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Research Article

An Approach for Understanding and Promoting Coal Mine Safety by Exploring Coal Mine Risk Network

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Capturing the interrelations among risks is essential to thoroughly understand and promote coal mining safety. From this standpoint, 105 risks and 135 interrelations among risks had been identified from 126 typical accidents, which were also the foundation of constructing coal mine risk network (CMRN). Based on the complex network theory and *Pajek*, six parameters (i.e., network diameter, network density, average path length, degree, betweenness, and clustering coefficient) were employed to reveal the topological properties of CMRN. As indicated by the results, CMRN possesses scale-free network property because its cumulative degree distribution obeys power-law distribution. This means that CMRN is robust to random hazard and vulnerable to deliberate attack. CMRN is also a small-world network due to its relatively small average path length as well as high clustering coefficient, implying that accident propagation in CMRN is faster than regular network. Furthermore, the effect of risk control is explored. According to the result, it shows that roof collapse, fire, and gas concentration exceeding limit refer to three most valuable targets for risk control among all the risks. This study will help offer recommendations and proposals for making beforehand strategies that can restrain original risks and reduce accidents.

1. Introduction

China is the largest producer and consumer of coal in the world, from which it has derived about 65% of its energy over the past sixty years [1]. In China, more than 90% of fossil energy reserves are coal. That is to say, the energy consumption structure of energy, which relies mainly on coal, cannot be changed within quite a long time. Also, this standpoint can be validated by *China's National Energy Development Strategy Plan* (2014–2020) and *13th Five-Year Plan* (2016–2020). In 2015, China's coal output was estimated to be 3.747 billion tons, accounting for 47% of the total in the world (The State Administration of Coal Mine Safety, 2015). According to British Petroleum (BP) Statistical Review of World Energy 2016, the countries whose coal production is larger than 40 million tons can be shown in Figure 1.

Coal mining refers to one of the most hazardous industries worldwide [2–4]. Moreover, coal mine enterprises have to encounter various hazards regarding special geological condition [3]. In the process of coal mining, numerous hazards have the potential to trigger accidents frequently, such as rock stresses, harmful gases, humidity, high temperatures, coal and silica dust, and specialized equipment [5]. Worse still, the intensity and frequency of these hazards could result in extremely serious consequences for human health and life [6]. Coal mine accidents will considerably bring about injuries, casualties, and loss of major assets of enterprise. In China, coal mine accident suffers heavy losses every year. According to statistics, approximately 70% of the coal mine casualties worldwide are estimated to occur in China [7]. 6995 coal workers were killed in various accidents in 2002, which is the maximum record in a single year.

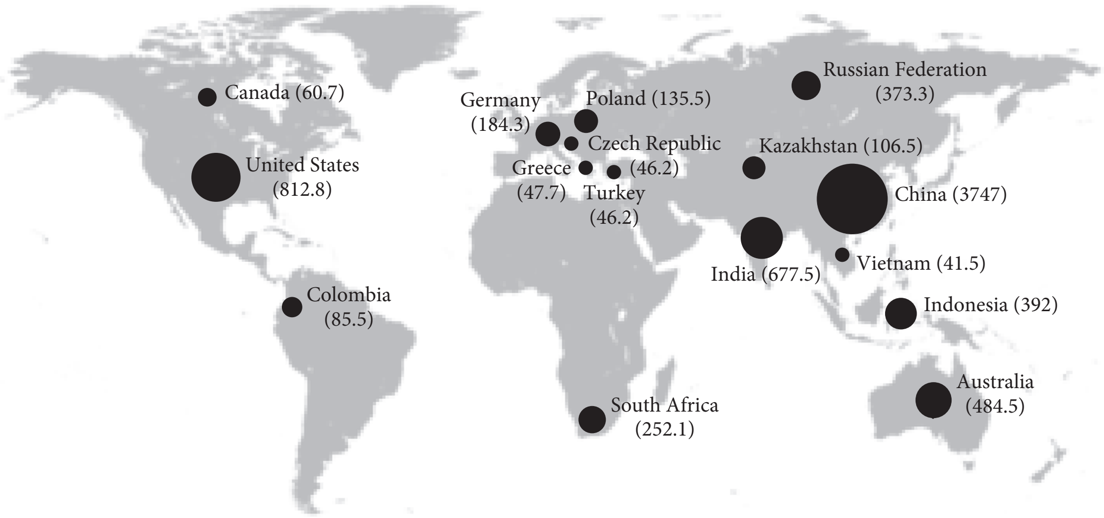

Figure 1: The coal production distributed by country in 2015 (one hundred million tons).

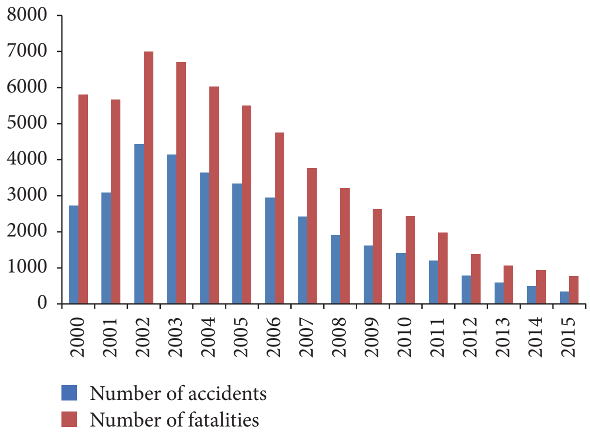

Figure 2: China's number of accidents and fatalities in coal mine from 2000 to 2015.

Then, it decreased year by year, as shown in Figure 2 (data source: State Administration of Coal Mine Safety). Although the practical situation seemingly gets better and better, still numerous accidents occurred every year in China. All in all, safety management in coal production is still quite critical and serious due to harsh production conditions as well as complicated production processes.

A more valuable process to improve safety performance is to learn from the failure experiences of previous accidents [8]. Accident analysis is a powerful approach for preventing or eliminating similar hazards, risks, and accidents [9, 10]. Indeed, the existing studies often focus on one type of coal mining accident, or statistical analysis of accident in an area or country, while multiple interrelations among verified accidents are usually neglected. In industrial safety research, it is generally acknowledged that the accident is not caused by a single error or fault, but by the confluence of a sequence of hazard, risk, and accident [11]. Moreover, an occurred accident will possibly incur a sequence of the following accidents [12]. Accident chain exists in most of the coal mine accidents, which indicates the actual existence of risk network. These interactions among risks form a coal mine risk network (CMRN) which would bring about a big issue for the coal mine safety. Therefore, capturing the complexity of CMRN is both essential and beneficial to improve safety performance in coal mining.

The structure of this paper can be listed as follows. Section 2 presents a literature review of coal mine safety, and Section 3 elaborates the methodology, including an analytical framework, data collection and analysis, and network modeling. In Section 4, *Pajek* is employed to help explore CMRN (including network basic quantities metric and network property) and measure the effect of risk control. In Section 5, the potential contributions, limitations, and risk control methods are discussed. Lastly, the conclusions are drawn in Section 6.

