fire

Article

Superposition Risk Assessment and Calculation Model of the Working Position of Coal-Seam Fire Accidents in China

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Abstract: The coal-seam fire is one of the most significant disasters in the coal mining industry in China, affecting the safety of coal production in China. The working-position risk in coal mining has an important impact on the risk of fire occurrence, and thus it would be worthwhile to analyze working-position risks so as to effectively prevent and control coal-seam fires. Based on the kernel density estimation (KDE), this research puts forward an innovative calculation-model and assessment method of the superposition risk of the working position on coal-seam fire accidents. This research aims to evaluate the priority of risk management of working positions in coal-seam fire accidents. In order to achieve this research aim and objectives, this research carried out a statistical analysis of 100 classic cases of coal-seam fire accidents from 2000 to 2022, using the accident-tree-structure importance analysis method. This research contributed to the evaluation of the frequency and severity of various risk factors leading to fire accidents, and the development of the value at risk (VaR) of various risk factors in the coal-seam fire accidents. Integrating all the risk factors involved in each position and their risk values, and building a position-risk calculation model was carried out. In addition, in accordance with the kernel density estimation (KDE), a post-superposition risk model was established. Moreover, ArcGIS software was used to obtain the superimposed risk of posts and build a risk-distribution map. Based on the possibility of post-risk occurrence and the severity of the consequences, a risk-assessment matrix was developed, a post-risk grading standard was established, and risk levels of the working position were divided up in this research. Results indicated that (1) before risk superposition, working-position risks and risk levels are densely distributed, and nearly 80% of risk levels of the working position are focused on Level II and III, without Level I. (2) After risk superposition, the post-risk is affected by the surrounding post-risk, and the risk- and level-distribution is more hierarchical; the number of Level I risks in working positions increased to 12, which were mainly distributed among the comprehensive mining team, comprehensive excavation team and ventilation team, which accords more with the objective and actual production-conditions. The risk-distribution map directly showed that the post-fire risk at the mining face and shaft is higher, a result which will take on a significant guiding role in the effective control and prevention of risk in coal-seam fires in the future.

Keywords: coal-seam fire; working-position risks; risk superposition; nuclear density; risk classification

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1. Introduction

Coal is an important source of energy across the world. It is one of the main energy sources in industrial production, power production and other industries promoting the prosperous development of the global economy. Coal is one of the significant sources of energy and a valuable resource in China, which taking indispensible role in national energies for a long term [1] (Li et al., 2020). The underground production environment of the coal mine is complex and dangerous, and thus there are numerous factors contributing to disasters. Coal-seam fires occur frequently and unpredictably, and pose a great threat to the safety of workers' lives [2], leading to significant losses and serious consequences.

According to the data provided by the State Administration of Coal Mine Safety, although coal-seam fire accidents have decreased annually and numbers have become increasingly stable in recent years, it is still difficult to effectively prevent and control catastrophic coal-seam fires, which would show that China has met new challenges in the control and prevention of coal-seam fire accidents. The coal industry is in a stage of rapid development. In order to effectively contain the occurrence of coal mining accidents and transform passive management into active management, it would be necessary for Chinese coal mining to change from the traditionally qualitative method of the 'risk detection' safety-evaluation system to the quantitative method of the 'risk assessment' dual-prevention mechanism [3]. In recent years, the General Office of the State Council, the State Council of the People's Republic of China, and the newly revised production safety law of the People's Republic of China have also clearly proposed and emphasized the significance of dual-prevention mechanisms and safety-risk identification, assessment and control procedures. Therefore, the implementation of a risk-assessment model of coal-seam fires contributes to the efficient implementation of national policies.

Conventional analytical methods for assessing coal mine accidents mainly consist of event-tree analysis (ETA), fault-tree analysis (FTA), operation-condition analysis, and the analytic hierarchy process (AHP) [4]. With the development of computer science and mathematical science, the emergence of evaluation methods such as Bayesian networks (BN) [5], Monte Carlo [6], fuzzy mathematical simulation [7], and machine learning have improved the shortcomings of traditional methods in terms of probability calculation, parameter uncertainty, and other problems In order to effectively solve the problem of large deviation in the results from a single assessment method in the assessment process, the coal-mine risk assessment commonly adopts an assessment model combining multiple assessment methods. Considering the uncertainty of coal-seam fire occurrences and the fuzziness of various influencing factors, Jiang and other researchers used the set pair analysis (SPA) for analyzing the risk assessment of coal-seam fires, established a quaternion number-system based on the set pair analysis (SPA), and evaluated the safety state of coal-seam fires [8]. In addition, some scholars have studied the external and internal factors leading to coal-seam fires. In the case of external factors of coal-seam fires, they mainly analyzed electrical fires, machinery and equipment, emergency rescues, and so on. Jia and other researchers established a coal-seam fire-assessment model for external factors using the catastrophe progression method (CPM), the catastrophe theory and fuzzy mathematics [9]. A lot of research has been conducted into the spontaneous combustion of coal due to fire in coal mining, and the risks of the spontaneous combustion of coals were assessed mainly through the measurement of temperature, carbon monoxide, ethylene, acetylene and other gas concentrations. Based on the critical oxygen concentration and critical wind speed, Li and other researchers determined the risk area of coal spontaneous combustion around the shaft, and put forward the key technology to prevent the spontaneous combustion of coal [10]. Yu and Liu put forward a multi-index quantitative-risk-assessment model for different periods of the spontaneous combustion of coal by combining the analytic hierarchy process (AHP) and linear interpolation, and provided a development direction for the spontaneous coal-combustion fire risk assessment [11]. However, there are limited studies measuring the risk assessment of the working position in coal mining. The State Council of the People's Republic of China published a "Three-Year Action Plan for National Safety Special Rectification" in 2020, and it also requires SMEs to effectively manage the safety-risk classification in accordance with the risk assessment results, and to implement an enterprise safety production-responsibility system. In order to improve the objectivity and scientific values of the risk assessment results of coal-seam fires and the significance of risk management and control measures, this research mainly focuses on analyzing the working position of coal-mine fire accidents in China based on the superposition risk-assessment and calculation model.

