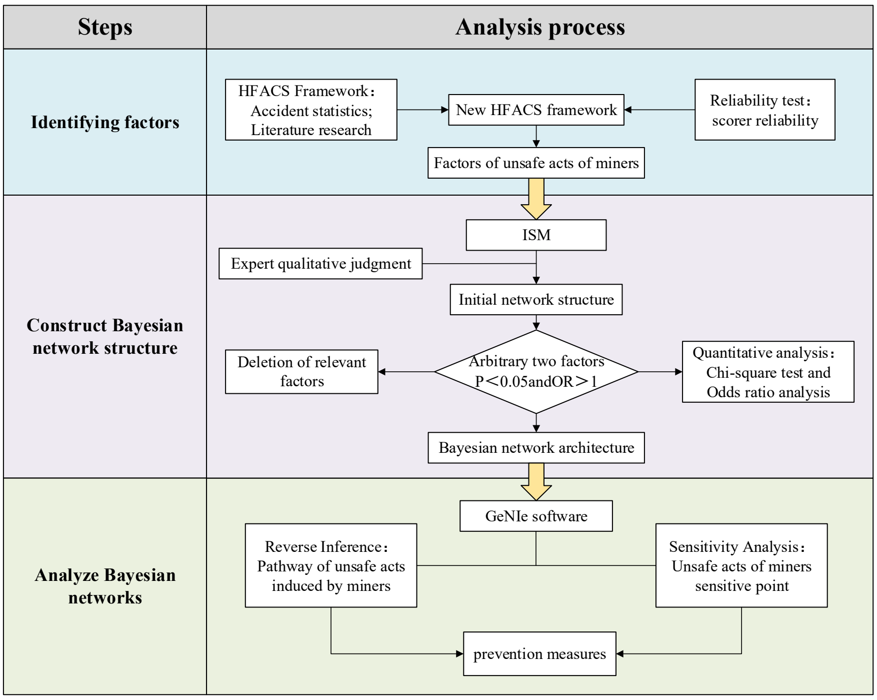

Figure 1. Unsafe acts risk analysis process of coal mine gas explosion accident.

2.1. Establishment of the Impacting Factors System

2.1.1. Improved HFACS Framework

HFACS framework was born in the field of aviation accident investigation, which is divided into unsafe acts level, preconditions of unsafe acts level, unsafe supervision level, and organizational influence level. As shown in Figure 2.

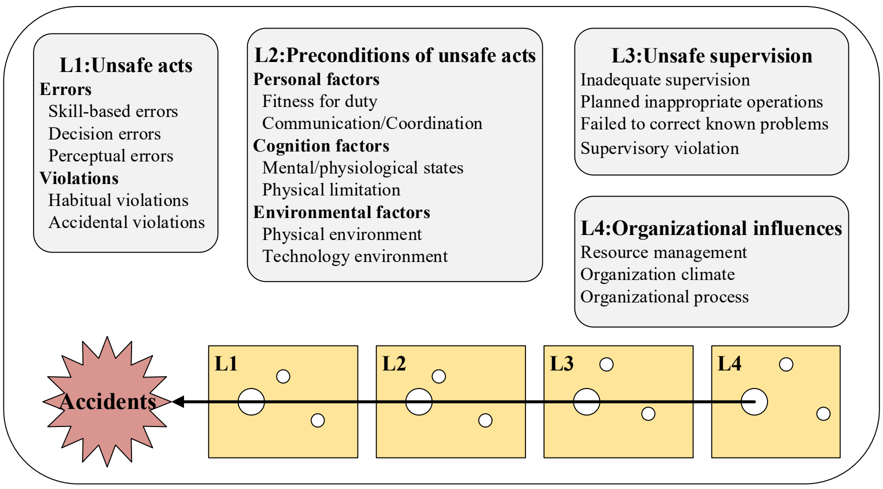

Figure 2. The HFACS framework.

However, the HFACS framework is not fully applicable to coal. There are three main differences.

1. In the coal industry, government regulators need to be considered. The coal mine gas explosion accident can be effectively controlled by the supervision department to strengthen the supervision of coal mine production [20].
2. In coal mining enterprises, the manifestations of management errors are more diverse [21]. For example, inadequate safety training will lead to secondary disasters, and imperfect safety management system will make the production process chaotic.
3. In specific coal mines, the factors of enterprise managers need to be considered. For example, managers participate in production by giving production orders, and their errors may cause huge accidents.