2. Literature Review

Coal mine provides essential energy for supporting high-speed development of Chinese economy and society. Multiple

Table 1: Summary of previous study in coal mine.

Theme	References	Objective
Supervision and regulation	[13–18]	Exploring complexity and ineffectiveness of regulation; analyzing rent-seeking mechanism, behavior, policy, and tax; identifying tendency of coal mine accidents and characteristics of human factors.
Risk management	[19–24]	Predicting the expected risk levels by using decomposition technique in time series analysis; analyzing and optimizing the risk management system; using public communication system to monitor unsafe behavior in real time; reducing the effects of coal mining on social and ecological exploitation; constructing potential hazards database in an underground mine; evaluating the reliability of human safety barrier in coal mine emergency evacuation; identifying the risk factors and evaluating the safety control capability.
Risk evaluation	[25–31]	Assessing the roof fall risk during retreat mining in room and pillar coal mines; evaluating explosion risk in underground coal mines; developing a comprehensive model for coal mine safety; using fuzzy set theory to assess the risk of mining equipment failure; assessing pot-hole subsidence risk in coal mine; using risk performance indicators to analyze coal mine accidents.
Monitoring and controlling technologies	[32–36]	Employing internet of things (IOT) and cloud computing (CC) to monitor mine safety based on prealarm system; using wireless sensor network (WSN) to monitor the temperature, humidity, gas, and status of smoke in underground mine; establishing a Web of Things-based remote monitoring system for coal mine safety; employing cable monitoring system (CMS) and the WSN to build an integrated environment monitoring system for underground coal mine; using iris identification and radio frequency identification (RFID) technique to improve safety management system.

studies have been carried out by worldwide researchers to improve the safety performance. The research topics mainly focus on supervision and regulation, risk management, evaluation, monitoring, and controlling technologies, which is shown in Table 1.

Supervision and regulation refer to two crucial influence factors in the coal mining. Before 2000, ineffective implementation of laws and regulations increases the difficulty for Chinese government to inspect actual situation of coal mine safety [13]. To promote coal mine safety, a variety of effective countermeasures, such as enhancing safety legislation and establishing independent coal mine safety monitoring system, were executed. These improvements in regulatory regime make a great contribution [14]. However, the interrelations between coal mine enterprises and supervision departments are complex and subtle. Rent-seeking exists widely in China's coal mine supervision, which is a huge obstacle to the further development of coal mining industry. The existing researches on rent-seeking mainly focus on rent-seeking behavior, policy, and tax [15–17]. In the rent-seeking scenario, Chen et al. [18] indicated that each level of the department had an intensity threshold above which coal mine accidents occurred.

The effective risk management is the fundamental guarantee of coal mine safety production based on various theories and methods. Sari et al. [19] developed a stochastic model to predict the number of accidents according to the randomness in the occurrence of accidents. Qing-gui et al. [20] constructed a system to supervise unsafe behavior, release early warning information, and improve controlling measures in coal mine. Based on case studies, Kowalska [21] identified and assessed the risk sources. As suggested by the results, it is necessary to undertake anticipatory activities aiming at reducing environmental and social risks during the colliery liquidation. Badri et al. [22] studied risk management in mining projects based on analytic hierarchy process method, and the results show the importance of considering occupational health and safety (OHS) in the process of coal mining. Wang et al. [23] put forward an analytical framework to analyze human error risk in the emergency evacuation from three perspectives, including organization level, group level, and individual level. Besides, Liu and Li [24] constructed a back propagation (BP) neural network to explore influence factors in coal mine safety.

The evaluation of hazards and risks has attracted much attention of multiple practitioners and researchers due to their serious consequences. These hazards and risks could be divided into three types, including "natural, technical, and human." Ghasemi et al. [25] developed a risk evaluation model and various possible risks are evaluated in Iran Tabas central mine. Pejic et al. [26] proposed a risk assessment tool to determine the risk of explosion of any work processes or activities in the underground coal mine. Also, the methodology can decide whether the proposal investments are well-justified or not for improving safety. Bahri Najafi et al. [27] proposed an artificial neural network model to predict the out-of-seam dilution. Based on uncertain random variables, Chen et al. [28] developed a practical evaluation model for coal mine safety based on uncertain random variables. According to fuzzy set theory, Petrović et al. [29] presented a risk evaluation model to evaluate the failures of electromechanical equipment. Lokhande et al. [30] came up with a risk evaluation approach based on the identified critical parameters, including depth to height of extraction

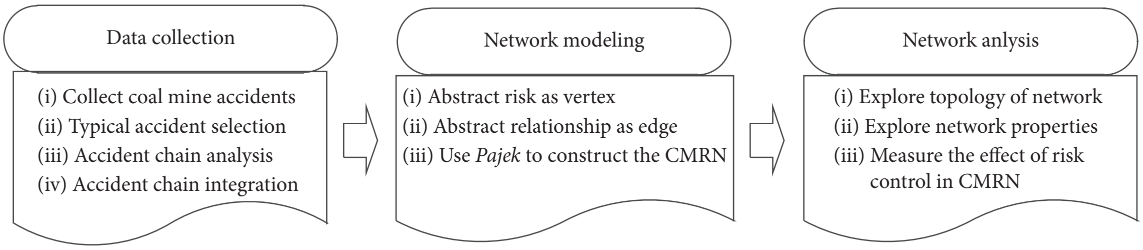

Figure 3: Analytical framework.

Table 2: Two examples of the stored accidents.

Number	Time	City	Type	Description	Death	Loss
28	2003.10.21	Wuhai	Coal dust explosion	Three blasters violated job regulations and implemented blasting without any safety precautions. Unfortunately, the blasting gave rise to naked light, and then the gas was lighted and began burning. As a result, the coal dust explosion happened.	6	120 thousand dollars
92	2004.2.23	Jixi	Gas explosion	Due to inadequate ventilation, the gas concentration exceeded the threshold. Meanwhile, a miner optionally disassembled his lamp, which triggered electric spark, and then the spark caused gas explosion.	37	370 thousand dollars

ratio, rock to soil ratio, brittleness index of rock, and rock density. Spada and Burgherr [31] analyzed the accident data in energy-related severe accidents database and suggested a nonsignificant decreasing tendency for Turkey as well as a significant one for USA.

Some new technologies, which are effective and powerful tools for improving safety performance, have been applied in coal mine. Sun et al. [32] accomplished a monitoring and prealarm system based on cloud computing (CC) and Internet of things (IOT). What is more, Dange and Patil [33] designed a wireless sensor network (WSN) based on MSP430 controller for monitoring smoke, gas, temperature, and humidity in coal mine. Based on wireless sensor network and controller area network (CAN), Bo et al. [34] proposed a remote monitoring system, which was tested in different remote monitoring scenarios. Zhang et al. [35] proposed an integrated environment monitoring system that takes full advantage of cable monitoring system (CMS) in combination with wireless sensor network (WSN). Xu et al. [36] put forward an improved safety management system based on several modern identification and communication techniques, including iris identification, radio frequency identification (RFID), computer network, and database technique.