In the process of coal-mine production and operation, various risk factors in the working position would commonly interact with each other, resulting in the risk superposition effect. At this stage, there are many studies on superimposed risks in transportation, the chemical industry, finance and other fields. Shi and other researchers established a CA model to quantify the impact of single-factor and multi-factor superposition on road traffic safety and efficiency. The results showed that the superposition of fatigue driving and environment aggravates traffic accidents and congestion problems [12]. Most research on coal-mine fire risk mainly focuses on the coupling effect between risk factors, but studies measuring the superimposed risk have rarely been developed up until the present. In recent years, scholars at home and abroad have analyzed the coupling effect of "human–machine-environment-management" risks [13]. Qiao and other researchers [14] studied and analyzed the coupling risk of the coal mine with the NK model, and concluded that the coupling risk of the human-management environment is the largest. At this stage, researchers looking at superimposed risk merely analyzed the risk factors in the man–machine-environment system, but did not evaluate a variety of risk factors and superimposed risks from the perspective of the working position. However, in the actual operation process, due to the existence of risk superposition effect, the size of a position risk will affect the size of other positions risk, especially in the job-intensive area this impact is particularly significant. Therefore, in order to objectively assess the risks of the working position, it is necessary to take the superposition effect of risks among working positions into consideration.

The research statistically analyzed the disaster process of classic coal-seam fire accidents. Based on the regional distribution of coal mining, the fire and risk factors of each working position were identified. Based on the relevant knowledge of safety-system engineering, the risk values of significant factors were verified, and a model constructed for calculating the working-position risk involved in coal-mine fire accidents. This research put forward the risk-calculation model of the working position. A post-superposition risk model was built, based on the kernel-density-estimation (KDE) method. In addition, ArcGIS software was used to analyze the superimposed risk of coal-mine fire posts, and obtain the risk distribution map. Moreover, a risk-classification standard was built, and the superposition risk of different working positions was evaluated, based on the risk-matrix method. Lastly, the priority of post-risk prevention and control was determined in this research, for taking on a significant guiding role in the effective control and prevention of risks in coal-seam fires in the future.

2. Risk Discrimination of Coal-Mine Fire

2.1. Analysis of Main Risk Factors

Risk discrimination is the main step in risk management, and also the premise and basis of risk avoidance. The research on the influencing factors of coal-mine safety production is mostly analyzed from four perspectives: human, machine, environment and management [14]. Because safety-management factors include safety organization systems, safety rules and regulations, safety training and education and many other factors, they is difficult to extract and quantify, and they also interact with the human–machine environment and other risk factors. Therefore, this article mainly analyzes the risk factors from three perspectives: human, machine and environment. This research analyzes 100 classic cases of coal-seam fire accidents in China from 2000 to 2022, and these public data are commonly from the National Mine Safety Production Supervision Administration, the Coal Mine Safety Production Network, and the provincial and municipal coal-mine safety-production-supervision bureaus. The accident distribution is shown by using 37 of the coal-seam fire factors (Figure 1). Taking these 37 relevant factors as the basic events, the fault-tree modeling is developed in accordance with the disaster chain of coal-seam fire accidents, as shown in Figure 2. The meaning of each event in the fault tree is shown in Table 1.

