

Article

Disaster-Causing Mechanism of Hidden Disaster-Causing Factors of Major and Extraordinarily Serious Gas Explosion Accidents in Coal Mine Goafs

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Abstract: Hidden disaster-causing factors (HDCFs) in coal mines can be identified via the re-refinement and classification of disaster-causing factors (DCFs) in coal mines. The study of the disaster-causing mechanism of accidents from the perspective of HDCFs in coal mines could be helpful to analyze the accident occurrence process from a new perspective, and new ideas for accident prevention and control could then be proposed. To clarify the disaster-causing mechanism of HDCFs of major and extraordinarily serious gas explosion accidents (MESGEAs) in coal mine goafs, 32 MESGEAs in coal mine goafs in China from 2000 to 2021 were adopted as a data source. By redefining the definition, connotation and characteristics of HDCFs in coal mines, 10 HDCFs were identified. Consequently, an improved decision-making trial and evaluation laboratory (DEMATEL)-interpretive structural model (ISM)-matrix of cross impact multiplications applied to classification (MICMAC) model was used to comprehensively analyze HDCFs in 3 aspects, including the centrality and cause degrees, hierarchical structure, and driving and dependence powers, from a completely objective perspective. The results demonstrated that (1) the considered MESGEAs in coal mine goafs were caused by DCFs in the management aspect by affecting the DCFs in the 3 aspects of human factors, equipment and environment, as well as under the combined effect of DCFs internal interaction contained in itself. (2) There were 2 types of disaster-causing mechanisms of HDCFs of MESGEAs in coal mine goafs: (a) the indirect disaster-causing by HDCFs in the management aspect and (b) the random coupling disaster-causing by HDCFs in human factors, equipment and environment 3 aspects.

Keywords: goaf of a coal mine; gas explosion accidents; hidden disaster-causing factors; disaster-causing mechanism; DEMATEL-ISM-MICMAC model



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1. Introduction

After underground coal mining, the overlying strata in the goaf are broken, collapsed, bent and subside due to the loss of coal support [1–3]. The irregularly shaped collapsed rock mass is subject to compaction degree differences, resulting in numerous hole and crack structures in the goaf. This structure not only provides air leakage channels but also provides a suitable space for gas accumulation [4–7]. Under the action of air flow in these air leakage channels, notable spontaneous combustion of residual coal in the goaf can occur [8–10]. Additionally, the gas desorbed from residual coal can migrate and become enriched in the goaf, forming “gas storage reservoirs” [11–14]. Conditions such as residual coal spontaneous combustion or sparks generated by rock friction or impact coupled with an appropriate gas concentration can easily cause gas explosion accidents [15–17]. Simultaneously, under the influence of various factors (air flow short circuit, etc.), the gas enriched in the goaf may flow and migrate into other areas of the mine and locally accumulate, thereby causing gas explosion accidents. The coal mine goaf is one of the key areas of concern for the prevention of major and extraordinarily serious gas explosion

accidents (MESGEAs). Therefore, from the perspective of hidden disaster-causing factors (HDCFs), the study of the disaster-causing mechanism of MESGEAs in coal mine goafs can provide new ideas for MESGEA prevention and control in goafs and guarantee coal mine safety production.

In the study of HDCFs in coal mines, most of the research results at the present stage focus on the exploration and prevention of HDCFs from a geological perspective. Fan [18] classified HDCFs based on the formation characteristics of HDCFs in coal mines and systematically proposed exploration technology for various HDCFs in coal mines. Xu et al. [19] identified and classified HDCFs of water disasters in small coal mines in great detail according to the classification results of the hydrogeological types of small coal mines. Liu et al. [20] proposed the detection technique involving the ground-road direct current resistivity method to identify the spatial location of hidden disaster-causing sources around roadways and working faces. In fact, coal mine HDCFs can be identified through the re-refinement and classification of coal mine disaster-causing factors (DCFs), and coal mine HDCFs comprise a subset of coal mine DCFs; coal mine HDCFs should not be limited to geological aspects. However, relatively few research results are available addressing other aspects of HDCFs in coal mines. Zhao and Tian [21] comprehensively identified HDCFs in coal mines from 4 aspects, namely, human factors, equipment, environment and management, and proposed an HDCF identification method based on the naive Bayesian algorithm. This method could provide many advantages, such as a high recognition rate and high recognition speed, but the identified HDCFs were very general, which is not conducive to providing specific guidance and suggestions for accident prevention and early warning.

In the aspect of research on the disaster-causing mechanism of gas explosion accidents in coal mine goafs, most researchers have achieved abundant research results via theoretical analysis and numerical and similar simulation experiments. Li et al. [22] performed a detailed analysis of the gas explosion formation process in a goaf considering the thermal buoyancy effect. Li et al. [23] used the numerical simulation method to study the influence of the air volume and gas emission in a goaf on the distribution of oxygen and gas concentrations. Ma et al. [11] performed similar simulation experiments to reveal the formation mechanism of gas explosions induced by spontaneous coal combustion. Currently, the safety management research objects of gas explosions mostly consider the overall mine area or individual mines. Li et al. [24] analyzed the DCFs of gas explosion accidents in coal mines by using the 24Model which is human-oriented and organization-oriented, and obtained various unsafe conditions, unsafe acts, safety knowledge, safety management systems and safety cultures that caused the occurrence of gas explosion accidents. Meng et al. [25] constructed a risk assessment model based on the analysis of the unsafe behavior characteristics of humans in gas explosion accidents, to obtain the priority of controlling unsafe behaviors by calculating the risk value. Li et al. [26] constructed a coal mine gas explosion accident model based on Bayesian network, and obtained the main causes of gas explosion accidents through modeling analysis. The safety management research objects of gas explosions rarely consider specific coal mine areas (such as the goaf in this paper) as the research object, while refinement of the research object of coal mine safety management could help prevent accidents [27–30].

To this end, this study selected MESGEA cases in coal mine goafs in China from 2000 to 2021 as the data source to identify HDCFs among DCFs in 4 aspects: human factors, equipment, environment and management. As such, the improved decision-making trial and evaluation laboratory (DEMATEL)-interpretive structural model (ISM)-matrix of cross impact multiplications applied to classification (MICMAC) model was used to study the disaster-causing mechanism of HDCFs of MESGEAs in coal mine goafs from a completely objective perspective. Countermeasures and measures for the prevention and control of MESGEAs in goafs were proposed from an HDCF perspective.

2. Identification of HDCFs of MESGEAs in Coal Mine Goafs

2.1. Definition of HDCFs in Coal Mines

The essential, existing definition of HDCFs in coal mines is that they are hidden in the coal seam and its surrounding rock, geological structures and adverse geological bodies that may induce disasters in the mining process, and disaster geological bodies formed under the coupled action of mining stress. Additionally, the literature proposes that HDCFs in coal mines exhibit hidden, time-varying and sudden characteristics [18].