3. Methodology

3.1. Analytical Framework. An analytical framework is proposed to conduct the in-depth analysis of coal mine accident, as presented in Figure 3. It is a step-by-step procedure consisting of three main modules. At first, the coal mine accidents are collected from literature and media, such as the website of State Administration of Coal Mine Safety. Then, typical accidents are selected as the data to analyze accident chains. After that, the accident chains will be integrated as a global network. In the second stage, the risk is abstracted as vertex, and meanwhile, the interrelation is abstracted as edge. Also, the software *Pajek* is employed to establish the coal mine risk network (CMRN). In the third stage, the topology of CMRN is analyzed and network properties are identified according to the network theory. Then, the effect of risk control in CMRN is calculated. According to the research result, the discussions and suggestions are provided to promote safety management in coal mine production.

3.2. Data Collection and Analysis. The data of historical coal mining accidents is used for risk analysis. There are several ways to collect accident cases, such as government, enterprise, literature, and media. In this study, the accidents are collected from literature and media. A coal mine accident database (CMAD), which records the detailed information of accident (including time, position, type, process, death, and losses), is established based on Microsoft Access 2010. Although hundreds of accidents have occurred in China over the past few years, the information of many accidents, especially the process of accident, is unclear. In the end, 176 accidents with exhaustive information are collected. Among these detailed accidents, some accident chains are unobvious, while some happen suddenly and unexpectedly without accident chain. These accidents are not considered in this research. Besides, since some accidents are exactly similar to the rest of the typical accidents, thus there is no need to analyze the repeating accidents. In the end, 126 typical accidents, including all types of coal mining accidents, are recorded in CMAD, and they are selected to conduct accident chain analysis for establishing the risk network model. Two examples of stored accidents can be illustrated in Table 2.

Although these accidents are selective, almost all kinds of accidents have been included. Also, there are no biases in the

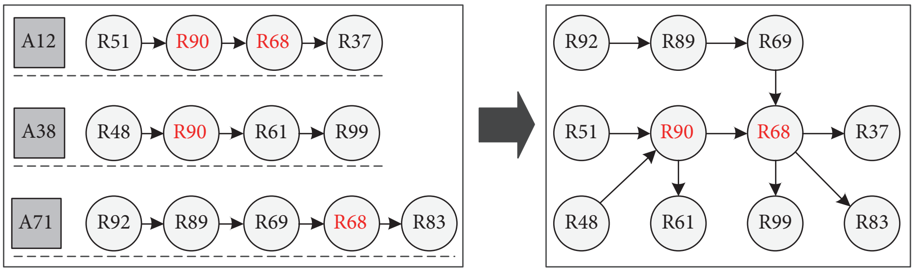

Figure 4: The formative process of CMRN.

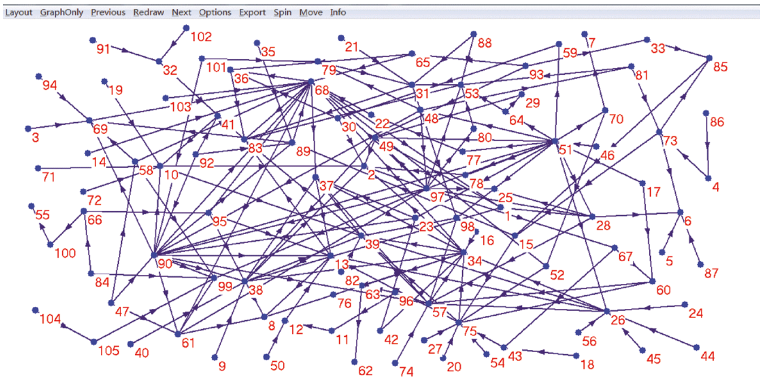

Figure 5: The coal mine risk network model in *Pajek*.

selection process. From the perspective of person, machine, environment, management, and technology, the accident chains in these accidents are identified and expatiated in Table 3. Most of the accidents have one accident chain, while some have two, such as accidents 41 and 75. As a result, a total of 135 accident chains are obtained from 126 cases.

3.3. Network Modeling. Multiple risks simultaneously appear in different accidents, indicating that the risk is correlated with others. It is essential to identify the risks and interrelations among them so as to establish CMRN. Through statistics, a total of 105 risks and 194 interrelations are obtained from 135 accident chains. Moreover, the vertex number and its type are expatiated in Table 4. After this study abstracts risk as vertex and interrelation as edge, different risks can be connected by these common vertexes into a global network. For a better explanation, accidents 12, 38, and 71 are taken as an example to illustrate the process of network modeling, as depicted in Figure 4. From the risks identification in accidents 12, 38, and 71, it can be seen that there are two same vertexes shown in red color, including R90 and R68. Through this method, the network can be established based on these common risks. Furthermore, software *Pajek* is employed to establish coal mine risk network (CMRN), as shown in Figure 5.

4. Results

4.1. Network Basic Quantities Metric. With the continuous development of complex network theory, the statistical indexes of network structure have obtained a lot of achievements, which are also the basis of statistical description of various topological characteristics. Compared with visual section, the calculation is much more precise and concise in exploring network [37]. This study uses several typical indexes to explore the properties of CMRN, including network diameter, network density, average path length, degree, betweenness, and clustering coefficient. These topological indexes are calculated by *Pajek*.

4.1.1. Network Diameter. The network diameter is defined as the maximum path length in the network, which can reflect the size of a network. The network diameter in CMRN is 7, which is from poor maintenance (vertex 64) to water leaking (vertex 99). This path is as follows: poor maintenance (vertex 64) causes electrified device failure (vertex 29), electrified device failure (vertex 29) triggers inadequate ventilation (vertex 49), inadequate ventilation (vertex 49) makes gas concentration exceed limit (vertex 38), gas concentration exceeding limit (vertex 38) incurs gas burning (vertex 37), gas burning (vertex 37) sparks off fire (vertex 34), fire (vertex 34) induces roof collapse (vertex 68), roof collapse (vertex 68) leads to penetration into goaf (vertex 61), and penetration into goaf (vertex 61) brings about water leaking (vertex 99). Although these risks may not occur simultaneity in a single accident, it can deeply reflect the process of risk spread. The spread rule of risk is conductive to developing prevention and control strategies for the risk control.

4.1.2. Network Density. Network density is used to describe the degree of affinity between the vertexes in a network from

Table 3: Accident chain analysis.