In order to make the HFACS framework more suitable for the analysis of coal gas explosion accidents in China, combined with the analysis of 100 accidents and previous studies [22,23], from the four levels of government regulatory dereliction of duty, organizational influence, the prerequisite of unsafe acts and the unsafe acts of miners, the HFACS framework suitable for the analysis of the causes of unsafe acts of miners in coal mine gas explosion accidents was constructed. Compared to the original HFACS framework, the new HFACS framework has the following modifications:

- Increase the level of government dereliction of duty, which includes two factors: safety supervision is inadequate and insufficient crackdown on illegal activities.
- Remove the level of unsafe supervision, but retain the factors in unsafe supervision, and integrate these factors into other levels.
- Increase the number of factors affecting this level from 3 to 5.
- The level of unsafe acts no longer classifies miners' errors and violations in detail, given that further subdivision of miner errors and violations based on accident cases could distort the data.

The new HFACS framework is shown in Figure 3.

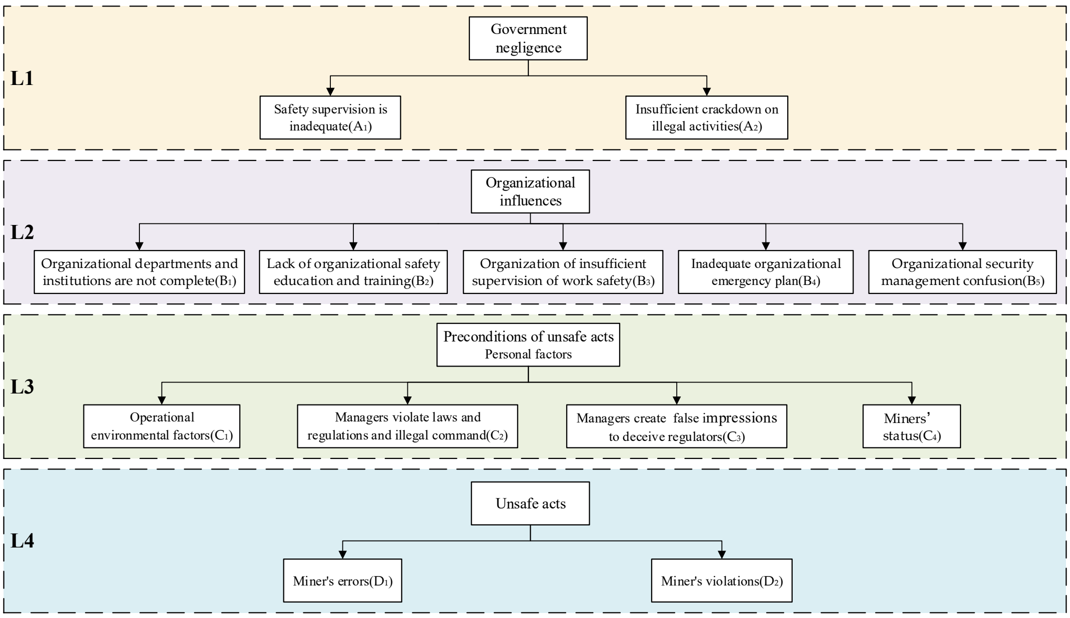

Figure 3. Improved HFACS framework.

The identification of factors at each level in the improved HFACS framework is shown in Table 1.

Table 1. Classification categories of factors.