Researchers have also referred to HDCFs as hidden disaster-causing geological factors in coal mines [31–33], and this study conforms to this view. We analyzed and reviewed the connotation of HDCFs in coal mines, as shown in Figure 1. It was concluded that the connotations of HDCFs and hidden disaster-causing geological factors in coal mines mainly differ in the following aspects:

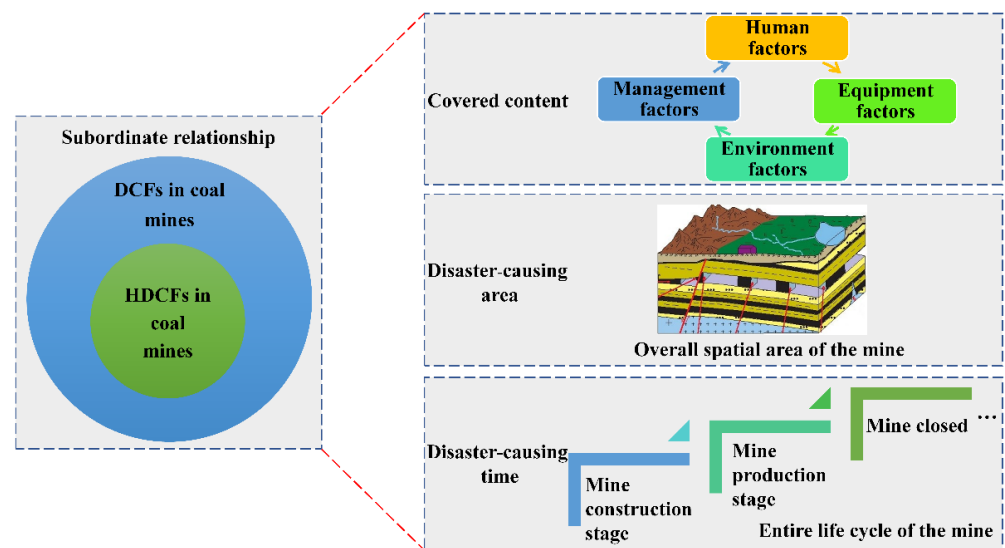


Figure 1. The connotation of HDCFs in coal mines.

(1) Based on subordinate relationship analysis, HDCFs in coal mines constitute a subset of DCFs in coal mines, which can be identified via secondary division and deep mining of DCFs in coal mines. Hidden disaster-causing geological factors in coal mines comprise a class of HDCFs in coal mines.

(2) From the covered content analysis, HDCFs in coal mines must contain 4 aspects, namely, human factors, equipment, environment and management, rather than only environmental (or geological) factors.

(3) Through disaster-causing area analysis, the disaster-causing scope of HDCFs in coal mines should cover the overall spatial area of the mine, not only the coal seam and its surrounding rock.

(4) Via disaster-causing time analysis, the disaster-causing time of HDCFs in coal mines spans the entire life cycle of the mine, i.e., from initial mine construction to management after mine closure. Coal mining activities belong to a subcategory of the disaster-causing time of HDCFs in coal mines.

Considering the characteristics of hidden disaster-causing geological factors in coal mines, the above analysis suggests that HDCFs in coal mines also exhibit the same 3 characteristics, i.e., hidden, time-varying and sudden characteristics. Among these characteristics, hidden suggests that DCFs are difficult to directly identify and are often determined through analysis after accident occurrence. Time-varying indicates that nondisaster-causing factors can be transformed into DCFs under the influence of external factors. Sudden suggests that after a given DCF is triggered (the trigger cause is often not the DCF), this could rapidly lead to an accident. Hidden is the basic characteristic of HDCFs, while time-varying

and sudden are additional characteristics of HDCFs. Therefore, HDCFs can be identified from DCFs based on the above characteristics.

In summary, HDCFs in coal mines can be defined as follows: HDCFs can occur throughout the entire life cycle of coal mines, these factors can be hidden within the overall spatial area of the mine, and they may induce DCFs of all types of coal mine disasters and accidents; HDCFs typically exhibit hidden, time-varying and sudden characteristics.

2.2. Identification of HDCFs of MESGEAs in the Goaf

2.2.1. Determination of DCFs of MESGEA in the Goaf

Via the adoption of MESGEAs in coal mine goafs in China from 2000 to 2021 as a data source (major and extraordinarily serious accidents refer to accidents resulting in the death of more than 10 people, serious injuries among more than 50 people, or direct economic losses of more than 50 million yuan), DCFs were condensed from accident investigation reports in 4 aspects: human factors, equipment, environment and management.

The reason for choosing MESGEAs as the data source is as follows: compared to general gas explosion accidents, the accident investigation reports associated with MESGEAs are more authoritative and reliable and easier to obtain. Through network retrieval, 32 complete investigation reports of MESGEAs were obtained (1 report with incomplete data). The main retrieval sources included the following: Coal Mine Safety Net (<https://www.mkaq.org/ssgl/shigual/>, accessed on 20 September 2022), Journal of Safety and Environment, China's Work Safety Yearbook, and Chinese government websites at all levels.

The annual number of MESGEAs from 2000 to 2021 is shown in Figure 2. Figure 2 shows that 268 MESGEAs occurred, and 33 MESGEAs occurred in goafs, accounting for 12.31% of the total MESGEAs. The number of MESGEAs decreased over time in the form of an exponential function, indicating that the safety situation was improving each year. However, MESGEAs in coal mine goafs still occurred year after year, and the safety situation in this area did not improve. To achieve the “zero accident vision” of MESGEAs in coal mines, it is urgent to effectively control MESGEAs in coal mine goafs.

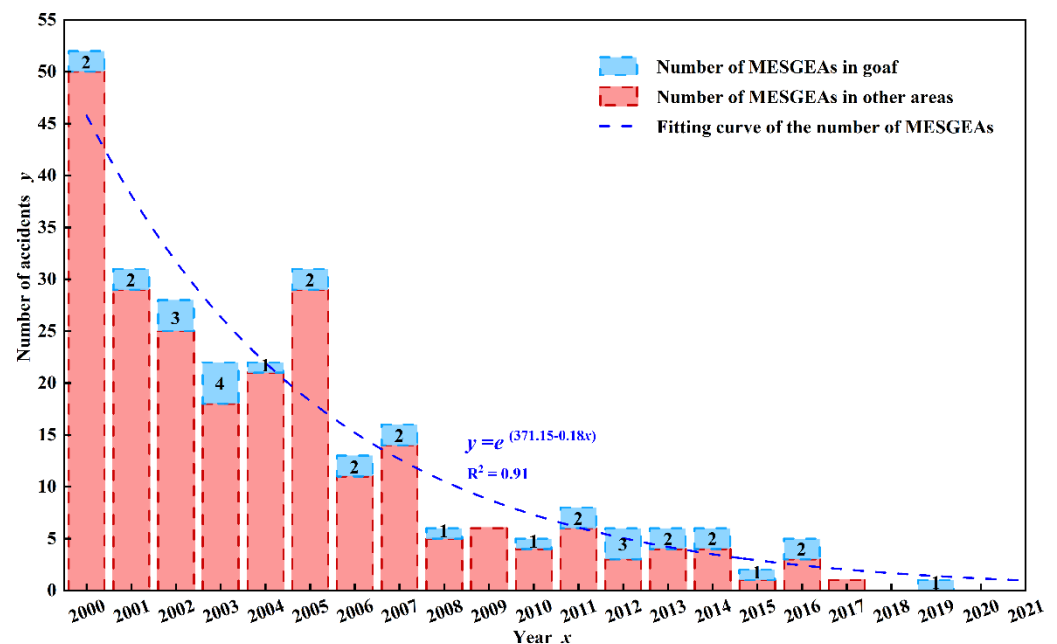


Figure 2. The number of MESGEAs.