Number	Accident chains
1	Smoking → naked light → fire → suffocation
2	Unreasonable blasting → gas concentration exceeding limit → gas burning → fire
3	Air blower failure → inadequate ventilation → gas concentration exceeding limit → gas burning → fire → gas explosion
4	Electric leakage → gas burning → gas explosion
5	Coal and gas outburst → suffocation
6	Electrical failures → air blower failure → inadequate ventilation → Gas concentration exceeding limit → fire
7	Violation operation → inadequate ventilation → gas concentration exceeding limit → gas explosion
8	Inadequate ventilation → gas concentration exceeding limit → suffocation
9	Violation operation → suffocation
10	Management negligence → violation weld → gas explosion
11	Management negligence → inadequate ventilation → suffocation
12	Management negligence → unreasonable blasting → roof collapse → gas burning
13	Mechanical friction → spark → gas explosion
14	Air blower failure → inadequate ventilation → gas concentration exceeding limit → gas explosion
15	Electric spark → gas burning → fire → gas explosion
16	Management negligence → violation operation → suffocation
17	Roof collapse → mechanical friction → spark → gas explosion
18	Inadequate ventilation → gas concentration exceeding limit → gas explosion
19	Unreasonable technique scheme → geostress concentration → coal and gas outburst → suffocation
20	Imperfect regulation → management negligence → unreasonable blasting → coal and gas outburst → suffocation
21	Management negligence → poor maintenance → electrical device failure → inadequate ventilation → gas concentration exceeding limit → gas explosion
22	Unreasonable blasting → coal dust explosion → carbon monoxide poisoning
23	Imperfect regulation → management negligence → electric spark → coal dust explosion
24	Management negligence → ruptured steel rope → mechanical friction → spark → gas explosion
25	Ruptured steel rope → mechanical friction → spark → coal dust explosion
26	Unreasonable blasting → roof collapse → ventilation failure → coal dust explosion → struck-by
27	Broken steel rope → sliding train → collision → spark → coal dust explosion
28	Violation operation → unreasonable blasting → naked light → gas burning → coal dust explosion
29	Electric spark → naked light → gas burning → fire → carbon monoxide poisoning
30	Electrical failures → naked light → fire → roof collapse
31	Cable short circuit → electric spark → fire → carbon monoxide poisoning
32	Electrical failures → cable short circuit → electric spark → fire → carbon monoxide poisoning
33	Violation operation → pressure fan failure → over-temperature → spark → fire → carbon monoxide poisoning
34	Inadequate training → violation weld → naked light → fire → carbon monoxide poisoning
35	Management negligence → electric spark → naked light → fire → roof collapse
36	Management negligence → conveyor failure → over-temperature → naked light → fire → suffocation
37	Management negligence → electrical failures → air blower failure → gas concentration exceeding limit → carbon monoxide poisoning
38	Inadequate training → unreasonable blasting → penetration into goaf → water leaking
39	Violation operation → penetration into goaf → water leaking
40	Management negligence → unreasonable blasting → penetration into goaf → water leaking
41	Unreasonable blasting → gas concentration exceeding limit Unreasonable blasting → naked light → gas burning → gas explosion
42	Inadequate geological prospecting → unreasonable blasting → penetration into goaf → water leaking
43	Inadequate geological prospecting → penetration into goaf → water leaking

Table 3: Continued.

Number	Accident chains
44	Penetration into goaf → water leaking
45	Management negligence → violation operation → water leaking
46	Management negligence → stagnant water → suffocation
47	Management negligence → violation operation → penetration into goaf → water leaking
48	Inadequate training → standing on conveyor belt → fall → mechanical injury
49	Management negligence → ruptured steel rope → falling of cage
50	Broken steel rope → sliding train → train derailment → collision
51	Inadequate training → broken steel rope → mechanical injury
52	Unscientific design → faulty track → train derailment → collision
53	Train overload → brake failure → sliding train → train derailment → collision
54	Management negligence → poor maintenance → mechanical injury
55	Violation operation → electrical failures → electric shock
56	Management negligence → violation operation → electric shock
57	Cable short circuit → electric shock
58	Management negligence → inadequate training → fall → mechanical injury
59	Stray current → gas explosion
60	Management negligence → electric leakage → unreasonable blasting
61	Unscientific design → poor tunnel support → roof collapse
62	Float coal → tunnel support failure → roof collapse
63	Train derailment → collision → tunnel support failure → roof collapse
64	Optional withdrawal of pillar → roof collapse → struck-by
65	Inadequate geological prospecting → neglect of geostress concentration → roof collapse
66	Neglect of geostress concentration → roof separation → roof collapse
67	Poor tunnel support → flying rock → struck-by
68	Unreasonable blasting → tunnel support failure → roof collapse
69	Unscientific design → poor tunnel support → roof collapse → flying rock
70	Violation operation → roof collapse
71	Unreasonable technique scheme → tunnel support failure → roof separation → roof collapse → struck-by
72	Unreasonable technique scheme → unreasonable blasting → roof separation → roof collapse
73	Poor tunnel support → roof collapse → flying rock
74	Weakness of safe consciousness → standing on conveyor belt → fall → mechanical injury
75	Roof collapse → penetration into goaf → carbon monoxide poisoning
76	Air blower failure → inadequate ventilation → gas concentration exceeding limit Electrical failures → cable short circuit → electric spark → fire
77	Inadequate geological prospecting → neglect of geostress concentration → water leaking
78	Weakness of safe consciousness → unreasonable blasting → water leaking
79	Management negligence → spontaneous combustion of dynamite → dynamite explosion → roof collapse
80	Transformer overload → cable short circuit → electric spark → fire
81	Sudden torrential rain storm → water leaking
82	Spontaneous combustion of coal seam → fire
83	Unreasonable blasting → naked light → fire
84	Violation operation → electric shock
85	Inadequate training → violation operation → mechanical injury
86	Unreasonable blasting → coal and gas outburst → gas explosion
87	Drilling blasting hole → spark → gas explosion

Table 3: Continued.