Level	Factors	Description of Risk Category
Government negligence	Safety supervision is inadequate (A_1)	The daily supervision of coal mining enterprises by coal-related departments at all levels of government is inadequate, leading to the difficulty in implementing coal mine production rules and regulations, and the inadequate investigation of coal mine safety risks.
	Insufficient crackdown on illegal activities (A_2)	Coal-related departments at all levels of government have not cracked down enough on the illegal production and business activities of coal mining enterprises.
Organizational influences	Organizational departments and institutions are not complete (B_1)	The internal organization of coal mining enterprises is incomplete, resulting in incomplete departments in charge of coal mine safety, or personnel in charge of safety management are unprofessional or incompetent.
	Lack of organizational safety education and training (B_2)	Coal mine enterprises do not carry out safety training for managers and employees on time, including special meetings, emergency drills and job training, or the training carried out by coal mine enterprises is just a formality.
	Organization of insufficient supervision of work safety (B_3)	Coal mining enterprises, including the various organizations within the enterprises and the managers responsible for safety work, did not check the safety risks in coal mines on time, or the checks were not meticulous.
	Inadequate organizational emergency plan (B_4)	Coal mining enterprises have not formulated emergency measures to deal with emergencies, or the formulated emergency measures have insufficient timeliness and adaptability.
	Organizational security management confusion (B_5)	The responsibility of the institutions and departments in coal mine enterprises is not clear, which leads to the duplication and absence of the management of each system in coal mine.
Preconditions for unsafe acts	Operational environmental factors (C_1)	Poor physical environment: Poor working place for employees, including but not limited to noise, dust, and temperature discomfort.
		Poor technical environment: including but not limited to staff without professional and technical guidance and equipment performance deficiencies.
	Managers violate laws and regulations and illegal command (C_2)	Managers of coal mining enterprises violate laws and rules and regulations of the coal industry to organize employees to carry out production operations.
	Managers create false impressions to deceive regulators (C_3)	Managers of coal mining enterprises falsified accounts, drawings, and data to deceive government departments.
	Miners' status (C_4)	Poor physiological condition: The employee has, including but not limited to, fatigue, sleepiness, and other conditions at work.
		Poor mental state: employees in the work, including but not limited to the existence of fluke psychology, paralysis, bravura psychology, etc.
Unsafe acts	Miners' errors (D_1)	Skill-based errors: An employee's failure at work due to improper execution of procedures or inadequate operational skills.
		Decision errors: An error of judgment by an employee due to insufficient information, knowledge, or experience.
		Perceptual errors: When an employee's perception and awareness of something deviates from the actual situation.
	Miners' violations (D_2)	Habitual violations: When employees are working, they often choose to violate rules even though they clearly know the violation.
		Accidental violations: The violation caused by various accidental factors at work, and the violation is not intended by the employee.

2.1.2. Reliability Test of the System of the Impacting Factors

The rater's reliability is an effective method to verify HFACS framework [24]. The method of consistency test is usually adopted, that is, different evaluators analyze the same data, and the framework is considered to be reliable when the proportion of consistent results is no less than 70% [25,26]. The calculation formula is:

$$IOC = \frac{X}{X+Y} \quad (1)$$

where *IOC* is indexing consistency, *X* is the same number of judgment results between two raters, and *Y* is the different number of judgment results.

When there are many Bayesian network nodes, at least three experts should be selected for evaluation [27]. Therefore, this study invited four researchers and practitioners of coal mining industry to conduct reliability test. Four evaluators were trained in the meaning and use of the framework. Then, the evaluator analyzed and judged the cause factors of the 100 accident cases in turn. For example, in 100 accidents, the consistency test results of evaluators 1 and evaluators 2 on factor A_1 are the same number of evaluators 'judgment results on whether factor A_1 occurs, divided by 100. The index consistency of all factors of the four evaluators was calculated in turn, and the results were shown in Table 2.

Table 2. Reliability test results of the improved HFACS framework.

Level	Factors	Index Consistency (%)						
		All	1 & 2	1 & 3	1 & 4	2 & 3	2 & 4	3 & 4
Government negligence	Safety supervision is inadequate (A_1)	80.17	90	97	68	70	87	69
	Insufficient crackdown on illegal activities (A_2)	85.17	93	97	77	79	87	78
Organizational influences	Organizational departments and institutions are not complete (B_1)	80.83	91	97	69	68	88	72
	Lack of organizational safety education and training (B_2)	87.17	94	96	81	77	90	85
	Organization of insufficient supervision of work safety (B_3)	80.17	87	94	72	69	81	78
	Inadequate organizational emergency plan (B_4)	79	93	88	67	68	86	72
	Organizational security management confusion (B_5)	90.17	91	94	92	93	87	84
Preconditions for unsafe acts	Operational environmental factors (C_1)	71.17	87	94	52	53	85	56
	Managers violate laws and regulations and illegal command (C_2)	86.67	88	97	81	77	85	92
	Managers create false impressions to deceive regulators (C_3)	87.5	94	86	89	85	90	81
	Miners' status (C_4)	85	96	95	77	75	91	76
Unsafe acts	Miners' errors (D_1)	71.67	87	92	53	60	83	55
	Miners' violations (D_2)	78.5	89	93	67	68	82	72
Total		81.78	90.77	93.85	72.69	72.46	86.31	74.62

According to the consistency test results, the overall reliability of the index system established by HFACS framework reached 81.78%. Rater reliability for all factors was basically no less than 70%, indicating high reliability.

2.2. Determination of Hierarchies and Dependencies

2.2.1. Construction of Hierarchy Structure Based on ISM

Interpretive structural model (ISM) can determine the relationship between various factors in a complex environment [28]. ISM can analyze not only the relationship between adjacent factors, but also the relationship between factors at different levels [29].