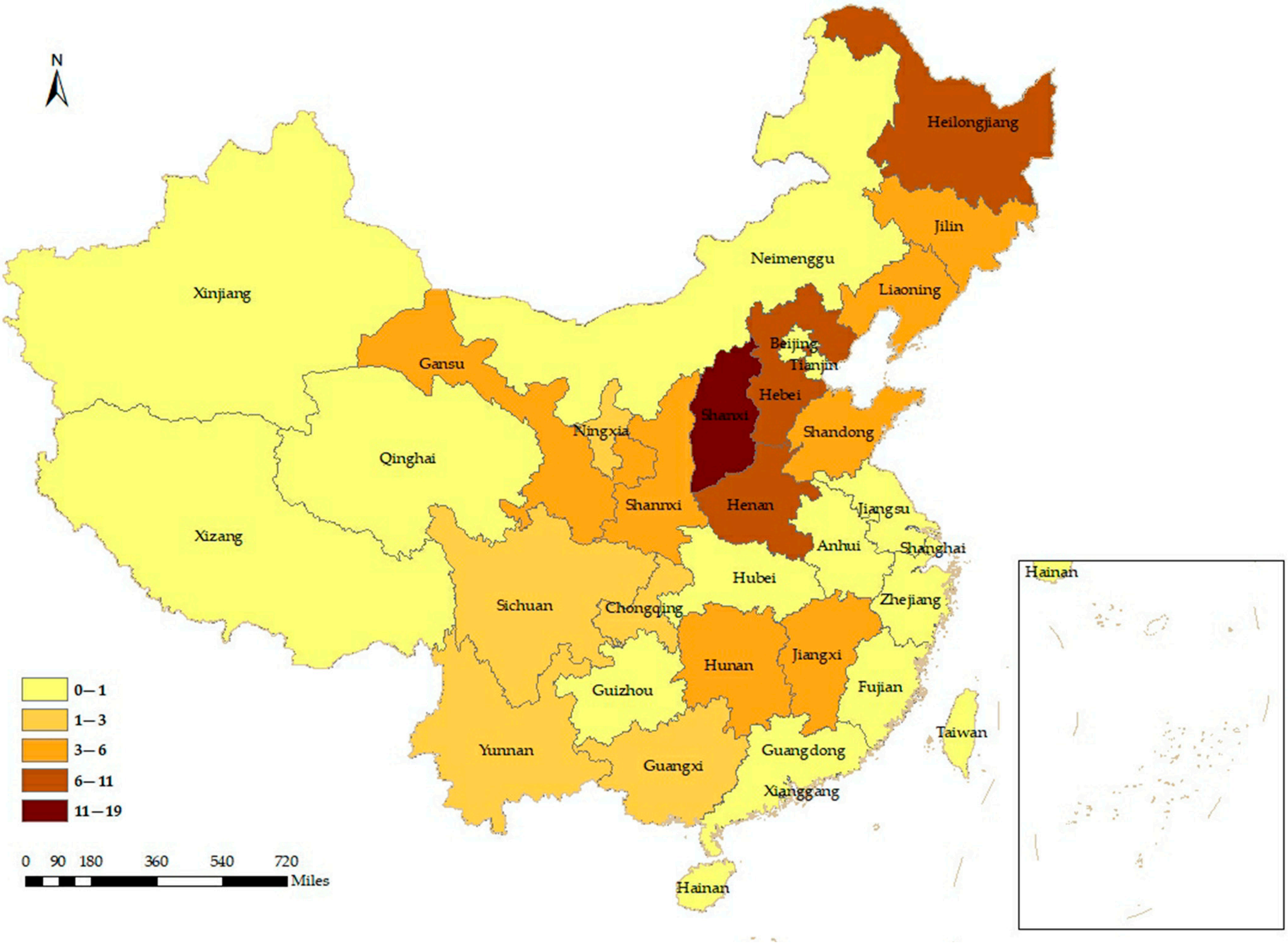

Figure 1. Distribution of Coal-seam Fires in China from 2000 to 2022.

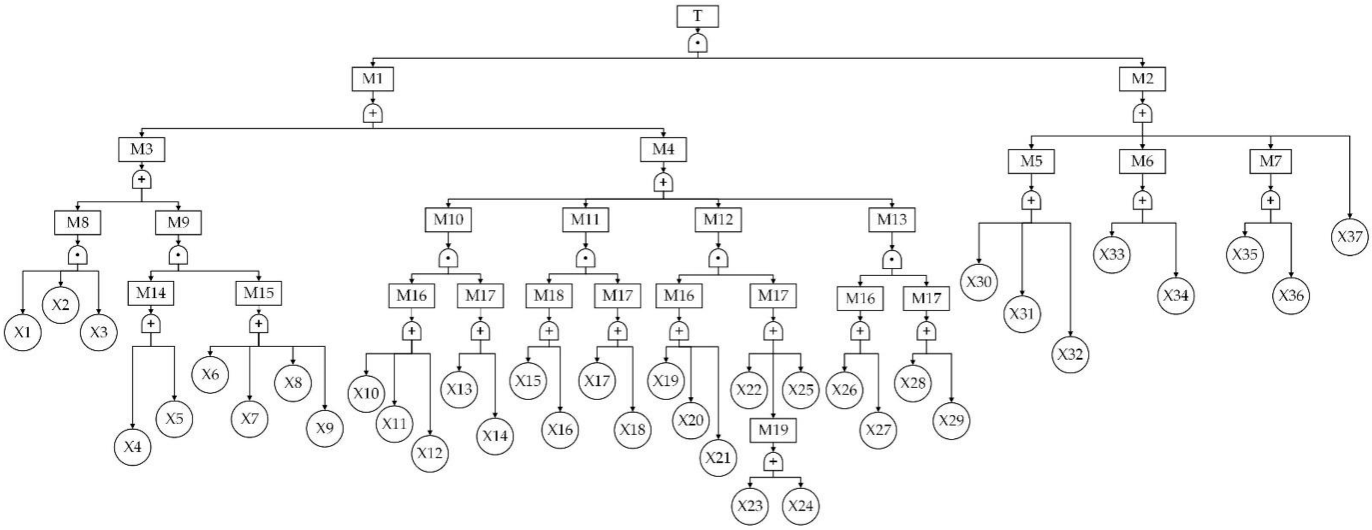

Figure 2. Regional distribution and statistics of coal-seam fire accidents.

Table 1. Hazard Factors and Frequency of Coal-Seam Fire Accidents.

Serial Number	Items	Serial Number	Items
T	Coal-seam fire	X10	High-temperature slag
M1	Fire occurs	X11	f < flammable support material
M2	Inadequate disaster -elief system	X12	Other combustible materials (glass fiber reinforced plastic)
M3	Internal fire	X13	Welding and cutting-work sparks
M4	External fire	X14	Shaft-cable spark (poor cable quality)
M5	Insufficient fire-protection system	X15	Improper storage of explosives
M6	Insufficient self-rescue system	X16	Illegal use of pyrotechnics
M7	Insufficient safety monitoring and monitoring system	X17	Dynamite-explosion sparks
M8	Falling-area fire	X18	Gas welding, cutting sparks
M9	Gob fire	X19	Non-flame retardant belts and surrounding flammables
M10	Shaft	X20	Remaining coal and slag cleaning is not timely
M11	Warehouse of explosives	X21	Inferior quality and improper placement of air compressors
M12	Transport roadway	X22	Belt conveyor friction sparks
M13	Other places	X23	Winch-cable short circuit
M14	Presence of pyrophoric substances	X24	Transformer-overload operation
M15	Spontaneous-combustion conditions exist	X25	Air-compressor switch jumps on fire
M16	Flammable	X26	Flammable items (woven bags)
M17	Ignition source	X27	Long-term accumulation of pulverized coal
M18	Flammable pyrotechnics	X28	Illegal hot work
M19	Electrical spark	X29	Cable sparks in other places
X1	Improper filling material	X30	Inadequate firefighting facilities
X2	Insufficient ventilation	X31	Insufficient extinguishing material
X3	Monitoring is not in place	X32	Fire piping is not properly installed
X4	Untimely cleaning of floating coal and leftover coal	X33	Self-rescuer does not meet the regulations
X5	High-voltage power distribution Oil leakage	X34	Employees have poor self-rescue awareness and self-rescue ability
X6	Not closed tightly	X35	Not equipped with specialized technical personnel
X7	Improper filling	X36	The monitoring equipment is damaged and not replaced in time
X8	Improper gas drainage	X37	Inadequate emergency-rescue system
X9	Air leakage		