Through review and analysis of accident investigation reports, it could be concluded that there were 22 DCFs of MESGEAs in goafs in 4 aspects, i.e., human factors, equipment, environment and management, as shown in Figure 3. The serial numbers of the DCFs are

provided in parentheses in Figure 3. The occurrence frequency of each DCF in the accidents is provided in Table 1.

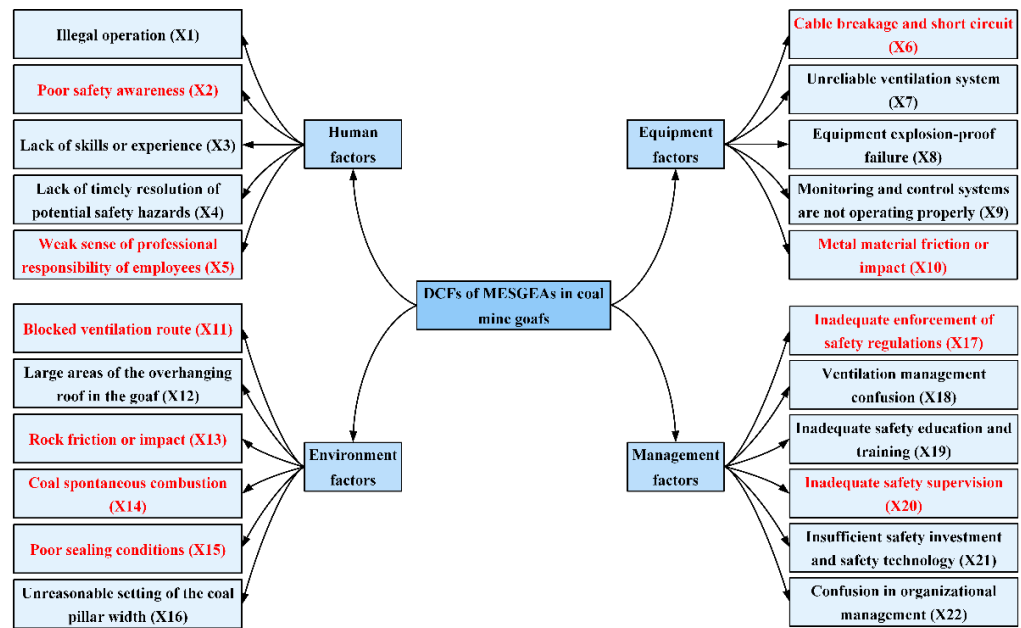


Figure 3. DCFs of MESGEAs in coal mine goafs.

Table 1. The occurrence frequency of the DCFs.

DCF Serial Number	Frequency	DCF Serial Number	Frequency	DCF Serial Number	Frequency
X1	17	X9	10	X17	27
X2	9	X10	2	X18	13
X3	7	X11	2	X19	15
X4	13	X12	6	X20	25
X5	6	X13	3	X21	22
X6	4	X14	7	X22	23
X7	8	X15	5	—	—
X8	3	X16	3	—	—

2.2.2. Identification of HDCFs of MESGEAs in the Goaf

The 3 characteristics of HDCFs in coal mines are important criteria for the identification of HDCFs among DCFs. The contents covered by each DCF and its corresponding characteristics of HDCFs are summarized in Table 2, and the DCFs indicated in red font in Figure 3 are HDCFs.

Table 2 indicates that there were 10 HDCFs of MESGEAs in coal mine goafs, accounting for nearly half (45.45%) of the total number of DCFs. The HDCFs in the human factors and management aspects all exhibited hidden characteristics, mainly because of the following: the HDCFs in the human factors and management aspects encompassed indirect causes of accidents. The HDCFs in the equipment aspect all revealed time-varying characteristics, largely because these HDCFs were not DCFs in their own right, they were mainly influenced by external factors, and they could be transformed into DCFs (for example, a cable is not a DCF, but as a result of the impact of falling objects, damage could occur and sparks could be generated due to a short circuit). The number of HDCFs in the environment aspect was the largest, and these HDCFs exhibited 2 characteristics, namely, time-varying and sudden characteristics. The main reasons were as follows: the HDCFs in the environment aspect included both essential nondisaster-causing factors transformed into DCFs (for example, sparks generated by friction or the impact of rocks, in which the rocks do not constitute a DCF) and DCFs in long-term dynamic equilibrium; these HDCFs could be triggered by

other factors to cause disasters (for example, spontaneous combustion of residual coal and gas concentration in the goaf maintained under a long-term dynamic balance, where a sudden change in the external pressure difference may cause gas explosions due to residual coal spontaneous combustion).

Table 2. The identification of HDCFs of MESGEAs in the goaf.

DCF (Serial Number)	Contents Covered	Characteristics
Illegal operation (X1)	Illegal blasting, illegal entry into the goaf to operation, ...	—
Poor safety awareness (X2)	Insufficient understanding of hazards, poor awareness of regulations and measures, ...	Hidden
Lack of skills or experience (X3)	Low technical quality, lack of timely adjustment of the ventilation system, ...	—
Lack of timely resolution of potential safety hazards (X4)	Hazard investigation goes through the motions, long-term unresolved hazards, ...	—
Weak sense of professional responsibility of employees (X5)	Gas monitoring probes were not installed in place, unattended gas monitoring system, ...	Hidden
Cable breakage and short circuit (X6)	Short circuit caused by the impact of a falling object, short circuit caused by miners' pulling and damage at will, ...	Time-varying
Unreliable ventilation system (X7)	Poor quality of ventilation facilities, air ducts are disconnected, ...	—
Equipment explosion-proof failure (X8)	Explosion-proof failure of various types of electrical equipment	—
Monitoring and control systems are not operating properly (X9)	There are various problems in system operation, imperfect system equipment, ...	—
Metal material friction or impact (X10)	Sparks generated by friction or impact of metal materials	Time-varying
Blocked ventilation route (X11)	Roadway blockage due to falling objects	Time-varying
Large areas of the overhanging roof in the goaf (X12)	The main roof is hard and does not easily fall, and caving the roof is not in time	—
Rock friction or impact (X13)	Sparks generated by friction or impact of rocks	Time-varying
Coal spontaneous combustion (X14)	Spontaneous combustion of residual coal in the goaf	Sudden
Poor sealing conditions (X15)	Poorly sealed goaf, poorly sealed abandoned coal mines, ...	Sudden
Unreasonable setting of the coal pillar width (X16)	The coal pillar width is smaller than the minimum blast resistance line width, section coal pillars fail to provide a supporting effect, ...	—
Inadequate enforcement of safety regulations (X17)	Laws, regulations and rules have not been implemented, inadequate safety assurance measures, ...	Hidden
Ventilation management confusion (X18)	Auxiliary fans are activated and stopped at will, the mine ventilation mode is randomly adjusted, ...	—
Inadequate safety education and training (X19)	Lax safety education and training, no custom safety education and training, ...	—
Inadequate safety supervision (X20)	Government and group company supervision is a mere formality, insufficient supervision, investigation and treatment, ...	Hidden
Insufficient safety investment and safety technology (X21)	Inadequate equipment and facilities, irrational technical scheme, ...	—
Confusion in organizational management (X22)	Confusion in labor organization and management, deliberate concealment and supervision evasion, ...	—