Number	Accident chains
88	Violation blasting → naked light → gas explosion → struck-by
89	Miner's lamp failure → electric spark → gas explosion
90	Unscientific design → inadequate ventilation → gas concentration exceeding limit Cable insulation failure → cable short circuit → electric spark → gas explosion
91	Smoking → naked light → gas explosion
92	Inadequate ventilation → gas concentration exceeding limit Illegal disassembly of miner's miner's lamp → electric spark → gas explosion
93	Defective geological condition → coal and gas outburst Electric locomotive failure → electric spark → gas explosion
94	Gas monitoring system failure → gas concentration exceeding limit → gas explosion
95	Lack of dedusting device → coal dust concentration exceeding limit → coal dust explosion
96	Violation blasting → collapse of coal bunker → coal dust concentration exceeding limit → coal dust explosion
97	Violation weld → conveyor belt burning → fire → suffocation
98	Sudden torrential rain storm → power cut → water pump failure → mine flooding
99	Power cut → ventilation failure → gas concentration exceeding limit Violation blasting → naked light → gas explosion
100	Violation blasting → poisonous gas leakage → poisoning
101	Severe vibration in coal cutting → coal and gas outburst
102	Explosion of electric switch → spark → gas explosion
103	Roof collapse → air blower failure → inadequate ventilation → gas concentration exceeding limit Cable short circuit → electric spark → fire
104	Metal crash → spark → gas explosion
105	Illegal restart → electric spark → gas explosion
106	Optional close of ventilation → gas concentration exceeding limit Illegal disassembly of miner's miner's lamp → electric spark → gas explosion
107	Severe vibration in anchor construction → coal and gas outburst
108	Broken steel rope → sliding train → cable short circuit → electric spark → coal dust explosion
109	Mechanical friction → spark → coal dust explosion
110	Management negligence → electric leakage → ignition of cable → fire → poisonous gas leakage → poisoning
111	Conveyor over-temperature → ignition of engine oil → spark → fire
112	Violation operation → water leaking
113	Wrong geologic survey → wrong holing-through → water leaking
114	Delay of support → roof separation → roof collapse
115	Pressure fan failure → ignition of engine oil → spark → fire
116	Unstable pillar → roof separation → roof collapse
117	Winch brake failure → falling object → struck-by → mechanical injury
118	Trip → fall → struck-by
119	Trip → mechanical injury
120	Collapse of support structure → roof collapse → struck-by
121	Drinking → fall → mechanical injury
122	Violation operation → steel rope bouncing → mechanical injury
123	Management negligence → no warning sign Flying rock → struck-by
124	Management negligence → no warning sign → entering danger zone → suffocation
125	Entering danger zone → flying rock → struck-by
126	Unreasonable dismantling of elevator → falling object → struck-by

Table 4: Risk number and type.

Number	Risk	Attribute
1	Air blower failure	Machine
2	Asphyxiation	Environment
3	Delay of support	Management
4	Brake failure	Machine
5	Cable insulation failure	Machine
6	Cable short circuit	Machine
7	Falling of cage	Machine
8	Carbon monoxide poisoning	Environment
9	Optional close of ventilation	Management
10	Coal and gas outburst	Environment
11	Collapse of coal bunker	Environment
12	Coal dust concentration exceeding limit	Environment
13	Coal dust explosion	Environment
14	Collapse of support structure	Technology
15	Collision	Machine
16	Conveyor belt burning	Machine
17	Conveyor failure	Machine
18	Conveyor over-temperature	Machine
19	Defective geological condition	Environment
20	Drilling blasting hole	Technology
21	Drinking	Person
22	Dynamite explosion	Management
23	Electric leakage	Machine
24	Electric locomotive failure	Machine
25	Electric shock	Machine
26	Electric spark	Machine
27	Explosion of electric switch	Machine
28	Electrical failure	Machine
29	Electrified device failure	Machine
30	Entering danger zone	Person
31	Fall	Person
32	Falling object	Environment
33	Faulty track	Machine
34	Fire	Environment
35	Float coal	Environment
36	Flying rock	Environment
37	Gas burning	Environment
38	Gas concentration exceeding limit	Environment
39	Gas explosion	Environment
40	Gas monitoring system failure	Machine
41	Geostress concentration	Environment
42	Ignition of cable	Machine
43	Ignition of engine oil	Machine
44	Illegal disassembly of miner's miner's lamp	Person
45	Illegal restart	Person
46	Imperfect regulation	Management
47	Inadequate geological prospecting	Management
48	Inadequate training	Management
49	Inadequate ventilation	Management
50	Lack of dedusting device	Management
51	Management negligence	Management
52	Mechanical friction	Machine
53	Mechanical injury	Machine
54	Metal crash	Machine
55	Mine flooding	Environment
56	Miner's lamp failure	Machine
57	Naked light	Machine
58	Neglect of geostress concentration	Management
59	No warning sign	Management
60	Over-temperature	Environment
61	Penetration into goaf	Technology
62	Poisoning	Environment
63	Poisonous gas leakage	Environment
64	Poor maintenance	Management
65	Poor tunnel support	Technology
66	Power cut	Machine
67	Pressure fan failure	Machine
68	Roof collapse	Environment
69	Roof separation	Environment
70	Ruptured steel rope	Machine
71	Severe vibration in anchor construction	Technology
72	Severe vibration in coal cutting	Technology
73	Sliding train	Machine
74	Smoking	Person
75	Spark	Machine
76	Spontaneous combustion of coal seam	Environment
77	Spontaneous combustion of Dynamite	Management
78	Stagnant water	Environment
79	Standing on conveyor belt	Person
80	Steel rope bouncing	Machine
81	Broken steel rope	Machine
82	Stray current	Machine
83	Struck-by	Person
84	Sudden torrential rain storm	Environment
85	Train derailment	Machine
86	Train overload	Machine
87	Transformer overload	Machine
88	Trip	Person
89	Tunnel support failure	Technology
90	Unreasonable blasting	Technology
91	Unreasonable dismantling of elevator	Technology
92	Unreasonable technique scheme	Technology

Table 4: Continued.

Number	Risk	Attribute
93	Unscientific design	Technology
94	Unstable pillar	Technology
95	Ventilation failure	Machine
96	Violation blasting	Management
97	Violation operation	Management
98	Violation weld	Management
99	Water leaking	Environment
100	Water pump failure	Machine
101	Weakness of safe consciousness	Person
102	Winch brake failure	Machine
103	Optional withdrawal of pillar	Management
104	Wrong geologic survey	Technology
105	Wrong holing-through	Technology

an overall perspective. It specifically refers to the proportion of actual edges to potential edges in a network. Consisting of 105 vertexes, the maximum number of edges in CMRN should be $105 * 104 = 10920$. Since the actual edges in CMRN is 194, thus the network density of CMRN is $194/10920 = 0.178$. In general, the more the vertexes, the smaller the network density. Low density means that CMRN is a relatively sparse network. Moreover, the vertex in CMRN is less connected with all others. That is to say, the degree of a vertex in CMRN directly affected by others is relatively low.

4.1.3. Average Path Length. The transmission efficiency of information or energy is significantly correlated with the average path length. A shorter average path length means higher efficiency. The average path length can be defined as the average number of steps between all possible pairs of vertexes in a network. The value of the average path length in CMRN is 3.0841, indicating that a risk can transmit to another only in three steps on average. For example, cable short circuit (vertex 6) and carbon monoxide poisoning (vertex 8) refer to two correlative risks, which can be connected by electric spark (vertex 26) and fire (vertex 34) in three steps, as shown in accident 31 in Table 3.