Let the adjacency matrix be F, a_{ij} be an element in F, and the value of a_{ij} be [29]:

$$a_{ij} = \begin{cases} 1, Factor\ i\ has\ a\ direct\ effect\ on\ factor\ j \\ 0, Factor\ i\ has\ no\ direct\ effect\ on\ factor\ j \end{cases} \quad (2)$$

Let the identity matrix be E, and the reachable matrix be M. According to expert judgment, ISM adjacency matrix F is constructed as shown below.

$$F = \begin{vmatrix} 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix} \tag{3}$$

F is calculated by Boolean algebraic rules to get M, which is calculated in the following way:

$$F_1 = (F+E), F_n = (F+E)^n \tag{4}$$

$$F_1 = (F+E) \neq F_2 \neq \cdots \neq F_{n-1} = F_n \tag{5}$$

where, F_{n-1} is the reachable matrix M, M is shown as follows.

$$M = \begin{vmatrix} 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{vmatrix} \tag{6}$$

The hierarchy thus determined is shown in Figure 4.

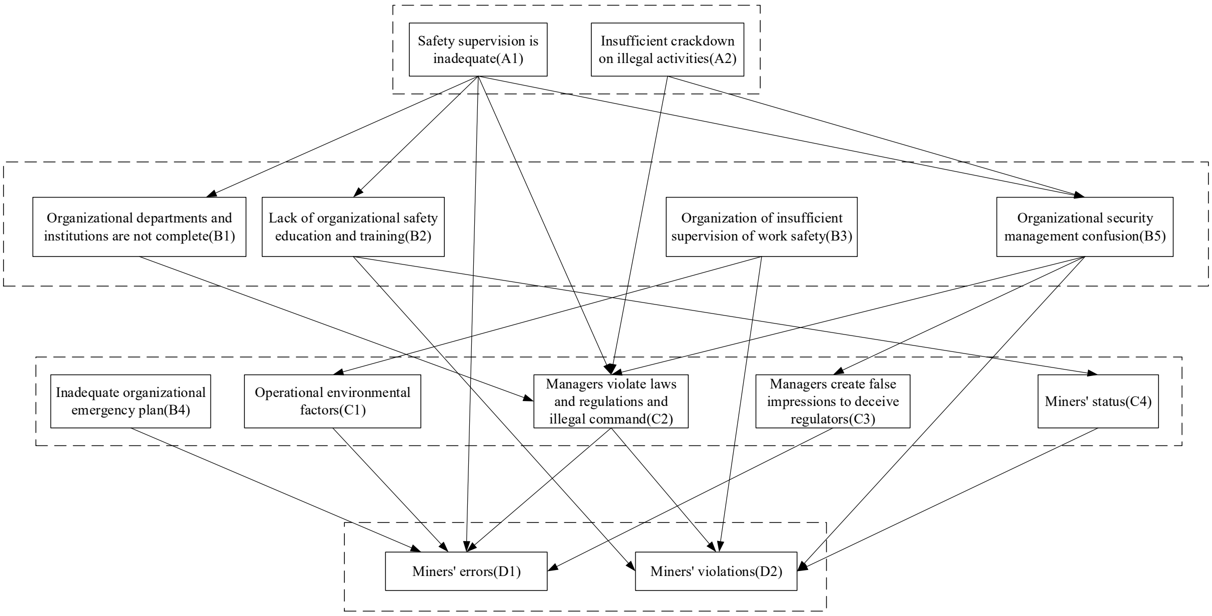

Figure 4. Initial hierarchy.

2.2.2. Test for Correlation of the Impacting Factors

The hierarchy diagram constructed by ISM is qualitatively divided according to expert experience. In order to ensure accuracy, it is necessary to conduct tests on this basis, especially quantitative tests. A chi-square test can be used to determine whether the two categorical variables are correlated. When the *p* value is less than 0.05, the correlation cannot be ruled out [30]. Odds ratio (OR) analysis can analyze whether the occurrence of one factor affects the occurrence of another factor. When the OR value is greater than 1, it has a greater impact.

Chi-square test and odds ratio analysis were carried out for 100 coal mine gas explosion accidents. The results with both *p* value and OR value meeting the requirements are shown in Table 3.

Table 3. Chi-square test and OR values statistics table.

