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MINE SAFETY MANAGEMENT AND CONTROL COUNTERMEASURES ON THE BASIS OF RISK ASSESSMENT

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Abstract: Based on modern intelligent concepts, smart mines deeply integrate technologies such as the Internet of Things (IoT), big data, artificial intelligence (AI), robotics, intelligent equipment, and 5G into modern coal development and utilization, creating an intelligent system with comprehensive perception, real-time connectivity, autonomous learning, dynamic prediction, and collaborative control. The intelligentization of mine production safety has become a core technological support for the high-quality development of the industry. This paper addresses the technological needs of smart mines, utilizes digital twin technology to achieve interconnectivity and intelligent application of mine management, and improves the overall effectiveness of the safety management system, risk assessment and control, accident analysis and prevention, and other fields. Based on digital twin and 5G technology, the company puts forward the concept of "prevention-oriented" safety management and formulates systematic solutions to effectively reduce the incidence of accidents. Combining Monte Carlo simulation, gray correlation analysis, GIS and remote sensing technology and other methods, it builds an innovative intelligent mine risk management system and proposes key technical paths to achieve high-quality development, including information network architecture, safety production control mode, intelligent decision-making and situational analysis mode. At the same time, the important role of management and personnel subsystems in mine safety risk management is emphasized to improve productivity and safety. Finally, the article puts forward countermeasure suggestions to promote the high-quality development of smart mines, the mining industry is moving towards the direction of intelligence and wisdom, and gradually realize the less manned or unmanned production mode, laying a solid foundation for the future development of smart mines.
Keywords: Intelligent mine; Internet of things; Digital twin; Safety management system; Risk assessment and control; Accident analysis and prevention

1 INTRODUCTION

Energy security is the cornerstone of national security and stable development, mines have long played a crucial role in China's energy security, is the stabilizer of energy supply and ballast, mine production safety is a multi-level, comprehensive integrated system, from management to technology, culture to regulations, personnel to the environment and other aspects of the core elements together. With the rapid development of the Internet of Things, artificial intelligence and big data technology, the smart mine will be a high degree of integration of informationization, automation and intelligence, and its ultimate goal is to realize the unmanned or less manned key production links in the mine, so as to improve production efficiency and safety [1].

China's mine safety problems are analyzed from several dimensions, which are usually divided into three major categories: accident types, accident causes, and accident consequences. In recent years, as the safety situation in mines has become increasingly serious, scholars have conducted in-depth research in this field, focusing mainly on the "prevention-oriented" approach to propose systematic solutions to reduce the incidence of accidents. The following three scholars' researches jointly promote an integrated mine safety risk management system: the studies of Wu Yongguang and Wang Guohui [2,3] laid a scientific theoretical foundation and management framework for the construction of the system, focusing on risk identification, assessment, and the development of emergency response plans; while Liu Wenhua's study [4] introduced intelligent and efficient means through technological innovation, providing the system with technical support and guarantee.In summary, the prevention of mine safety has shifted from the traditional "post-rescue" approach to "precautionary measures." In the future, the combination of intelligent technology and scientific management means will help realize the continuous improvement of mine safety. At the same time, all parties should strengthen cooperation to promote the construction of mine safety culture, enhance the safety awareness and sense of responsibility of all employees, and create a safer and healthier working environment for the mining industry.

The traditional safety management model has the shortcoming of "focusing on post-disposal, light on pre-prevention", and there is an urgent need to realize the forward movement of prevention and control through systematic risk assessment. This paper focuses on the application of risk assessment and control in mine safety management by combining the research results at home and abroad in the past decade. According to the previous discussion, the research objectives of this paper can be summarized as follows: 1) The research focuses on improving mine safety management and the construction of comprehensive safety systems to ensure effective hazard prevention and control; 2) This study explores advanced risk assessment techniques and control methods to identify potential dangers and mitigate risks in mining operations; 3) Through detailed accident analysis, the study proposes effective prevention countermeasures to reduce the occurrence of mining accidents and enhance overall safety.