2.2. *Risk Discrimination of Working Positions of the Coal-Seam Fire*

The occurrence of a coal-mine fire is closely related to the geological conditions of coal seams, the development and mining conditions, ventilation conditions, disaster-relief systems, and so on, which involve numerous working positions in coal mining [15]. At present, there is no specific classification standard for coal-mine posts [6]. Therefore, by describing accident cases and analyzing the main safety management processes of coal-mining enterprises in Hebei, Henan, Shanxi, Inner Mongolia Autonomous Region, Xinjiang and other regions in China, this research summarizes five teams related to 37 factors and 24 job positions, as well as the relevant factors contained in each working position (Table 2). These five teams mainly include the comprehensive mining team, the comprehensive excavation team, the electromechanical transportation team, the ventilation team and the safety-supervision department. The results show that the main coal miners in the comprehensive mining team and the underground-electrical-maintenance workers in the mechanical and electrical transport-team suffered from the most factors, followed by the filling workers in the fully mechanized mining-team, the blasting workers in the fully mechanized mining-team and the electric welders in the mechanical and electrical transport-team. ArcGIS software was used to mark the coordinate positions of each working position on the map, in accordance with the actual distribution of the mining area. The working-position distribution is shown in Figure 3.

Table 2. The Classification of working positions and relevant factors.

Team	Working Position	Factor	Value at Risk
1: Comprehensive mining team	1. Coal miners	X1, X2, X4, X5, X6, X7, X9, X34	43
	2. Filler	X1, X2, X7, X9, X34	22
	3. Belt-conveyor driver and maintenance worker from comprehensive mining team	X19, X20, X22, X34	43
	4. Mining electrician	X4, X5, X9	21
	5. Coal cleaner	X4	13
2: Comprehensive excavation team,	1. Excavation electrician	X26, X27, X29	16
	2. Belt-conveyor driver and maintenance worker from the comprehensive excavation team	X19, X20, X22, X34	43
	3. Blasting worker	X26, X27, X28, X29, X34	31
	4. Lane-clearing worker	X20	5
3: Electromechanical transportation team	1. Electrician	X5, X23, X24	9
	2. Air -compressor driver, maintenance worker	X21, X25, X34	17
	3. Electrical- and mechanical- transport-team belt-conveyor drivers and maintenance workers	X19, X20, X22, X34	43
	4. Downhole electrical-maintenance worker	X4, X5, X9, X12, X14, X23, X24, X29	40
	5. The winch driver	X19, X20, X23, X34	46
	6. Welder	X10, X11, X12, X13, X18	20
4: Ventilation team	1. Gas drainer	X4, X8, X9, X34	33
	2. Ventilator-installation worker	X2, X9	8
	3. Monitoring and monitoring workers	X3, X35, X36	28
	4. Damper	X2, X3, X9	8
	5. Sealer	X4, X5, X6, X9	28
5: Safety-supervision department	1. Pyrotechnics-management worker	X15, X16, X17, X34	46
	2. Mine-rescue workers	X30, X31, X32, X37	69
	3. Pullback work	X26, X27, X29	16
	4. Miner's lamp and self-rescuer manager	X26, X33	27

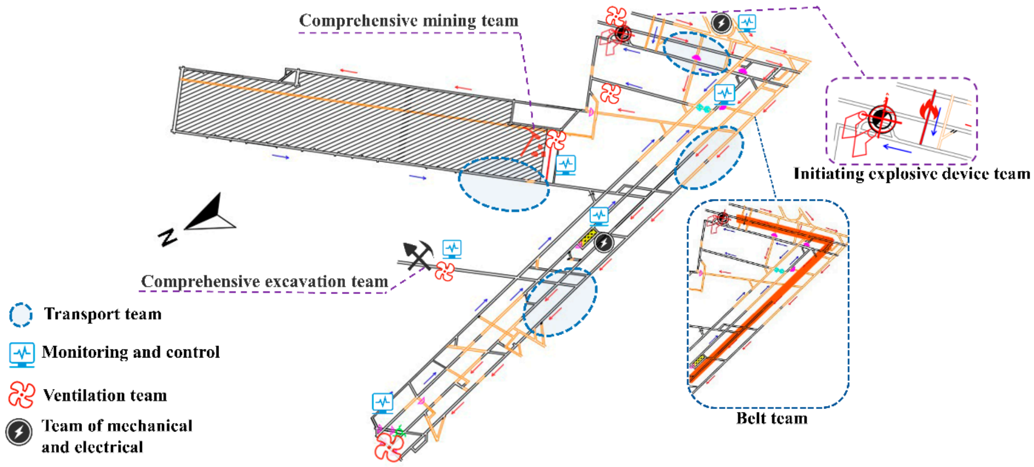

Figure 3. Distribution map of coal-seam fire positions.