Factor Correlation	χ^2	p	OR
A_1 & B_1	10.083	0.001	1.361
A_1 & B_2	11.068	0.001	1.485
A_1 & B_5	16.549	0.0001	1.153
A_1 & C_2	6.75	0.009	1.407
A_2 & B_5	62.916	0.0001	1.082
A_2 & C_2	44.541	0.0001	1.6596
B_1 & C_2	32.013	0.0001	1.0303
B_2 & C_4	19.946	0.0001	10.286
B_2 & D_2	12	0.001	1.249
B_3 & C_1	7.623	0.006	1.511
B_5 & C_2	8.515	0.004	1.287
B_5 & D_2	15.502	0.0001	1.643
C_1 & D_1	8.791	0.003	2.026
C_2 & D_1	42.925	0.0001	1.617
C_2 & D_2	6.047	0.014	2.1465
C_4 & D_2	54.656	0.0001	1.1633

It can be seen from Table 3 that there are 16 groups of significant correlation. Based on this, Figure 3 is simplified, and the hierarchy diagrams after testing is shown in Figure 5.

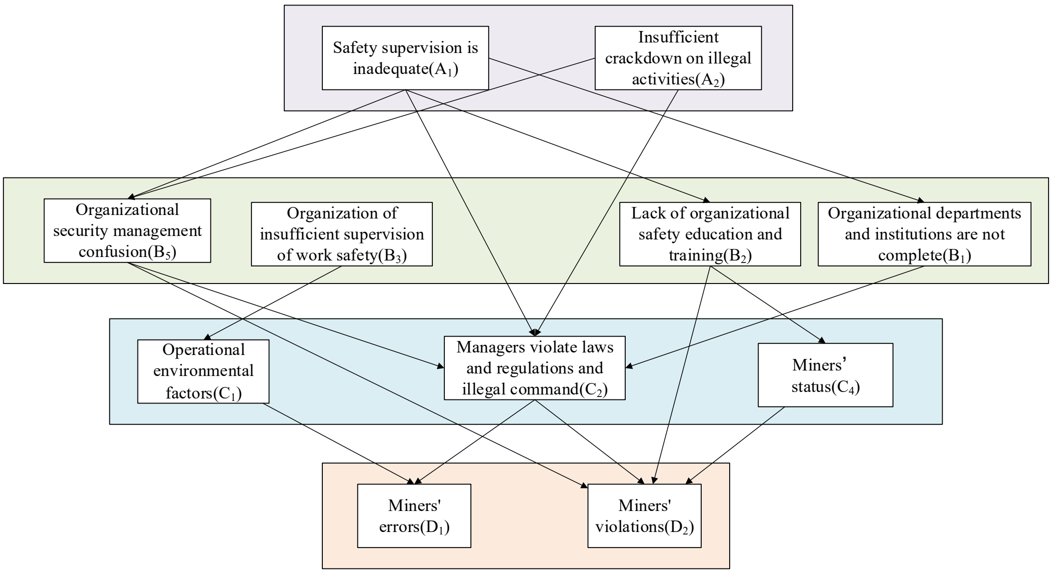

Figure 5. Initial BN model for unsafe acts in gas explosion accidents.

2.3. Construct Bayesian Networks

The Bayesian network is often used in the analysis of coal mine risk management. It can build a graphical model according to the dependence relationship between data variables, and realize causality analysis, statistical analysis, and prediction [31]. The BN is the principle of independence and the conditions of joint probability distribution as shown in Equation (7), Equation (7) of the parent(X_i) is a set of variables X_i parent node. The BN can also update the prior probability of variables. When there is new node data, the updated posterior probability is shown in Equation (8).

$$P(X) = P(X_1, X_2, \cdots, X_n) = \prod_{i=1}^{n} P(X_i \mid \mathrm{Parent}(X_i)) \quad (7)$$

$$P(X_1, X_2 \cdots X_n \mid U) = \frac{P(X, U)}{P(U)} = \frac{P(X, U)}{\sum_X P(X, U)} \quad (8)$$

2.3.1. Determination of BN Parameters

The method of determining BN parameters by relying on expert experience was not adopted in this study, because the results may be subjectively influenced by the knowledge, experience, and preferences of experts, etc. In this study, the network parameters were determined by the method of statistical frequency of the impacting factors.

Firstly, the occurrence frequency of each root node in the structure chart is counted, and the frequency is regarded as a prior probability, as shown in Table 4.

Table 4. Probability of three root nodes.

	A_1	A_2	B_3
State0	0.5	0.78	0.56
State1	0.5	0.22	0.44

It is assumed that each node has only two states occurring (State = 1) and not occurring (State = 0). For non-root nodes, given the value of the parent node, the frequency of different states of the node are taken as the conditional probability. Take the node C_1 as an example. The parent node of C_1 is only B_3, so the frequency and conditional probability of C_1 are shown in Table 5.