4.1.4. Degree. The degree of a vertex is defined as the number of edges connected to the vertex. In a directed network, the degree can be either in-degree (number of incoming edges) or out-degree (number of outgoing edges), with the total degree being the sum of the two. Since there are 105 vertexes in CMRN, it is impossible to show all the vertex degree in a radar graph. Consequently, 30 vertexes with the highest degree are selected as the example to display vertex degree. The values of the in-degree, out-degree, and total degree of these 30 vertexes are presented in Figure 6. Roof collapse (vertex 68) has the highest degree of 17, with an in-degree 10 and out-degree 7. This indicates that the roof collapse is in a relatively central position and plays a critical role in the accident chain. Its in-degree is also the highest in the network, implying that it refers to the biggest "risk recipient" in CMRN and many risks such as poor tunnel support can lead to roof collapse. Multiple paths make it difficult to control for roof collapse, compared to other vertexes with low in-degree. The second is unreasonable blasting (vertex 90) and the third is the management negligence (vertex 51). The in-degree and out-degree of unreasonable blasting are 7 and 9, respectively. It means that 7 risks could give rise to unreasonable blasting, and meanwhile, unreasonable blasting might cause 9 risks in production. Additionally, the management negligence (vertex 51) has the highest out-degree, demonstrating that management negligence is the most serious risk source. If there is something wrong in safety management, many risks might be triggered at any time, such as gas concentration exceeding limit. Controlling these key vertexes can positively influence the safety of coal mine, which is also referential in resource distribution under the condition of limited security resource. Besides, it would greatly help disrupt the connectivity among risks to prevent risks from spreading and propagating in CMRN.

4.1.5. Betweenness. Betweenness is used to describe the extent to which a vertex plays an intermediary role in the interaction between all possible pairs of vertexes in a network [38]. Two types of betweenness, vertex betweenness and edge betweenness, are used extensively in the network analysis [39, 40]. According to the research object, only vertex betweenness is utilized in this study. High betweenness indicates greater importance in the whole network. The vertex betweenness in the CMRN ranges from 0 to 0.059852, as shown in Table 5. Only 47 vertexes are invisible because their vertex betweenness is zero, which indicates that they do not play the role of intermediary among interactions between other vertexes. The roof collapse (vertex 68) has the highest value of vertex betweenness, meaning that the maximum number of the shortest paths passes through roof collapse (vertex 68). It is a key link in the process of risk spread. The stagnant water (vertex 78) has the lowest value of vertex betweenness, meaning that the minimum number of the shortest paths passes through stagnant water (vertex 78). It is not a key link in the process of risk spread. According to the value of betweenness, the impact of roof collapse (vertex 68) is much larger than stagnant water (vertex 78) in the process of risk spread. Furthermore, fire (vertex 34) and spark (vertex 75) are 0.048486 and 0.020668, respectively. The cumulative vertex betweenness of the five highest vertex betweenness is equal to 0.542701, which indicates that about 55% shortest paths pass through these five vertexes. These vertexes should be focused in the safety management. It seems that effectively controlling these few key vertexes can slow down the risk diffusion and decrease the chain reaction in CMRN.

4.1.6. Clustering Coefficient. The clustering coefficient is used to describe which vertexes in a network tend to cluster together from a local perspective [41]. The clustering coefficient of a vertex is defined as the probability of two randomly selected neighbors of the vertex being connected. It can be found that 33 vertexes get the missing value of 999999998 because the degrees of these vertexes are equal to 1, and 34 vertexes have the value of 0. The clustering coefficients of

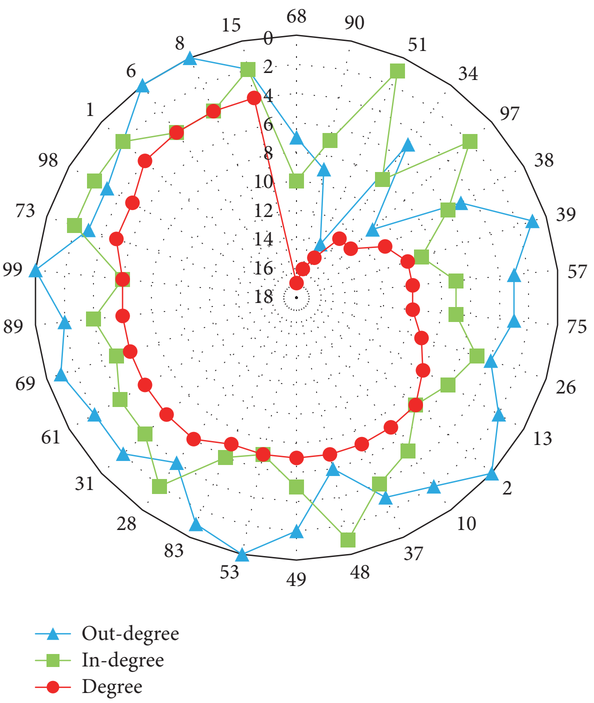

FIGURE 6: In-degree, out-degree, and total degree values.

other 38 vertexes are presented from high to low in Table 6. The clustering coefficient of vertex in CMRN ranges from 0 to 0.5. The vertexes with the highest clustering coefficient are vertex 25 and vertex 80. The network clustering coefficient can be defined as the average value of all vertexes in the network, and it is 0.0623 in CMRN which is larger than a random network with the same network scale. The large clustering coefficient denotes that CMRN has a high degree of cliquishness.

4.2. Network Property. With the development of network theory, it can be found that small-world property and scale-free property are the most obvious distinction between real network and random network. To obtain greater insight into the nature of CMRN, this section explores these two properties.

4.2.1. Small-World Property. A small-world network is a special kind of graph, in which most vertexes can be reached from every other vertex by a short path. In general, small-world network is associated with the possession of relatively high value of clustering coefficient and small average path length [42, 43]. For comparison, three random networks with 105 vertexes and 194 edges are created by *Pajek*, which are the same scale as CMRN. The clustering coefficient and average path length of CMRN and random networks are presented in Table 7. Obviously, CMRN is a relatively small-world network according to its clustering coefficient and average path length, indicating that the risk propagation in CMRN is much faster than a random network. To avoid a worse consequence under the condition of an occurred accident, controlling the catenation among accidents is of great significance.

4.2.2. Scale-Free Property. A scale-free network is a network whose degree distribution satisfies power-law decay. In such network, numerous vertexes are poorly connected and relatively few vertexes are linked to many other vertexes [44]. Due to rare vertexes with high degree, analyzing statistic data in the tail of the degree distribution is meaningless. The degree distribution $P(k)$ is defined as the proportion of vertexes with degree k, while the cumulative $P(k)$ is defined as the proportion of vertexes equaling to or greater than k [45]. In practice, the cumulative $P(k)$ is preferred in statistical analysis using double logarithmic coordinate system, with the purpose of reducing statistical errors caused by finite network size [46]. The cumulative $P(k)$ of CMRN is depicted in Figure 7 with approximate fit $P(k) = 2.1217 \times k^{-1.545}$, which basically follows the power-law. This indicates that the CMRN has scale-free property according to complex network theory. The property means that CMRN is robust to random risks to some extent. The vertex with degree equaling to or less than 4 accounts for 75%, and the influence of these vertexes on the network is relatively small. However, CMRN is vulnerable to simultaneous attacks aiming at vertexes with high degree. In other words, only targeted actions can greatly prevent the cascading effects in CMRN.