3. Superposition Risk Assessment of the Working Position of Coal-Seam Fire

3.1. Determination of Risk Value of Influencing Factors

Risk value represents the hazard degree of risk, and is the product of accident likelihood and severity [16]. The probability of accidents caused by factors is determined by the frequency of the factors. This is the proportion of factor frequency in the total frequency. The formula for calculating the probability of accidents caused by factors is as follows:

$$P_i = \frac{n_i}{N} \quad (1)$$

P_{i}—possibility of occurrence of the ith factor; $\mathrm{n_i}$—frequency of the ith factor; N—total frequency of all factors.

The severity of the influencing factors indicates the degree of influence of the factors on the occurrence of fire accidents. Therefore, the importance of each influencing factor is determined by using the importance of the fault-tree structure, and then the severity is determined [17]. The calculation formula of accident severity caused by factors is as follows:

$$I(\mathrm{i}) = \frac{1}{37}\sum_{\mathrm{r}=1}^{37} \frac{1}{m_r(X_i \in E_r)} \tag{2}$$

$I(i)$—severity of the ith factor; Xi—the ith factor; E_r—the rth minimum cut set; m_r—the rth minimum cut set; E_r contains m_r basic events.

In Formulas (2) and (3), the occurrence probability and severity of each factor from X1 to X37 are verified, and they are brought into the risk-calculation formula (Formula (3)). The risk value of each factor is calculated, and the results are shown in Table 3.

Table 3. Risk Factors.

Basic Event	Frequency	Severity	Likelihood	Value at Risk	Modified VaR
X1 Improper filling material	3	0.014	0.0117	0.0001638	2
X2 Insufficient ventilation	1	0.014	0.0039	0.0000546	1
X3 Monitoring is not in place	5	0.014	0.0195	0.000273	3
X4 Untimely cleaning of floating coal and leftover coal	9	0.038	0.0352	0.0013376	13
X5 High-voltage distribution-oil leakage	1	0.038	0.0039	0.0001482	1
X6 Poorly sealed	9	0.019	0.0352	0.0006688	7
X7 Improper filling	2	0.019	0.0078	0.0001482	1
X8 Gas pumping improperly	3	0.019	0.0117	0.0002223	2
X9 Air leakage	10	0.019	0.0391	0.0007429	7
X10 High-temperature slag	5	0.019	0.0195	0.0003705	4
X11 Flammable support materials	4	0.019	0.0156	0.0002964	3
X12 Remaining combustible materials (fiberglass, etc.)	4	0.019	0.0156	0.0002964	3
X13 Welding and cutting-work sparks	5	0.029	0.0195	0.0005655	6
X14 Wellbore-cable sparks (e.g., poor cable quality)	2	0.029	0.0078	0.0002262	2
X15 Improper storage of explosives	7	0.019	0.0273	0.0005187	5
X16 Illegal use of pyrotechnics	22	0.019	0.0859	0.0016321	16
X17 Dynamite-explosion sparks	19	0.019	0.0742	0.0014098	14
X18 Sparks from gas-cutting operations	6	0.019	0.0234	0.0004446	4
X19 Non-flame-retardant belt and surrounding flammables	16	0.038	0.0625	0.002375	24
X20 More than coal residues are not cleaned up in time	4	0.038	0.0156	0.0005928	5
X21 Poor quality and improper placement of air compressors	3	0.038	0.0117	0.0004446	4
X22 Belt conveyor-belt friction sparks	3	0.029	0.0117	0.0003393	3
X23 Winch-cable short circuit	5	0.029	0.0195	0.0005655	6
X24 Transformer is overloaded	2	0.029	0.0078	0.0002262	2
X25 Air-compressor switch jumps on fire	2	0.029	0.0078	0.0002262	2
X26 Flammable items (woven bag, etc.)	12	0.019	0.0469	0.0008911	9
X27 Pulverized coal accumulated for a long time	2	0.019	0.0078	0.0001482	1
X28 Illegal hot work	5	0.019	0.0195	0.0003705	4
X29 Other places cable-sparks	8	0.019	0.0313	0.0005947	6
X30 Firefighting facilities are not fully equipped	13	0.041	0.0508	0.0020828	21
X31 Insufficient extinguishing material	5	0.041	0.0195	0.0007995	8
X32 Fire-pipeline installation is not in place	4	0.041	0.0156	0.0006396	6
X33 Self-rescuers not compliant	11	0.041	0.0429	0.0017589	18
X34 Employees have poor self-rescue awareness and self-rescue ability	7	0.041	0.0273	0.0011193	11
X35 Does not have dedicated technicians	4	0.041	0.0156	0.0006396	6
X36 Monitoring equipment is damaged and not replaced in time	12	0.041	0.0469	0.0019229	19
X37 Insufficient emergency-rescue system	21	0.041	0.0820	0.003362	34

The calculation formula for the risk value is as follows:

$$R = P \times I \tag{3}$$

R—risk value of factor; P—likelihood of occurrence of factors l; I—severity of factors.

In order to make the final result meet the expectations of the evaluators, this research took the correction coefficient of the risk value as 10,000, that is, the risk value was multiplied by 10,000 to get the modified risk value, 3. It can be seen from Table 3 that the main high-risk factors are an insufficient emergency-rescue system, non-flame-retardant belts and surrounding flammables, insufficient firefighting facilities, and damaged monitoring equipment and the failure to replace it in time. The risk values are 34, 24, 21 and 19, respectively.