Table 5. C_1 frequency statistics and conditional probability table.

B_3	State0	State1	B_3	State0	State1
State0	40	25	State0	0.714	0.568
State1	16	19	State1	0.286	0.432

According to this method, the conditional probabilities of other nodes are derived successively.

2.3.2. Using GeNIe Software to Construct BN

GeNIe software is developed by the Decision Systems Laboratory at the University of Pittsburgh for reasoning BN [32]. The GeNIe software version is 2.3. After the network structures and network parameters are imported into GeNIe software, the Bayesian network is obtained, as shown in Figure 6.

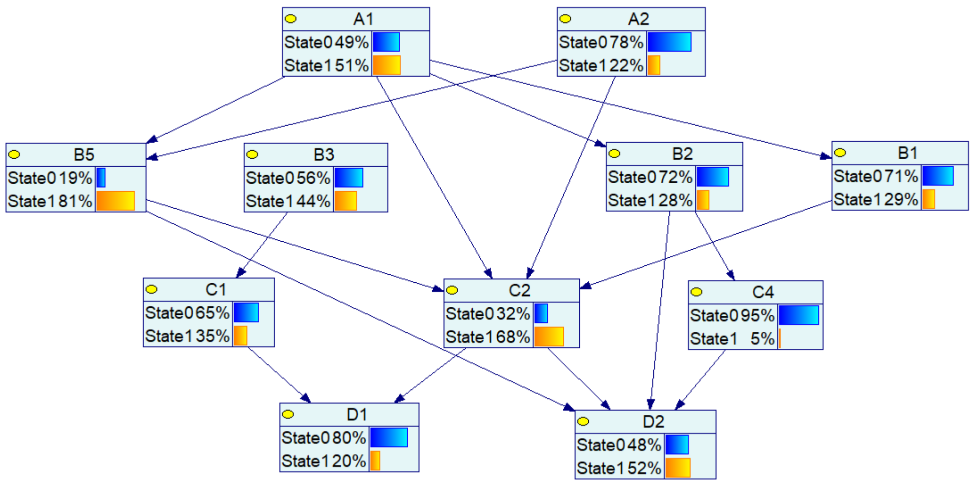

Figure 6. BN model.

3. Results

As can be seen from Figure 5, The probability of miners' errors is 20%, the probability of violations is 52%, and the probability of unsafe acts is relatively high, which requires further analysis.

3.1. Induced Path Analysis

Evoked pathways represent processes that may lead to unsafe acts. The induction path of miners' unsafe acts and miners' errors and violations is obtained by backward reasoning through BN. In GeNIe software (developed by the decision systems laboratory at the University of Pittsburgh, version 2.3 of GeNIe), if the state of D_1 and D_2 is set to state1 = 100%, the insecure acts occur. If state1 = 0% is set to other nodes at the same layer, the insecure acts do not occur. The statistical induced paths are shown in Table 6.

Table 6. Summary of unsafe acts risk paths for miners.

Factor	Induced Path
Miners' errors (D_1)	(1) (A_1) Safety supervision is inadequate (50%) → (B_5) Organizational security management confusion (76%) → (C_2) Managers violate laws and regulations and illegal command (67%) → (D_1) Miners' errors (100%)
	(2) (A_1) Safety supervision is inadequate (50%) → (C_2) Managers violate laws and regulations and illegal command (67%) → (D_1) Miners' errors (100%)
	(3) (A_1) Safety supervision is inadequate (50%) →(B_1) Organizational departments and institutions are not complete (28%) → (D_1) Miners' errors (100%)
	(4) (A_2) Insufficient crackdown on illegal activities (21%) → (B_5) Organizational security management confusion (76%) → (C_2) Managers violate laws and regulations and illegal command (67%) → (D_1) Miners' errors (100%)
	(5) (A_2) Insufficient crackdown on illegal activities (21%) → (C_2) Managers violate laws and regulations and illegal command (67%) → (D_1) Miners' errors (100%)
	(6) (B_3) Organization of insufficient supervision of work safety (45%) → (C_1) Operational environmental factors (39%) → (D_1) Miners' errors (100%)
Miners' violations (D_2)	(1) (A_1) Safety supervision is inadequate (54%) → (B_5) Organizational security management confusion (86%) → (D_2) Miners' violations (100%)
	(2) (A_1) Safety supervision is inadequate (54%) → (B_5) Organizational security management confusion (86%) → (C_2) Managers violate laws and regulations and illegal command (82%) → (D_2) Miners' violations (100%)
	(3) (A_1) Safety supervision is inadequate (54%) → (B_1) Organizational departments and institutions are not complete (27%) → (C_2) Managers violate laws and regulations and illegal command (82%) → (D_2) Miners' violations (100%)
	(4) (A_1) Safety supervision is inadequate (54%) → (C_2) Managers violate laws and regulations and illegal command (82%) → (D_2) Miners' violations (100%)
	(5) (A_1) Safety supervision is inadequate (54%) → (B_2) Lack of organizational safety education and training (33%) → (D_2) Miners' violations (100%)
	(6) (A_1) Safety supervision is inadequate (54%) → (B_2) Lack of organizational safety education and training (33%) → (C_4) Miners' status (8%) → (D_2) Miners' violations (100%)
	(7) (A_2) Insufficient crackdown on illegal activities (26%) → (B_5) Organizational security management confusion (86%) → (D_2) Miners' violations (100%)
	(8) (A_2) Insufficient crackdown on illegal activities (26%) → (B_5) Organizational security management confusion (86%) → (C_2) Managers violate laws and regulations and illegal command (82%) → (D_2) Miners' violations (100%)
	(9) (A_2) Insufficient crackdown on illegal activities (26%) → (C_2) Managers violate laws and regulations and illegal command (86%) → (D_2) Miners' violations (100%)