2 MINE SAFETY MANAGEMENT SYSTEM

2.1 Construction and Challenges of Mine Safety Management System

With the increasingly stringent national requirements for mine safety production, the construction of mine safety management system has become a top priority. This system covers the entire life cycle of mine safety production [5], including geological exploration, mine construction, mine rescue and safety management and other business areas, with a special emphasis on building 5G network + platform intelligent production scenarios, artificial intelligence[6], internet of things [7], digital twins [8], intelligent equipment [6,7], etc. t The development and integration of modern mining technologies play a crucial role in achieving intelligent operations across all stages of a mine's life cycle. This includes risk management, production, transportation, safety, environmental protection, energy efficiency, and business management. By fully utilizing these advancements, it is possible to significantly enhance coal mine safety, effectively prevent and address major safety risks, and reduce the occurrence of serious production and safety accidents. This approach is of great importance in ensuring safer and more sustainable mining operations. At the same time, mining enterprises must adhere to relevant laws and regulations(https://www.mem.gov.cn/fw/flfgbz/), including the Mine Safety Law, the Work Safety Law, the Labor Law of the People's Republic of China, and the Regulations on Mine Safety Supervision. Compliance with these legal frameworks is essential for protecting the lives and safety of miners, improving productivity, promoting the high-quality development of the industry, fostering social harmony and stability, and enhancing international competitiveness.

Despite some progress in mine safety management at home and abroad, many problems remain [9]. Domestically, the main problems are institutional fragmentation, inadequate safety culture, lagging technical facilities and local protectionism; while abroad, the challenges are limited risk assessment, insufficient regulatory enforcement and inadequate implementation of laws. Based on this, we need to establish a new type of safety management system to further improve and strengthen mine safety management at home and abroad, enhance the level of safety production, ensure the safety of miners' lives and promote the sustainable development of the mining industry [7].

2.2 Construction of a New Mine Safety Management System

In order to establish a new type of effective mine safety management system, this paper discusses the direction of safety production risk management in mining enterprises, focusing on analyzing the impact of various subsystems and safety inputs on overall safety management. Based on the dynamic reduction algorithm in rough set theory (RS), mine safety management is divided into five subsystems: personnel, material and equipment, technology, environment and management. On this basis, the comprehensive weights of each type of risk factors were calculated [9] and analyzed by combining the subjective and objective assignment method, the network analysis hierarchy method (AHP) [10] and the fuzzy comprehensive evaluation method [11]. The results of the study show that management and people subsystems have a significant impact in safety risk management in mining companies. Meanwhile, based on the resilience of the economic system, the difference between the target performance of the system and the interrupted performance is measured by reconfiguring the capacity of the subsystems to ensure that an acceptable growth path can be maintained in the long term in terms of production capacity, safety, and growth in wealth to further improve the overall economic performance of the enterprise.

Mine safety risk management is an important task to safeguard the health and safety of mine workers, especially in the whole life cycle of a mining enterprise, and the accident causation theory provides an important perspective to understand the mechanisms and causative factors of accidents. As the requirements for mine safety management become more stringent, risk management strategies are increasingly focused on addressing safety issues through preventive and protective measures. Using the fuzzy TOPSIS and PFVIKOR methods, mine safety risks can be divided into different levels, so as to build a dual prevention mechanism of risk classification and control and hidden danger investigation and management [11,12]. The establishment of a system dynamics (SD) model can effectively simulate the effect of safety risk management in mining enterprises under different safety input distributions, and help to formulate the optimal safety input program. The study again shows that the trend of mine safety improvement is most significant when safety funds are mainly invested in the management and personnel subsystems. This conclusion was simulated by Vensim PLE system dynamics software to analyze the interrelationships between factors within the system [13]. The study shows that the key influencing factors of the personnel subsystem, in order of importance, are: employee safety awareness, employee behavioral norms, employee technical level, managerial management level, physical and mental state of employees, and the basic quality of employees, which provide managers with a dynamic basis for safety risk management, and more comprehensively establish a mine safety management system.

However, this new safety risk system looks at the key system variables involved in the construction process and seeks to minimize the gap between the model and the actual mine while taking into account system integrity and applicability. Future research could further optimize the risk factors and associated data, and incorporate additional variables to refine the model. In addition to safety inputs, systematic objectives such as mine type and mining progress should be gradually incorporated into the research framework to improve the effectiveness and practicality of the mine safety management system. Through a series of exploration and research, the mine safety management system will gradually develop from a single safety input to a more comprehensive and integrated systematic management direction [12], helping mining enterprises to be more efficient and scientific in safety prevention and control in the face of a complex and changing safety risk environment.

3 RISK ASSESSMENT AND CONTROL

3.1 Risk Dynamic Evolution Model

In order to enhance the scientific, real-time and adaptability of mine safety management and promote the development of mine safety management in the direction of modernization and intelligence, it is crucial to establish a risk dynamic evolution model. The model can not only provide more accurate decision-making support for mining enterprises, reduce the incidence of accidents, optimize resource allocation, but also comprehensively improve the overall level of mine safety management. Combined with the actual situation of mines in China, the whole life cycle of a mine [5] can be divided into the exploration and construction stage, the mine production stage, the mine reconstruction and expansion stage and the waste treatment stage.