3.2. *Risk Assessment of Working Positions*

By determining the numerical value of risk factors involved in each working position and calculating the sum, the risk value of each working position is obtained. The risk level of each working position can be determined by developing a risk-assessment matrix, determining the risk rating standard, and combining the calculated risk value [18]. The construction of the risk matrix involves two important factors, which are the possibility and severity of accidents [19]. Combining the classification of production-safety accidents and the assignment rules of the LEC evaluation method, as well as the value range of risk possibility and severity of overlapping posts, this research divided the possibility and severity of factors into four levels. Based on the principles of comprehensiveness, objectivity and balance of data distribution in the risk matrix, a four-level risk-assessment matrix was established, as shown in Table 4, and the risk rating criteria were verified. Level I risk: $R \geq 120$; Level II risk: $40 \leq R < 120$; Level III risk: $10 \leq R < 40$; Level IV risk: $0 \leq R < 10$.

Table 4. Risk-Assessment Matrix.

Likelihood of factors	**0.5**	**50**	**30**	**10**	**2.5**
	2	**200**	**120**	**40**	**10**
	6	**600**	**360**	**120**	**30**
	10	**1000**	**500**	**200**	**50**
		100	**60**	**20**	**5**
		the severity of the factors			

3.2.1. Superposition Risk Analysis of Working Positions

In the process of coal-mine production, two or more risks commonly interact with each other in practical working positions, due to the superposition effect of risks, thus making the working-position risk of coal-mine fire greater than the primeval risk [20]. In the study of superimposed risks of chemical plants, the risk of hazard sources declines with the increase of the distance from the hazard source without constraints [18,21]. Researchers from this study believe that the risks of working positions are also affected by the superposition principle of the risks in the surrounding working positions. The superposition effect is determined by the size and distance of the risk value of the surrounding working positions. The extent of the influence of the superposition risk decreases with the increase in distance of the working positions. When reaching the influence radius, the superposition influence can be ignored.

Kernel Density Analysis

Kernel density analysis is a commonly used spatial analysis method in GIS analysis, which is used to intuitively reflect the spatial continuity and distribution of feature points in the region [22]. At the same time, the distribution of factors can be analyzed on the basis of their severity The kernel density function is as follows [23]:

$$f(x) = \frac{3}{h^2\pi}\sum_{i=1}^{n}(1-\frac{d_{ix}^2}{h^2})^2 \tag{4}$$

$f(x)$ is the density value at position x; i represents the sample point; h is the search radius; n is the number of sample points within the search radius; d_{ix} is the distance between point i and position x.

Based on the analysis using the kernel density function, a post-superposition risk model is built. The formula of the post superposition risk model is:

$$R_G = \sum_{i=1}^{n} R_{Gi}(1-\frac{d_{ix}^2}{h^2})^2 \tag{5}$$

R_G—the actual risk value of a position; i—the position point; h—the search radius; n—the number of jobs in the search radius; R_{Gi}—the original risk-value of post i; d_{ix}—the distance between the post, i, and the position, x.

The process of calculating the superimposed risk of job points is shown in Figure 4. Firstly, the working-position points are covered on the fenced research area. Each working-position point is covered with a risk curved suface, and the risk surface at the location of the point takes the highest value (risk value). Within the search radius of a working-position point, other position points are brought within this radius in the risk superposition model, and then the sum is calculated, to calculate the superposition risk of the position point.

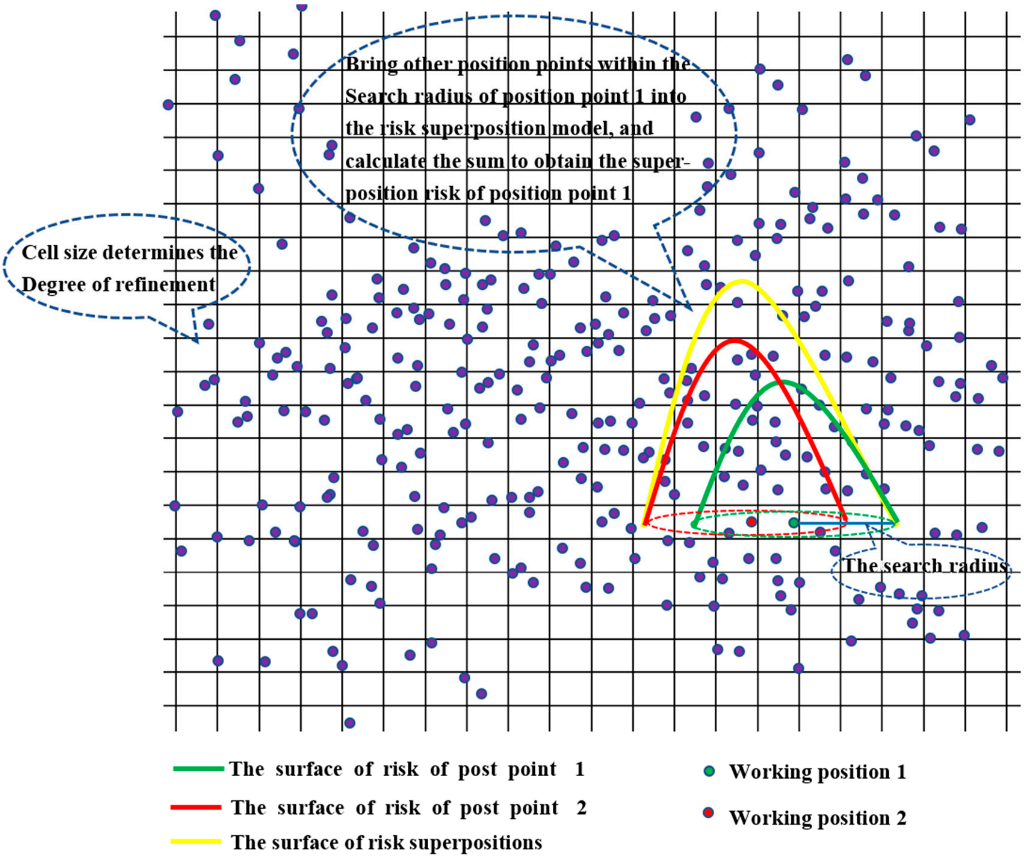

Figure 4. Schematic diagram of the post-overlay risk model.