3. Computational Model Construction

3.1. Overview of the DEMATEL, ISM and MICMAC Methods

MESGEAs in coal mine goafs were caused by the interaction of many DCFs in 4 aspects, namely, human factors, equipment, environment and management. To reveal the causal relationship among factors in complex systems, the application of the DEMATEL method for factor analysis of complex systems has become very widespread [34–36]. DEMATEL is a research method for complex directed networks. It relies on the experience and knowledge of experts, uses graph theory and matrix tools, constructs a direct influence matrix through qualitative judgment among factors in complex systems, and then calculates the 4 quantities of the influence degree, affected degree, centrality degree and cause degree of each factor, so as to measure the causal relationship among the factors and the magnitude of the role of these factors in the system [37]. The ISM mines the interaction relationship among system factors based on expert experience and knowledge; this model decomposes the complex and disorganized relationships among system factors into a multilevel hierarchical structure model through matrix calculations to clarify the interaction relationships and

hierarchical structure among factors [38]. The MICMAC method has been used to analyze the interaction relationship among various factors in the system, but this method focuses on analyzing the magnitude of the driving and dependence powers of each factor in the system.

The combined use of the above 3 methods could provide the following advantages: (1) these 3 methods focus on clarifying the interaction relationship among system factors in 3 dimensions: each factor in the system, the factor level, and the factors themselves. (2) The combined use of these 3 methods could reduce the number of matrix calculation and expert scoring steps. (3) The comprehensive influence matrix after threshold value screening could be employed as the adjacency matrix in the ISM method, which could help determine the interaction relationship among the factors more accurately.

Therefore, it is reasonable and feasible to use the DEMATEL-ISM-MICMAC model to study the disaster-causing mechanism of HDCFs of MESGEAs in coal mine goafs.

3.2. Calculation Steps of the Improved DEMATEL-ISM-MICMAC Model

The DEMATEL-ISM-MICMAC model still relies on expert scoring as the primary premise. The subjectivity of expert scoring may affect the subsequent calculation results, leading to deviation in the analysis of the interaction relationship among system factors. To overcome the subjectivity of expert scoring, a method for the calculation of the interaction strength between two DCFs was proposed from the perspective of the occurrence frequency of DCFs in accidents. This method adopts the idea of data association mining, through statistical analysis of the frequency of the pairwise co-occurrence of DCFs in 32 accident investigation reports, and then the interaction strength value among DCFs can be calculated, to ensure that the subsequent analysis of HDCFs is based on the nonlinear relationship among the DCFs. Furthermore, this method could enable the application of the DEMATEL-ISM-MICMAC model to study the disaster-causing mechanism of HDCFs of MESGEAs in coal mine goafs from a completely objective perspective. The computational framework of the improved DEMATEL-ISM-MICMAC model is shown in Figure 4.

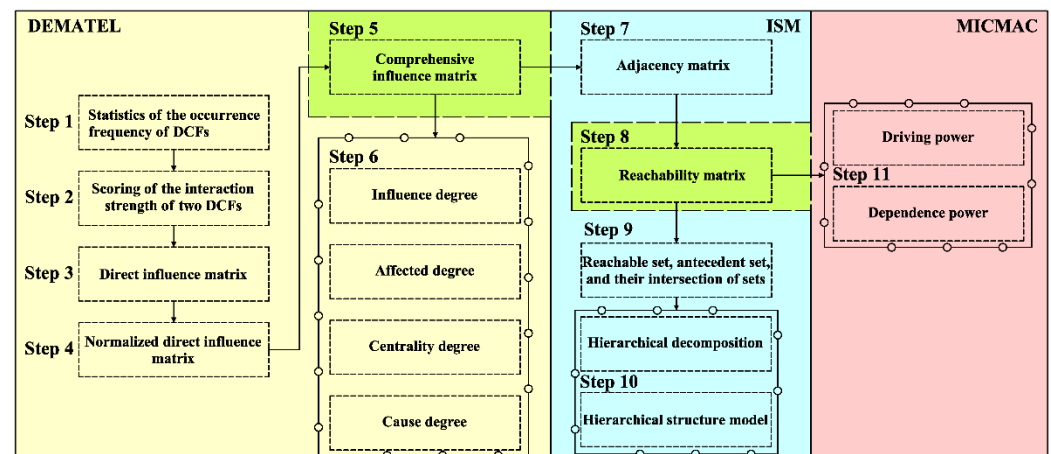


Figure 4. A model of the computational framework.

The specific calculation steps of the improved DEMATEL-ISM-MICMAC model are as follows:

Step 1: Statistics of the occurrence frequency of DCFs.

(1) Statistics of the frequency of the pairwise co-occurrence of DCFs in accidents were obtained, recorded as n_{ij} ; i and j denote the serial number of the DCFs, with $i = 1, 2, \dots, q$; $j = 1, 2, \dots, q$; and $i \neq j$; q is the number of DCFs.

(2) The frequency of DCFs appearing alone in accidents was determined and recorded as N_i .

Step 2: Calculation and scoring of the interaction strength between two DCFs.

The action strength of DCF i on DCF j can be understood as the ratio of the frequency of the co-occurrence of i and j in the accident to the occurrence frequency of j alone in the accident, as shown in Figure 5.

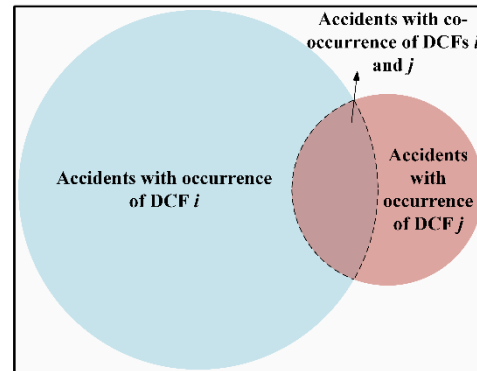


Figure 5. A principle diagram for the calculation of the interaction strength between two DCFs.

Therefore, the action strength E_{ij} of DCF i on DCF j can be calculated as follows:

$$E_{ij} = \frac{n_{ij}}{N_j} \quad (1)$$

The corresponding score of the action strength value can be determined as follows:

$$g_{ij} = \begin{cases} 0(\text{none}) & E_{ij} = 0 \\ 1(\text{weak}) & 0 < E_{ij} \leq 0.25 \\ 2(\text{moderate}) & 0.25 < E_{ij} \leq 0.50 \\ 3(\text{strong}) & 0.50 < E_{ij} \leq 0.75 \\ 4(\text{extremely strong}) & 0.75 < E_{ij} \leq 1.00 \end{cases} \quad (2)$$

Step 3: Establishment of the direct influence matrix G .

The direct influence matrix is $G = [g_{ij}]_{q \times q}$. Moreover, the diagonal elements of the direct influence matrix G are all 0 because the DCFs themselves do not participate in the comparison and assessment process.

Step 4: Establishment of the normalized direct influence matrix U .