4.3. Measuring the Effect of Risk Control. The analysis on effect of risk control is conductive to providing recommendations and proposal for safety management in coal mine. To measure the effect of risk control, an assumption is made. Namely, a risk would be supposed not to occur if it is completely controlled in coal mine production. Furthermore, if a risk will not happen, it can be deleted from CMRN. Then, the effect of risk control can be measured by network global

Table 5: Betweenness in CMRN.

Vertex	Betweenness
68	0.059852
34	0.048486
75	0.020668
38	0.016303
15	0.012481
89	0.010105
90	0.009873
57	0.009704
26	0.008742
1	0.008044
73	0.007534
37	0.007143
83	0.007001
61	0.006588
95	0.006566
63	0.006068
52	0.005903
39	0.005813
51	0.005134
13	0.005128
49	0.004844
69	0.003734
60	0.003423
97	0.002563
43	0.002558
85	0.002474
4	0.002427
66	0.001960
10	0.001875
22	0.001867
29	0.001774
48	0.001147
65	0.000996
81	0.000937
28	0.000850
12	0.000794
16	0.000770
98	0.000745
31	0.000742
67	0.000660
36	0.000560
58	0.000490
70	0.000467
30	0.000436
33	0.000420
23	0.000373
32	0.000373
17	0.000280
64	0.000280
59	0.000249
79	0.000218
77	0.000187
100	0.000187
42	0.000179
11	0.000140
41	0.000101
105	0.000093
78	0.000062
⋮	0

Table 6: Clustering coefficient in CMRN.

Vertex	Clustering coefficient
25	0.5000
80	0.5000
88	0.5000
61	0.2000
36	0.1667
47	0.1667
65	0.1667
79	0.1667
85	0.1667
92	0.1667
37	0.1429
69	0.1333
89	0.1333
48	0.1190
31	0.1000
39	0.1000
98	0.1000
99	0.1000
49	0.0952
1	0.0833
8	0.0833
15	0.0833
23	0.0833
58	0.0833
97	0.0833
2	0.0714
53	0.0714
34	0.0705
28	0.0667
57	0.0667
38	0.0636
90	0.0583
73	0.0500
83	0.0476
26	0.0417
68	0.0368
51	0.0333
75	0.0111
⋮	0

efficiency. Although many definitions on network global efficiency are currently created and studied, they all have different limitations. The generally accepted measure method is average reciprocal shortest path lengths of networks, in

Table 7: The comparison between CMRN and random networks.

Network model	Clustering coefficient	Average path length
CMRN	0.0623	3.0841
Random network 1	0.0156	5.6134
Random network 2	0.0189	5.8130
Random network 3	0.0152	5.4532

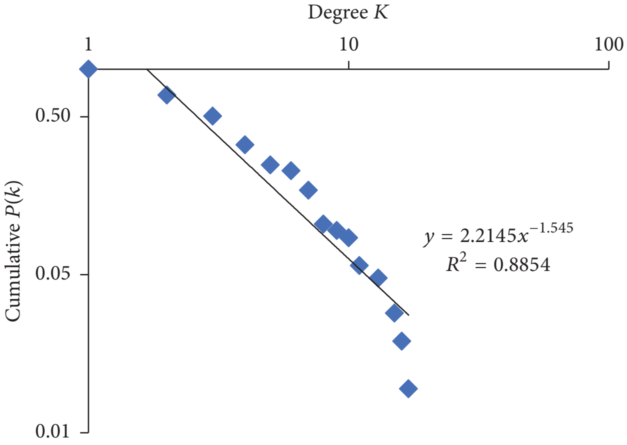

Figure 7: Cumulative degree distribution of CMRN.

which network global efficiency of a network G could be calculated by (1) [47, 48], where n refers to the number of vertexes and d_{ij} refers to the distance between two vertexes.

$$E(G) = \frac{1}{n(n-1)} \sum_{\forall i,j,i\neq j} \frac{1}{d_{ij}}. \qquad (1)$$

The effect of risk control of every risk in CMRN can be measured according to the degree of network global efficiency declined. For example, if the network global efficiency decreases by 0.1 after deletion of vertex 8, it means that the effect of risk control of vertex 8 is 0.1. The better the effect is, the greater the risk will be. The 30 most serious risks in CMRN are identified through calculation, and the risk control effects can be shown in Figure 8. It is observed that roof collapse is the most serious risk and controlling roof collapse could help decrease 32.63% of network global efficiency of CMRN, followed by fire (25.96%) and gas concentration exceeding limit (11.22%). However, due to the interaction between roof collapse and gas concentration exceeding limit, the effect of controlling “roof collapse” and “gas concentration exceeding limit” is not equal to 32.63% plus 25.96%, but 44.03% by calculation. Obviously, measuring the effect of risk control can suggest and designate the directions and key points to further safety management. Anyway, controlling several most serious risks is the most appropriate and most effective approach for preventing accident and further promoting the safety management level in the coal mine production.

5. Discussion

Based on the network theory, an analytical framework has been put forward to promote coal mine production safety, which turns out to be feasible and effective. The proposed network modeling method is a powerful and promising tool to analyze risk in various disciplines. It is envisaged that this study can help managerial personnel deeply understand coal mine risk for the sake of developing necessary strategies that can improve safety management in a dynamic operating environment, especially in emergency.

The potential contributions of this study include four aspects. First, it is beneficial to understand the complexity and transitivity of risks in coal mine. The main topology properties and network properties of CMRN are captured and analyzed. Second, it is conductive to enhance the safety performance by controlling original risks and avoiding derivative accidents. Third, this study has the potential benefits in coal mine emergency and relief, which can help managers make decisions in emergency rescue for lightening the casualties and losses. Additionally, network modeling technique is employed in this study, which may offer a promising approach for the analysis of the accident. Also, the application range of network theory will be enlarged.

The main limitation of this research is that the established network model fails to take the vertex weight into consideration. Moreover, the frequency of risks in Table 3 cannot reflect the vertex weight in current study, and it is very difficult to discern and distinguish the different importance for different risks. Therefore, assigning the weight is quite difficult. That may explain why the network model in this study is unweighted. In the future study, more attention should be paid to improve the network model based on more precise understanding of risks in coal mine. Also, how to reduce the risks in coal mine is a significant direction that deserves further research. Meanwhile, a particular failure knowledge database (FKD) would be significant in studying the coal mine accidents, which is the foundation of case based reasoning (CBR) for analyzing hazard and risk.

What is more, several identified risks seem to be general, rather than specific. There are two reasons for this result. First, the risk identification is carried out on the basis of accident data collected from literature and media. If some detailed information is ignored and not recorded during the investigation of these accidents, the unavailable information may affect the accuracy of risk identification. Second, this research is implemented from a holistic perspective. If the identified risks are too specific, finding the common vertex and constructing the coal mine risk network will be difficult.