Risk Assessment of Working Positions

The search radius and the primeval risk value of the working position are extremely important for the superimposed risk analysis The primeval risk value of the post is shown in Table 5: the search radius is determined, based on the size of the damage range of the coal-mine fire accidents; the article selects the flame-spread range within 20 min of the coal-mine fire as representing the search radius, that is, 100 m [24].

Table 5. Risk Value and Classification of Working Positions.

Serial Number	Working Positions	Value at Risk R_G'	Risk Level	Superimposed VaR R_G	Risk Level
1	Main coal miners	43	II	152	I
2	Filler	22	III	151	I
3	Sealer	28	III	150	I
4	Mining electrician	21	III	151	I
5	Coal cleaner	13	III	136	I
6	Excavation electrician	16	III	116	II
7	Blaster	31	III	117	II
8	Lane clearing	5	IV	116	II
9	Electrician	9	IV	16	III
10	Air-compressor driver, maintenance worker	17	III	27	III
11	Underground electrical maintenance worker	40	II	147	I
12	Miner's lamp and self-rescuer manager	27	III	77	II
13	Pyrotechnics manager	46	II	86	II
14	Mine-rescue worker	69	II	92	II
15	Pullback worker	16	III	16	III
16	Ventilator-facility worker	8	IV	141	I
17	Belt-conveyor driver, maintenance worker-1	43	II	78	II
18	Belt-conveyor driver, maintenance worker-2	43	II	147	I
19	Belt-conveyor driver, maintenance worker-3	43	II	59	II
20	Belt-conveyor driver, maintenance worker-4	43	II	117	II
21	Winch driver-1	46	II	81	II
22	Winch driver-2	46	II	145	I
23	Welder-1	20	III	84	II
24	Welder-2	20	III	143	I
25	Air-compressor driver, maintenance worker-1	17	III	79	II
26	Air-compressor driver, maintenance worker-2	17	III	27	III
27	Gas Extractor-1	33	III	57	II
28	Gas Extractor-2	33	III	65	II

Table 5. *Cont.*

Serial Number	Working Positions	Value at Risk R'_G	Risk Level	Superimposed VaR R_G	Risk Level
29	Monitoring Worker-1	28	III	139	I
30	Monitoring Worker-2	28	III	59	II
31	Monitoring Worker-3	28	III	90	II
32	Monitoring Worker-4	28	III	64	II
33	Monitoring Worker-5	28	III	117	II
34	Monitoring Worker-6	28	III	81	II
35	Damper worker-1	8	IV	16	III
36	Damper worker-2	8	IV	8	IV
37	Damper worker-3	8	IV	17	III
38	Damper worker-4	8	IV	43	II
39	Damper worker-5	8	IV	46	II
40	Damper worker-6	8	IV	8	IV

By using the kernel-density-analysis function of the ArcGIS software, the post-superimposed risk was simulated and the results calculated by researchers to obtain the risk-distribution map of the working positions. Based on the established risk-grading standard, the post-superimposed risk was graded. The original risk, superimposed risk and risk level of the post are shown in Table 5, and the distribution map of the working positions of the coal-seam fire accident is shown in Figure 5.

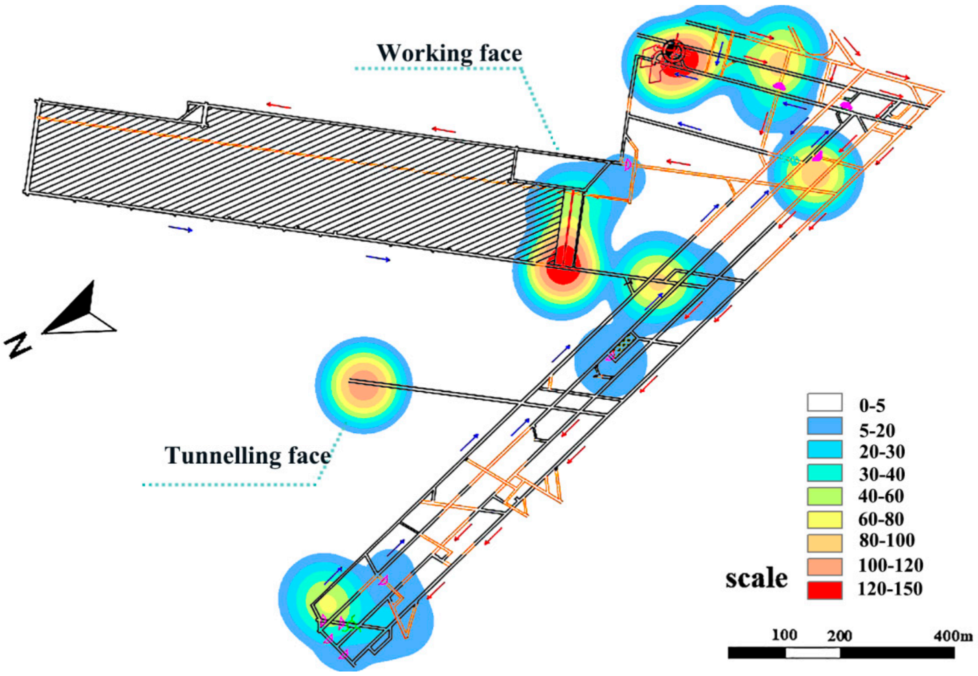

Figure 5. Distribution map of risks of working positions in coal-seam fire accidents.