The direct influence matrix G can be normalized using the maximum value between the row and column sums to obtain the normalized direct influence matrix U , which satisfies $[u_{ij}]_{q \times q} \in [0, 1]$ and can be calculated as follows:

$$M = \max(\max(\sum_{i=1}^q g_{ij}), \max(\sum_{j=1}^q g_{ij})) \quad (3)$$

$$U = [u_{ij}]_{q \times q} = \frac{G}{M} \quad (4)$$

Step 5: Establishment of the comprehensive influence matrix T .

$$T = [t_{ij}]_{q \times q} = \lim_{o \rightarrow \infty} (U + U^2 + U^3 + \dots + U^o) = U(I - U)^{-1} \quad (5)$$

where I is the identity matrix.

Step 6: The influence degree e_i , affected degree a_i , centrality degree c_i , and cause degree r_i of the DCFs can be calculated as follows:

$$e_i = \sum_{j=1}^q t_{ij} \quad (6)$$

$$a_i = \sum_{j=1}^q t_{ji} \quad (7)$$

$$c_i = e_i + a_i \quad (8)$$

$$r_i = e_i - a_i \quad (9)$$

Step 7: Establishment of the adjacency matrix Z .

The threshold λ can be introduced to eliminate relationships with a low action strength in the comprehensive influence matrix T and thus simplify the system structure. The threshold value λ can be obtained using the sum of the average value and standard deviation (each element of the comprehensive influence matrix T) based on the statistical distribution to replace the subjective experience assignments of the experts. The threshold value λ and adjacency matrix Z can be calculated as follows:

$$\lambda = \alpha + \beta \quad (10)$$

$$Z = [z_{ij}]_{q \times q} = \begin{cases} 1 & t_{ij} \geq \lambda \\ 0 & t_{ij} < \lambda \end{cases} \quad (11)$$

where α and β are the average value and standard deviation, respectively, of each element of the comprehensive influence matrix T .

Step 8: Establishment of the reachability matrix D .

The adjacency matrix Z can be added to the identity matrix I , and the resulting matrix is subjected to the exponentiation operation. When the result of the exponentiation operation satisfies the condition of Equation (12), matrix D is the required reachability matrix.

$$D = [d_{ij}]_{q \times q} = (Z + I)^{s+1} = (Z + I)^s \neq (Z + I)^{s-1} \quad (12)$$

Step 9: The reachable set Y_i , antecedent set B_i , and their intersection of sets W_i can be expressed as follows:

$$Y_i = \{d_j | d_j \in D, d_{ij} = 1\} \quad (13)$$

$$B_i = \{d_j | d_j \in D, d_{ji} = 1\} \quad (14)$$

$$W_i = Y_i \cap B_i \quad (15)$$

Step 10: Hierarchical decomposition of DCFs.

All the DCFs with $Y_i = W_i$ are identified, and the DCFs obtained during the first search are designated as Level 1 DCFs of the hierarchical structure model. Subsequently, the Level 1 DCFs contained in the reachable set Y_i are removed, and all the DCFs with $Y_i = W_i$ are again identified. The DCFs identified during the second search are denoted as Level 2 DCFs of the hierarchical structure model. The above process is repeated until all the DCFs are removed.

Step 11: The driving power QD_i and dependence power YL_i of the DCFs can be obtained as follows:

$$QD_i = \sum_{j=1}^q d_{ij} \quad (16)$$

$$YL_i = \sum_{j=1}^q d_{ji} \quad (17)$$

4. Disaster-Causing Mechanism of HDCFs

By calculating the interaction strength score between two DCFs of MESGEAs in goafs, the direct influence matrix G could be obtained, as shown in Figure 6. The direct influence matrix G was substituted into Equations (3)–(5) for calculation, and the comprehensive influence matrix T could be obtained, as shown in Figure 7. Additionally, the comprehensive influence matrix T was determined with Equations (10)–(12), and the reachability matrix D

was obtained, as shown in Figure 8. In addition, the calculation results of Steps 1, 2, 4, 7 and 10 are in the File S1.

	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18	X19	X20	X21	X22
X1	0	3	3	2	2	1	2	0	3	0	4	1	0	2	2	4	2	3	3	3	3	3
X2	2	0	3	1	2	1	2	3	2	0	2	2	0	2	3	0	2	2	2	2	2	2
X3	1	2	0	1	1	0	1	2	1	2	0	1	0	1	2	2	1	1	2	1	2	1
X4	1	2	2	0	2	2	2	3	2	4	0	3	3	2	2	2	2	2	2	2	2	2
X5	1	1	1	1	0	1	1	3	1	0	2	1	0	1	1	2	1	1	1	1	1	1
X6	1	1	0	1	1	0	1	2	1	0	0	1	0	0	0	0	1	1	1	1	1	1
X7	1	2	2	2	1	2	0	2	1	2	2	0	0	1	1	0	2	2	1	1	2	1
X8	0	1	1	1	2	1	1	0	1	0	0	1	0	0	0	0	1	1	1	1	1	1
X9	2	3	1	2	1	2	1	3	0	0	2	2	0	2	2	0	2	2	2	2	2	2
X10	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1
X11	1	1	0	0	1	0	1	0	1	0	0	0	0	0	0	0	1	1	0	1	1	1
X12	1	1	1	2	1	1	0	2	1	0	0	0	4	1	1	0	1	0	1	1	1	1
X13	0	0	0	1	0	0	0	0	0	0	0	2	0	0	0	0	1	0	0	1	1	0
X14	1	1	1	1	1	0	1	0	1	0	0	1	0	0	4	2	1	1	1	1	1	1
X15	1	2	2	1	1	0	1	0	1	0	0	1	0	3	0	2	1	1	1	1	1	1
X16	1	0	1	1	1	0	0	0	0	0	0	0	0	1	1	0	1	0	1	1	1	1
X17	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	0	4	3	4	4	4
X18	2	3	2	2	2	1	3	3	3	4	4	0	0	1	1	0	2	0	2	2	2	3
X19	3	4	3	2	2	3	2	3	3	0	0	2	0	1	2	3	2	2	0	2	2	3
X20	4	4	3	4	2	3	3	3	4	4	2	4	4	4	4	4	4	4	3	0	3	4
X21	4	4	4	3	3	2	3	4	3	2	4	3	3	3	3	3	3	3	3	0	3	0
X22	4	4	3	3	4	3	3	3	4	4	4	2	0	3	3	4	3	4	4	3	3	0

Figure 6. The direct influence matrix.