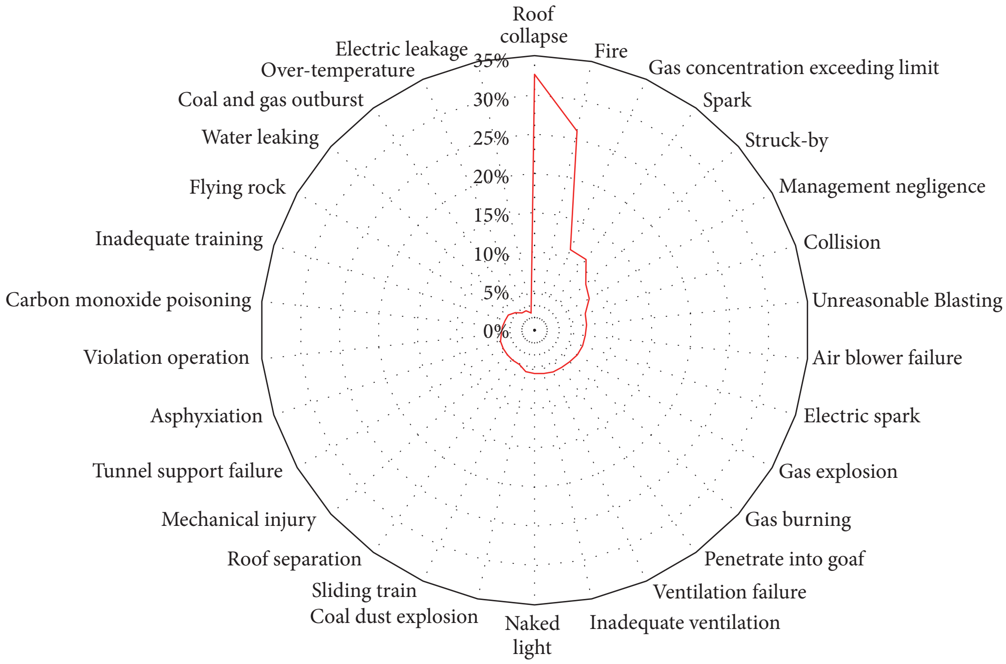

Figure 8: The effect of risk control of 30 most serious risks.

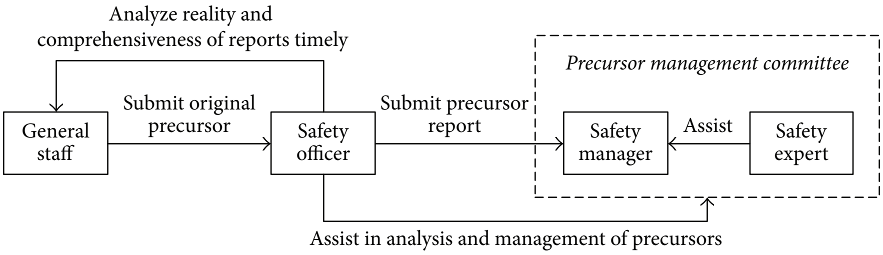

Figure 9: The proposed organization structure.

Hence, the similar risks are divided into the same category for the sake of convenience.

Safety researchers assiduously aim to lower the prevalence of accident and raise the safety level. Accident precursor is studied in various industries, and many studies indicate that a series of precursors always occur before the accident [8, 11, 49]. Therefore, lowering precursor frequency is an effective approach to reduce the accident probability [50]. An accident precursor is broadly defined as the "conditions, events, and sequences that precede and lead up to an accident" by the National Academy of Engineering [51]. Even though it is impossible to completely prevent coal mine accident, monitoring and controlling precursory information is a useful and effective approach for safety managers to identify hazards or risks in advance. Also, this can reduce the possibility of accident or alleviate their consequence. Hence, precursor analysis seemingly has huge potential to promote safety management of coal mine production.

According to the results of network analysis, it can be known that some key vertexes play an important role in accident prevention. In practice, precursor can be used to reduce the frequency and probability of these key risks. For example, the precursor of water leaking mainly includes the following: air turns cold; mist appears on the roadway; and coal wall has water seepage. If the coal miner can pay more attention to these precursors, the water leaking will be reduced to a large extent. Therefore, an organization structure should be proposed to manage and control precursors, as depicted in Figure 9. The real executors of precursor management include general staff, safety manager, and safety expert. General staff should report precursor to the safety officer, and then safety officer submits precursor reports to the safety manager. Furthermore, safety expert assists safety manager to analyze risk as well as factor and propose processing measures. The proposed measures or solutions are executed by general staff and safety officer, and meanwhile, the evaluation of them is implemented by safety manager and safety expert. The coal mine enterprise can set up a committee, mainly including safety manager and safety expert, to deal with precursor management.

6. Conclusion

The accidents in the coal industry have been widely analyzed to promote safety production. By changing the original method of analyzing a single accident, this research aims to develop an innovative approach of fusing various risks that can explore the full complexity of CMRN based on network theory.

The CMRN is constructed by software *Pajek* based on 135 typical accident chains, which are obtained from 126 typical accidents in coal mine accident database (CMAD). As an unweighted directed network model, CMRN includes 105 vertexes and 194 edges. The network diameter in the CMRN is 7 and the network density of CMRN is 0.178, which indicates that CMRN refers to a relatively sparse network. The value of the average path length in CMRN is 3.0841, suggesting that a risk can transmit to another only in three steps on average. Roof collapse (vertex 68) has the highest degree of 17, which indicates that roof collapse plays a critical role in the accident chain. In general, this type of vertex is regarded as a key point. The vertex betweenness in the CMRN ranges from 0 to 0.059852. Additionally, the roof collapse (vertex 68) has the highest value of vertex betweenness, which means that the maximum number of shortest paths passes through roof collapse (vertex 68). It is a key link in the process of risk spread. Next, fire (vertex 34) and spark (vertex 75) are 0.048486 and 0.020668, respectively. About 55% shortest paths pass through these five highest betweenness vertexes. Effectively controlling roof collapse, fire, spark, gas concentration exceeding limit, and collision could not only increase the network diameter and average path length but also slow down the efficiency of accident propagation and weaken the chain reaction. The vertex clustering coefficient in CMRN ranges from 0 to 0.5. Moreover, the clustering coefficient of CMRN is 0.0623 in CMRN, which denotes that CMRN has a high degree of cliquishness. Besides, CMRN is a relatively small-world network according to its clustering coefficient and average path length, demonstrating that the risk propagation in CMRN is much faster than a random network. CMRN also has the scale-free property because cumulative $P(k)$ follows the power-law. The property indicates that CMRN is robust to random risks to some extent. Furthermore, the effect of risk control is calculated precisely. Overall, roof collapse, fire, and gas concentration exceeding limit are not only three most valuable targets in safety management but also the three most dangerous risks in coal mine production.

Precise calculation of these six parameters and effective risk control are beneficial to capture the complexity and nature of coal mine accident and designate the targets for risk control. Also, the results can help promote coal mine safety management in controlling original risks and preventing derivative accidents. In view of the sequential interrelations among accidents in CMRN, this research may also positive influence the early warning of accidents. In practice, the safety managers should focus more on the identified and valuable targets of risk control and put more resources to help promote safety performance in coal mine production.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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