The result analysis shows that after risk superposition, the risk- and grade-distribution are more obvious, and the difference is increased. The risk range increased from 64 to 144, with an increase of 2.3 times. Superposition risks have a greater impact on the densely distributed positions. For instance, for the fully mechanized mining team, the risk related to the mining electrician increased from 21 to 151. At the same time, it can be seen that the risk level of each working position was below Level I before the risk superposition. However, the number of Level I posts increased to 11 after the superposition, including all relevant working positions on the fully mechanized mining team, the underground-electrical-maintenance workers on the mechanical and electrical transport-team, the winch drivers located in the return-air roadway, the welders at the shaft, and those working on the construction of ventilators in the ventilation team, the monitoring workers located in the shaft, and the sealing workers located in the goaf, which implies that these workers are the priority control-posts for preventing mine fire-accidents. At the same time, it can be seen that the risk rating of the blasters, electricians, lane cleaners and nearby monitoring and monitoring workers of the comprehensive excavation team approach Level I, and belong to the Level II control-posts.

The risk-distribution map of fire-risk accidents is shown in Figure 5. The depth of color reflects the size of the regional risk value: the more intensive the position, the greater the risk-impact range, which shows directly the specific distribution of post-personnel risk. We can see intuitively that the stations with risks greater than 100, that is, the level 1 stations, are at the coal-mining face, the shaft and the tunneling face. Among them, the posts at the coal-mining face and the tunneling face are densely distributed, and are prone to fire, due to mining, maintenance, stress and other reasons, and the risk value is high; There are many posts involved in the shaft, which has a great impact on ventilation. The consequences of fire are extremely serious, and the risk value is high. The inlet and return airways involve ventilation workers, winch drivers, tape-conveyor drivers and other positions, and the risk value is more than 80. In the actual coal-mine-production process, these areas are also coal mine fire-prone areas.

4. Discussion

In this research, through the establishment of the coal-mine fire-post-superposition-risk model, the coal-mine fire-accident risk in China is effectively assessed qualitatively and quantitatively. Compared with traditional superposition-risk studies into integrated "human–machine-environment-management" factors, this research mainly focused on 24 working positions related to coal-seam fires, and analyzed the superposition risks among them. The research results show that after risk superposition, the assessment was more organized, and the proportion of Level I, II, III and IV posts changed from 0%, 25%, 52.5% and 22.5%, to 27.5%, 52.5%, 15% and 5% respectively. This is in line with the practical application in the coal-mine production process, to a large extent. In addition, through the assessment of post-superposition risks, key management objects can be determined for safety management, forming management priorities. Therefore, compared with Level II and III, the risks of Level I jobs need more attention. The assessment results were combined with ArcGIS software functions to visualize job risk, which is particularly conducive to the hierarchical management and control of coal-mine job risks and the correct management of risk in the coal-mine-production process. In the cases especially of the jobs with a higher risk-level, such as the 11 Level-1-risk jobs among the comprehensive mining team, the mechanical- and electrical-transport team and the ventilation team, measures should be taken to construct vivid warning signs and alarm devices, emergency measures should be provided for the field site, and the hidden-danger investigation should be continuously intensified, to ensure that the risk could be effectively controllable.

5. Conclusions

In order to enhance the correctness of the risk assessment of coal-mine fire positions and optimize the classification management of operational positions, this research proposes a superposition-risk-model of positions, combining the structural importance in fault-tree analysis (FTA) and the kernel-density-analysis (KDE) method in ArcGIS software to study the superposition risk of coal-mine fire positions. The main findings can be summarized as follows:

(1) Based on 100 coal-mine fire-accident cases and enterprise post standards, 37 risk factors and 24 important operation posts were recognized, and the risk factors related to each post were obtained. The results show that the types of posts prone to coal-mine fire accidents mainly existed in the comprehensive mining team, the comprehensive excavation team, the mechanical- and electrical-transport team, the ventilation team and the safety-supervision department. Among them, the main coal miners in the comprehensive mining team and the underground-electrical-maintenance workers in the electromechanical-transport team have the most factors, followed by the filling workers in the comprehensive mechanized-mining team, the blasting workers in the comprehensive mining team and the electric welders in the electromechanical-transport team.

(2) Based on the statistical methods of analysis of the cases and the accident-tree-structure-importance analysis method, the likelihood and severity of the accidents were verified. Based on the system-engineering algorithm, the risk values of the factors were derived, and based on the summation-calculation method, the risk-calculation model of each position was established. In addition, the risk-assessment matrix were established, the risk-level-division standard was determined, and the working-position risk level was divided up for this research. The results showed that nearly 80% of risk levels of working positions were focused on Level II and III before risk superposition.

(3) In accordance with the analysis of the kernel density estimation (KDE) in ArcGIS software, the superimposed-risk and post-risk distribution map of coal mine fire posts was obtained. The results indicated that, after risk superposition, there is a greater difference among post risks, the range of risk value increased by 2.3 times, and the number of Level-I risk posts reached 11. Through the visual display of the risk-distribution map showing the post-risk of a coal-mine fire, it is concluded that the mining face, mining face and shaft had the higher level of risk.

(4) The priority of post-risk management is divided, in accordance with the risk level of post superposition: the 11 Level-I risk posts are key management posts in the prevention of coal-mine fire accidents. In addition to daily safety management, risk control and management should also be carried out looking at the factors of alarm devices, emergency measures, etc.

The superposition-risk-analysis result of the coal-mine fire post is consistent with the real safety-production risk in the coal mine. Results of this research provide a theoretical basis for the classification management of coal-seam fires. In conjunction with this study, adjusting the risk factors according to the actual situation of specific coal mines in China and applying the superimposed-risk model to practical applications, is the next research focus.

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