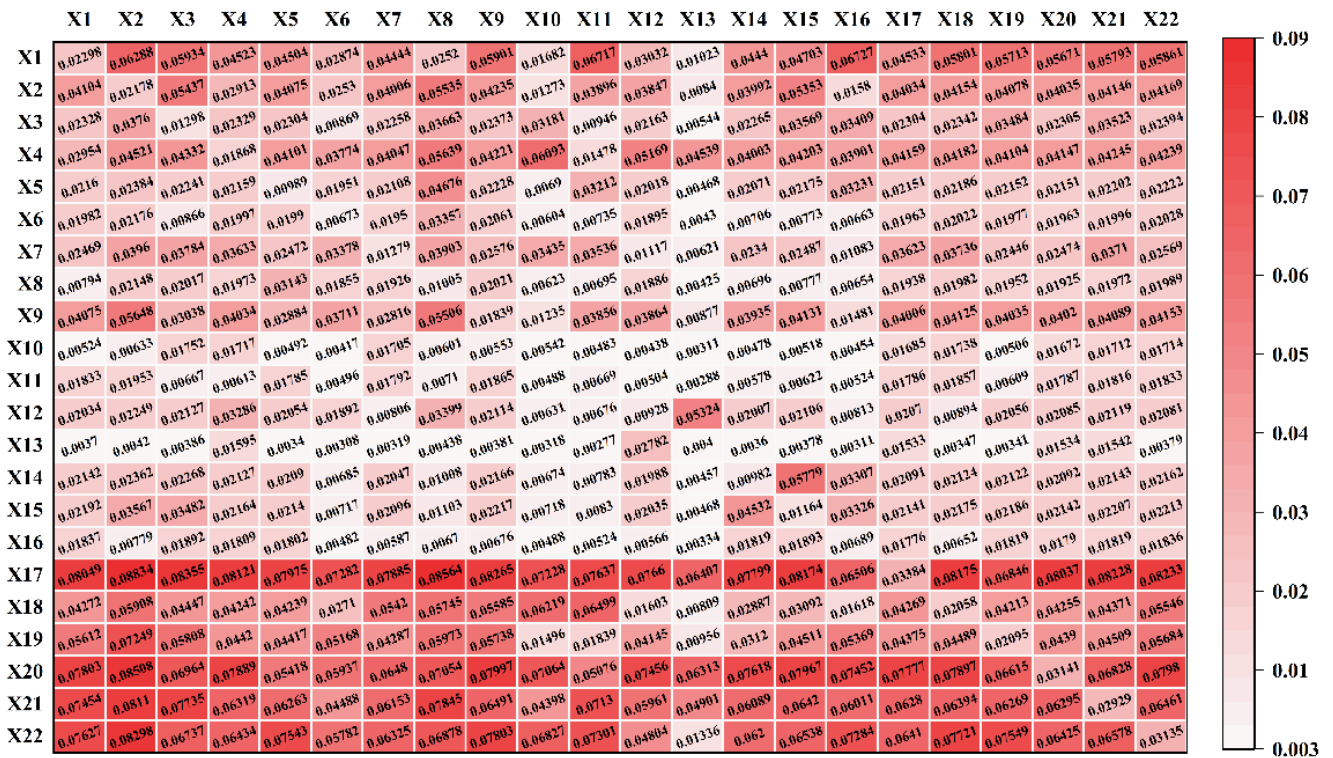


Figure 7. The comprehensive influence matrix.

in the management aspect by influencing the DCFs in the human factors, equipment and environment 3 aspects, resulting in accidents.

The distribution of the centrality and cause degrees of the HDCFs exhibited an obvious polarization state, as shown by the dotted line circle in Figure 9. The centrality and cause degrees of HDCFs X17 and X20 in the management aspect ranked 1st and 2nd, respectively, among all DCFs, indicating that HDCFs X17 and X20 comprehensively affected the occurrence of accidents from 2 aspects, namely, themselves and the other DCFs, and these HDCFs were the key DCFs of accidents. The prevention and control of MESGEAs in coal mine goafs should focus on HDCFs X17 and X20. The centrality and cause degrees of the HDCFs in the human factors, equipment and environment aspects were all low, indicating that the HDCFs in these 3 aspects weakly impacted the occurrence of accidents and were easily affected by other DCFs, which altered the strength of the impact of these HDCFs on accident occurrence. The centrality and cause degrees of the nonhidden disaster-causing factors basically varied between those of the HDCFs in the management aspect and the HDCFs in the human factors, equipment and environment aspects.

4.2. Analysis of the ISM Calculation Results

By substituting the comprehensive influence matrix T into Equations (10)–(15) for calculation purposes, hierarchical decomposition of the DCFs could be realized, and a hierarchical structure model of the DCFs of MESGEAs in coal mine goafs could be established, as shown in Figure 10. The red font and red dotted line circles in Figure 10 indicate the HDCFs.

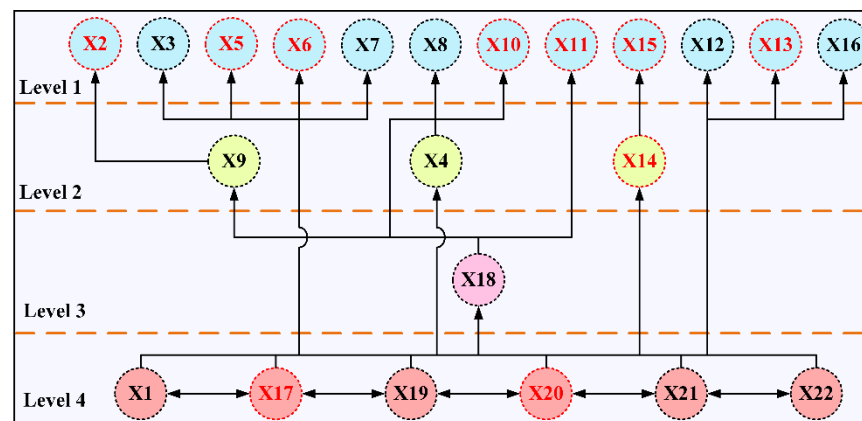


Figure 10. The hierarchical structure model of the DCFs.

According to Figure 10, the DCFs of MESGEAs in coal mine goafs could be divided into 4 levels (Levels 1–4). The DCFs in the management aspect were basically located at Level 4, indicating deep-level DCFs. The DCFs in the human factors, equipment and environment aspects were basically located at Levels 1 and 2, indicating surface and shallow DCFs, respectively. Level 4 DCFs X1, X17, X19, X20, X21, and X22 interacted with each other and simultaneously influenced the DCFs at each level (Levels 1–3), thus causing accidents.

The HDCFs also exhibited a polarization state in the hierarchical structure model. HDCFs X17 and X20 in the management aspect were located at Level 4 and constituted deep-level DCFs. X17 and X20 were difficult to directly identify (very easy to ignore), and these Level 4 DCFs interacted with each other; therefore, it was extremely easy to cause DCF intervention and governance failure of MESGEAs in coal mine goafs, resulting in accidents. Therefore, we should focus on implementing effective intervention measures targeting HDCFs X17 and X20 to prevent the failure of countermeasures and measures for the prevention and control of accidents at the early stage due to the neglect of X17 and X20. In addition to HDCF X14, the HDCFs in the human factors, equipment and environment aspects were all located at Level 1 and comprised surface DCFs, and their appearance could directly promote accidents. This also corresponds to the time-varying and sudden

characteristics of the HDCFs in the equipment and environment aspects and the random, uncontrollable, and other characteristics of the HDCFs in the human factors aspect.

4.3. Analysis of the MICMAC Calculation Results

By substituting the reachability matrix D into Equations (16) and (17) in the calculation process, results can be obtained for the driving and dependence powers of the DCFs, as shown in Figure 11. As shown in Figure 11, the red font and red balls denote the HDCFs, and the light red balls indicate the HDCFs among the DCFs. The sphere radius is proportional to the number of DCFs indicated.