The main risk paths leading to miners' errors are government's safety supervision is inadequate (50%) → organizational security management confusion (76%) → managers violate laws and regulations and illegal command (67%) → miners' errors (100%). The main risk paths leading to miners' violations are government 's safety supervision is inadequate (54%) → organizational security management confusion (86%) → miners' violations (100%). It can be seen that the safety supervision of government departments and the safety management of organizations have an important impact on the unsafe acts leading to coal mine gas explosion accidents in China, and both government departments and organizations should strengthen safety supervision.

3.2. Sensitivity Analysis

The value of the sensitivity coefficient represents the influence of the node on the target node. In GeNIe software (developed by the decision systems laboratory at the University of Pittsburgh, version 2.3 of GeNIe), the D_1 and D_2 nodes were set as target nodes in turn, and the sensitivity coefficients of related nodes were deduced. All sensitivity coefficients were calculated, as shown in Table 7. The distribution of sensitivity coefficients in the impacting factors was shown in Figure 7.

Table 7. Ranking table of sensitivity coefficients.

	Nodes	Sensitivity Coefficient	Rank		Nodes	Sensitivity Coefficient	Rank
	C_1	0.059	1		A_2	0.132	1
	A_2	0.038	2		C_2	0.086	2
	C_2	0.026	3		C_4	0.083	3
$\mathbf{D_1}$	A_1	0.016	4	$\mathbf{D_2}$	B_5	0.077	4
	B_1	0.016	5		A_1	0.063	5
	B_3	0.015	6		B_2	0.06	6
	B_5	0.013	7		B_1	0.048	7

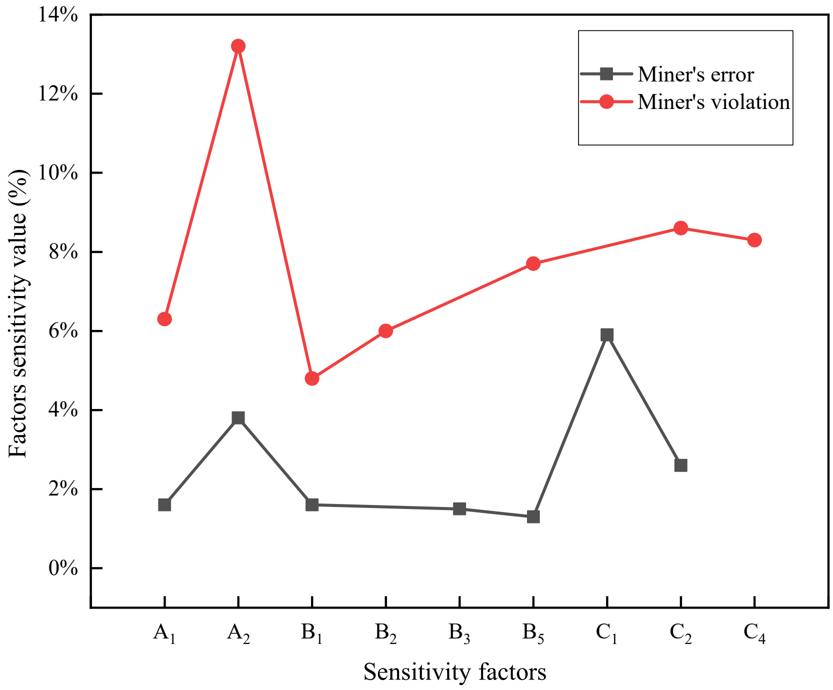

Figure 7. Sensitivity coefficient distribution diagram.