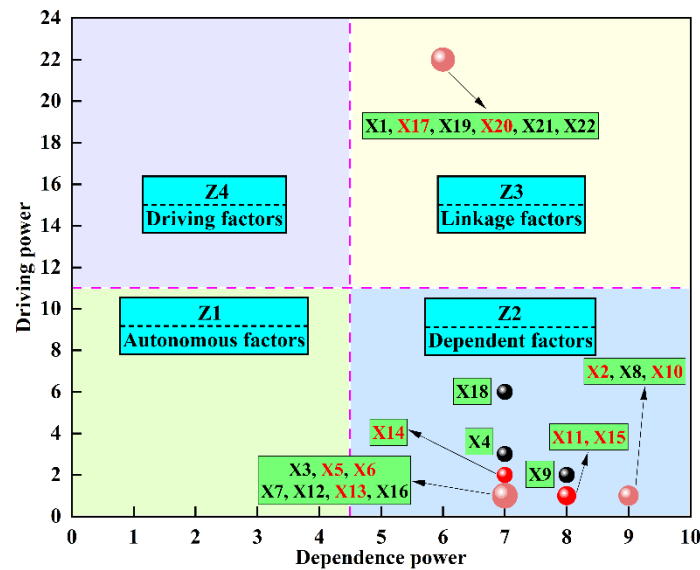


Figure 11. The calculation results for the driving and dependence powers of the DCFs.

The driving power indicates the strength of the impact of a certain factor on the other factors in the system. Factors with a high driving power should be prevented and controlled to help prevent and control the other factors. The dependence power indicates the strength of the impact of a certain factor influenced by the other factors in the system. The prevention and control of factors with a high dependence power should rely on the prevention and control of other factors. According to the magnitude of the driving and dependence powers of each DCF, the DCFs were divided into 4 categories, corresponding to the 4 quadrants Z1–Z4 in Figure 11:

(1) Autonomous factors (Z1 quadrant): the driving and dependence powers of the DCFs in this quadrant were very low, and there basically existed no relationship with the other DCFs (no driving effect; these DCFs also remained unaffected). Autonomous factors were excluded from the DCFs of MESGEAs in goafs.

(2) Dependent factors (Z2 quadrant): the DCFs in this quadrant exhibited a high dependence power and low driving power and were easily affected by the other DCFs but generated a weak driving action on the other DCFs. The DCFs in the human factors, equipment, and environment aspects of MESGEAs in goafs basically were dependent factors.

(3) Linkage factors (Z3 quadrant): the DCFs in this quadrant exhibited high dependence and driving powers, and they could easily affect the DCFs in the other quadrants and within the same quadrant, which could create extremely unstable conditions. The DCFs in the management aspect of MESGEAs in goafs basically were linkage factors. Consequently, accidents could occur due to internal interaction among the DCFs in the management aspect and their facilitation of the combined effect of the DCFs in the human factors, equipment and environment aspects. This was also mutually verified by the DEMATEL and ISM calculation results.

(4) Driving factors (Z4 quadrant): the DCFs in this quadrant exhibited a high driving power and low dependence power. These DCFs generated a notable driving effect on the

other DCFs but were weakly affected by the other DCFs. Driving factors were excluded from the DCFs of MESGEAs in goafs.

The HDCFs also exhibited a polarization state in terms of the driving and dependence powers. Compared to the other DCFs, the HDCFs in the human factors, equipment and environment aspects exhibited a very low driving power and high dependence power and were extremely easily influenced by the other DCFs to promote accidents. HDCFs X17 and X20 in the management aspect attained the highest driving power and lowest dependence power, and they could easily affect the other DCFs and each other. Therefore, in disaster-causing terms of HDCFs, we should focus on strengthening the intervention and prevention of HDCFs X17 and X20 in the management aspect. Nonhidden disaster-causing factors were randomly distributed in the Z2 and Z3 quadrants, without any obvious law.

4.4. Discussion

4.4.1. Comprehensive Analysis

According to the calculation results obtained with the improved DEMATEL-ISM-MICMAC model, the DCFs in the management aspect were deep-level accident causes, while the DCFs in the human factors, equipment and environment aspects were shallow and surface accident causes. MESGEAs in coal mine goafs were caused by DCFs in the management aspect by affecting the DCFs in the 3 aspects of human factors, equipment and environment, as well as under the combined effect of DCFs internal interaction contained in itself.

Figure 10 shows the disaster-causing mechanism of MESGEAs in coal mine goafs, and the disaster-causing mechanism of the HDCFs of MESGEAs in coal mine goafs could be revealed via deep-level reanalysis from the perspective of these HDCFs based on Figure 10. Through review and analysis of the contents of Sections 4.1–4.3, it could be considered that there existed 2 disaster-causing mechanisms of HDCFs of MESGEAs in coal mine goafs (as shown in Figure 12).

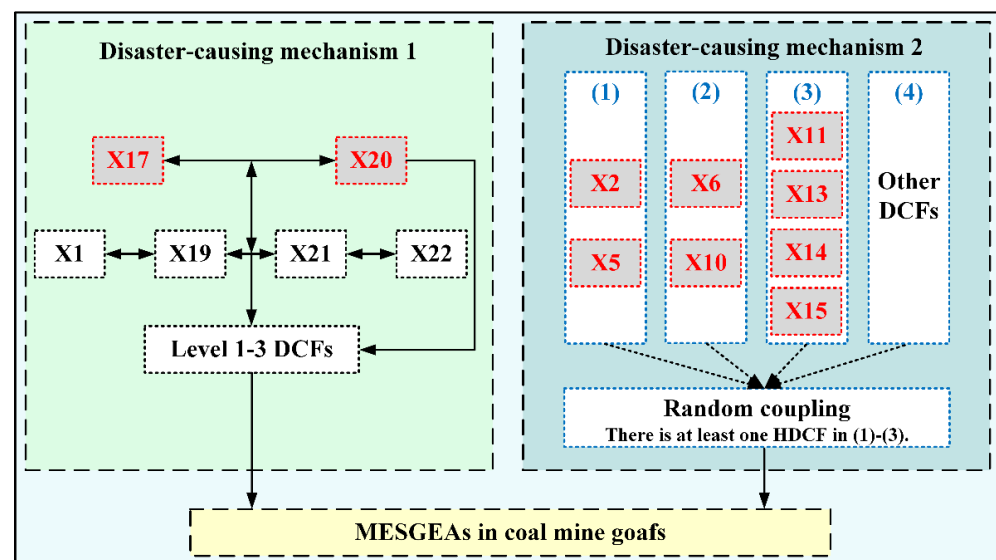


Figure 12. The disaster-causing mechanism of the HDCFs.

Disaster-causing mechanism 1: The HDCFs in the management aspect could indirectly cause disasters. The HDCFs in the management aspect of MESGEAs in coal mine goafs included inadequate enforcement of safety regulations (X17) and inadequate safety supervision (X20), which were the key DCFs of accident occurrence. Compared to the other DCFs in the management aspect, inadequate enforcement of safety regulations and inadequate safety supervision exhibited notable hidden characteristics. If enterprises ignored these 2 HDCFs and only focused on the prevention and control of other DCFs in daily hazard

investigation and governance activities, accidents could more likely occur. X17 and X20 mainly caused accidents in 2 ways, i.e., by influencing the other DCFs at Level 4, as shown in Figure 10, to indirectly impact the DCFs at Levels 1–3 and by directly influencing the DCFs at Levels 1–3.

Disaster-causing mechanism 2: The HDCFs in the human factors, equipment and environment aspects randomly coupled to cause disasters. The HDCFs in the equipment and environment aspects of MESGEAs in coal mine goafs exhibited both time-varying and sudden characteristics, while the HDCFs in the human factors aspect exhibited random, uncontrolled and other characteristics, in addition to notable hidden characteristic. Therefore, the HDCFs in the human factors, equipment and environment aspects were easily and randomly coupled (coupling among the HDCFs or coupling among the HDCFs and nonhidden disaster-causing factors) to cause accidents.

4.4.2. Suggested Measures for Accident Prevention and Control

According to the above analysis of the disaster-causing mechanism of the HDCFs of MESGEAs in coal mine goafs, it could be concluded that the formulation of targeted suggestions and measures from an HDCF perspective could achieve twice the result with half the effort in terms of accident prevention and control. The main suggested measures are as follows:

(1) Inadequate enforcement of safety regulations: Coal mine enterprises should establish a full-time supervision team (members could include enterprise leaders, industry experts and experienced workers), and according to the current laws, regulations and rules regularly, their full implementation on site should be assessed, while timely notification and rectification operations should be performed.

(2) Inadequate safety supervision: At the government level, supervision and inspection efforts should be strengthened, such as hiring industry experts to conduct comprehensive assessments and inspections of coal mining enterprises, improving the comprehensive quality of inspectors stationed in coal mines through education and training programs, and strictly implementing an accountability system. At the coal mining enterprise level, company groups should strengthen their supervision and inspection efforts of subordinate coal mines, such as archiving daily inspection data, real-time online monitoring of various production data of subordinate coal mines, timely discovery and resolution of problems, and assigning dedicated personnel to supervise problem rectification throughout the entire process.

(3) Poor safety awareness, weak sense of professional responsibility of employees: Safety education and training efforts for employees should be improved in various aspects, such as accident case study, regular education and training involving various vocational skills, condolence activities, team building and other activities, employee safety awareness improvement and creation of a working atmosphere of mutual trust and responsibility.

(4) Cable breakage and short circuit: Cables should be reasonable arranged to prevent external force-induced impact damage. Special personnel should regularly patrol cable lines to ensure that cables and related equipment remain protected.

(5) Metal material friction or impact: Changes in the stresses acting on coal mine roadways should be monitored in real time. When abnormal stresses occur, relevant measures should be implemented in a timely manner. During operation, equipment should be operated in strict accordance with operating procedures. Abnormal conditions should be identified in time to stop operations, and these conditions must be properly rectified before resuming operations.

(6) Blocked ventilation route: Through a real-time monitoring system of the mine air volume and field surveys of wind surveyors, blocked areas of mine ventilation routes should be studied, assessed and resolved in a timely manner to ensure normal mine ventilation and prevent gas accumulation.

(7) Rock friction or impact: The mineral composition of the overlying strata of the working face should be determined in advance to predict whether the collapse of these

overlying strata could generate sparks due to friction or impact. The periodic pressure step distance should be reduced, and caving the roof in time to slow down the strength of rock friction or impact.

(8) Coal spontaneous combustion: The combination of 2 identification methods—gas beam tube detection in the goaf and wireless ad-hoc network/optical fiber temperature measurement—should be employed to predict the coal spontaneous combustion area in advance, which can greatly facilitate the active prevention and control of coal spontaneous combustion.

(9) Poor sealing conditions: Air pressure monitoring points should be established within the goaf, attention should be given to fluctuations in the pressure difference inside and outside the goaf in real time, and measures such as timely blocking and adding a closed wall should be implemented to mitigate abnormal conditions.

4.4.3. Limitations of the Study

(1) From the perspective of the accident causation model of system theory, and based on the 4 aspects of human factors, equipment, environment, and management, this paper classifies and analyzes the DCFs of MESGEAs in coal mine goafs. Most of the DCFs obtained by identifying accident DCFs from different perspectives are consistent or similar, but they may all have the problem of incomplete identification of DCFs [39,40]. Therefore, in the future research work, we will identify and analyze again in depth the HDCFs of MESGEAs in coal mine goafs from multiple perspectives (such as organizational level, individual level, etc.) [41–43].

(2) Human factors, equipment factors, environment factors and management factors are the first-level DCFs. As shown in Table 2, this paper only analyzes the second-level DCFs (X1–X22) of human factors, equipment, environment and management aspects. We still have not conducted detailed research on the third-level DCFs included in the second-level DCFs. For example, research on the impact of decision-making bias factor on second-level HDCFs in the human factors and management aspects [44–47].

5. Conclusions

In this study, adopting MESGEAs in coal mine goafs in China from 2000 to 2021 as the data source, from a new perspective of HDCFs, an improved DEMATEL-ISM-MICMAC model was adopted to study the disaster-causing mechanism of HDCFs of MESGEAs in coal mine goafs. The main conclusions are as follows:

(1) The HDCFs in coal mines were redefined. By analyzing the contents covered by the existing definition of HDCFs in coal mines, it could be considered that the content of its definition was more in line with hidden disaster-causing geological factors in coal mines. The connotation of HDCFs in coal mines was analyzed in 4 dimensions, namely, subordinate relationship, covered content, disaster-causing area and disaster-causing time, and the HDCFs in coal mines were subsequently redefined. Additionally, it was proposed that the characteristics of HDCFs in coal mines could be employed as identification criteria of HDCFs in coal mines.

(2) An improved DEMATEL-ISM-MICMAC model was proposed and applied in the study of MESGEAs in coal mine goafs. This model could overcome the subjectivity of expert scoring. From a completely objective perspective, it could be concluded that MESGEAs in coal mine goafs were caused by DCFs in the management aspect by affecting the DCFs in the 3 aspects of human factors, equipment and environment, as well as under the combined effect of DCFs internal interaction contained in itself. The HDCFs in the management aspect and the HDCFs in the human factors, equipment and environment aspects of MESGEAs in coal mine goaf obviously exhibited a polarization state in terms of the centrality and cause degrees, hierarchical structure, and driving and dependence powers.

(3) There occurred 2 types of disaster-causing mechanisms of HDCFs of MESGEAs in coal mine goafs. Disaster-causing mechanism 1 was the indirect disaster-causing by HDCFs in the management aspect, and disaster-causing mechanism 2 was the random coupling

disaster-causing by HDCFs in the human factors, equipment and environment aspects. Moreover, from the perspective of HDCFs, 9 measures for the prevention and control of MESGEAs in coal mine goafs were proposed.

The results of this study could provide a certain guiding significance for early warning, active prevention and control, emergency response and other aspects of gas explosion accidents in coal mine goafs. In the future, based on the results of this research, the Bayesian network, system dynamics, N-K, catastrophe, and other models will be used to investigate the disaster-causing evolution process and formulate active prevention and control countermeasures for HDCFs of MESGEAs in coal mine goafs.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su141912018/s1>, File S1: Partial calculation results.

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