As can be seen from Figure 7, the sensitive value of the sensitive factors of miners' violations is higher than that of miners' errors on the whole. The operating environment is the most sensitive point for miners' errors. The government's lack of enforcement is the most sensitive point to miners' violations. In conclusion, no matter miners' errors or miners' violations, the most sensitive points are concentrated on the areas of government dereliction of duty and the prerequisite conditions of unsafe acts. Therefore, the government should pay more attention to coal mine accidents, strengthen the supervision of coal mine safety, increase the efforts to crack down on coal mine laws and regulations, and eliminate the prerequisite for unsafe acts.

4. Discussion

In the past, when scholars used HFACS framework as an indicator factor selection tool to study the causes of coal mine accidents, after establishing the hierarchical structure of the accident causes, they only carried out correlation analysis on the factors of adjacent levels, lacking a detailed analysis of the hierarchical structure. When the coal mine gas explosion accident is analyzed, the previous research methods cannot show the coupling relationship between the accident causes well. This study presents a probabilistic model for evaluating miners' unsafe acts in coal mine gas explosion accidents in China. After establishing the hierarchical structure of accident causes, the model in this study breaks through the hierarchical restriction and analyzes the correlation between accident factors in detail through quantitative inspection method and qualitative ISM method, and better displays the coupling relationship between accident causes. The effectiveness of the model is verified by 100 coal mine gas explosion accidents cases.

However, there are some limitations in this study. First of all, the results of this study are not enough to provide reference for all types of coal mines. On the one hand, the sample size of this study can be further increased; on the other hand, when selecting samples, it is not possible to cover all types of coal mines. Secondly, although this study adopts a series of quantitative analysis methods such as rater reliability test, chi-square test and odds ratio analysis to improve the reliability of the study, it still cannot completely eliminate the subjective influence of the evaluator in the qualitative evaluation. Finally, the results of this study are timeliness. With the development of intelligent construction of global coal mines, the causes of coal mine gas explosion accidents will also change, and the accuracy of the results of this study will also change.

In subsequent studies, we will collect more accident cases, not only to improve the standard in terms of quantity, but also to expand the coverage of coal mine types. Secondly, we will also explore more ways to reduce subjective influence, such as further subdividing the state of the impacting factors on the basis of occurrence and non-occurrence. Finally, we will also carry out more interviews and investigations of miners, especially survivors of related accidents, whose feelings and thoughts will greatly improve the accuracy of the research.

5. Conclusions

This study is based on coal mine gas accidents in China in recent decades. First, 100 typical cases were collected, and the HFACS framework was improved through previous studies and case analysis. The improved framework was used to identify the causes of the unsafe acts of miners at four levels: government negligence, organizational influence, prerequisite for unsafe acts, and the unsafe acts of miners and the reliability of the improved HFACS framework was verified by using the rater's reliability. The reliability of the impacting factor system is indirectly explained. Then, experts were invited to use the ISM method to construct the impacting factors hierarchy, and the correlation between the impacting factors at different levels was corrected by combining the quantitative analysis methods of the chi-square test and odds ratio analysis, and the BN structure was established. Finally, the conditional probability of each node is calculated according to the statistical frequency of the root node, and the Bayesian network diagram is drawn by GeNIe software (developed by the decision systems laboratory at the University of Pittsburgh, version 2.3 of GeNIe). The analysis structure showed that the probability of miners' errors and miners' violations was 20% and 52%, respectively. The main induced path of miners' errors is government's safety supervision is inadequate → organizational security management confusion → managers violate laws and regulations and illegal command → the miners' errors. The main induced path of miners' violations is government's safety supervision is inadequate → managers violate laws and regulations and illegal command → the miners' violations. The operating environment is the highest sensitive point of miners' errors, and the government's insufficient crackdown on illegal activities is the highest sensitive point of miners' violations. Therefore, the government should strengthen supervision and protect the safety of miners.

The study can not only provide reference for the framework establishment and analysis process of the probabilistic study of coal mine gas explosion accidents, but also can be used for the investigation and analysis of gas explosion accidents, which is of great significance for the safety of coal mine production.

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