In order to construct a dynamic evaluation model of safety risk in mining enterprises, the system dynamics (SD) method is introduced. System dynamics is a tool for synthesizing and analyzing social and economic problems and was first introduced by Professor J.W. Forrester of the Massachusetts Institute of Technology [14]. The method combines qualitative and quantitative analysis, is based on complex feedback theory and computer simulation technology, and is widely used in the fields of risk assessment and policy optimization. Especially in mine safety production, safety input is a comprehensive manifestation of human, material and financial resources of mines, which directly affects the safety level of the system. Based on the perspective of the whole life cycle of the mine, the dynamic evaluation of the safety risk of the mining enterprise is carried out by the improved system dynamics method, as shown in Figure 1, which is capable of clearly describing the system boundaries, the key variables and the safety production goals, and revealing the interactions between subsystems and their action paths [15]. With the increasing improvement of data mining, data processing capabilities and computer simulation technology, the system dynamics provide more scientific and accurate decision support for mine safety management and further enhance the overall safety management level.

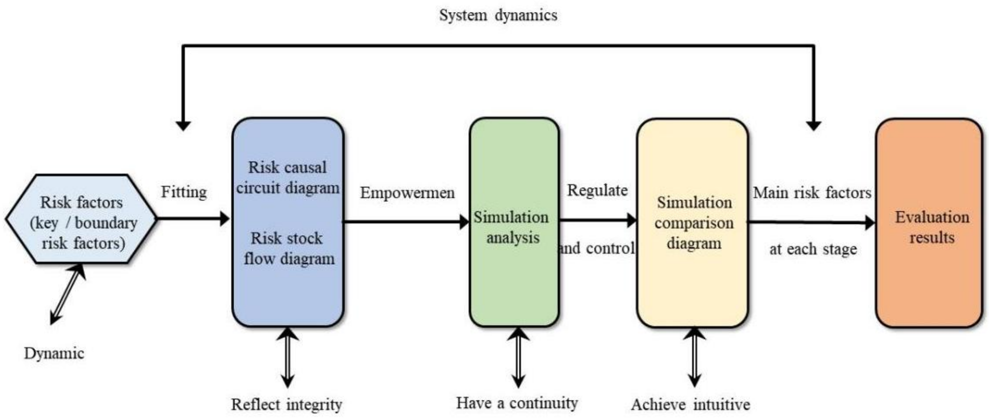

Figure 1 System Dynamics Flow Chart

As shown in Figure 1, by displaying the interrelationships and dynamic changes among the elements of the mining safety system, more targeted preventive measures and risk control strategies can be developed, ultimately optimizing the management of mine safety.

With the help of causal equations R_j , the system is divided into several subsystems P ,whose descriptive relations are expressed in the form[5]:

$$S=(P,R_j);P=\{P_i \mid i\in 1-5\} \tag{1}$$

In formula (1), S is the total system, P is the subsystem, and R_j is the relationship matrix used to describe the relationship between variables, which is generally an equation or a table function. In the SD model, the subsystem is composed of several fow level variables, velocity variables, time functions, and auxiliary variables. According to the characteristics of SD model, the following mathematical description is given [14]:

$$V=TR,\begin{bmatrix} R \\ A \end{bmatrix}=\begin{bmatrix} L \\ A \end{bmatrix} \tag{2}$$

In formula (2), T is the transfer matrix, V is the relationship matrix, L , R , and A are the level variable, fow rate variable, and auxiliary variable, respectively.

Based on formula (1–2), Vensim PLE is used to construct the system dynamic causality diagram of the fve subsystems of human–machine-technology-environment management of mining enterprises.

Currently, the State Administration of Work Safety (now part of the Ministry of Emergency Management) has introduced a series of new risk assessment indicators specifically for the mining industry, based on the current situation in the sector.

Table 1 New Indicators for Risk Assessment

Targets	Elements
Assessment of safety culture	Employee safety awareness, training and education, etc.
Equipment safety assessment	Level of automation, emergency equipment and facilities, etc.
Evaluation of risk control measures	Safety capital investment, safety technology measures, etc.
Social and Legal Risk Assessment	Compliance with laws and regulations, fulfillment of social responsibilities, etc.
Risk assessment of the work environment	Ventilation systems, geologic hazards, etc.
Risk assessment of operational processes	Operating procedures and standards, hazard identification, etc.

As shown in Table 1, these new indicators aim to more scientifically and accurately assess the various safety risks that may arise during the mining process, thus providing a more reliable basis for decision-making in mining safety management.

3.2 Innovations In Risk Assessment Methodologies

Mine safety production is a highly complex and dynamically changing system involving interactions between multiple risk factors. Traditional risk assessment methods usually focus on the analysis of a single factor, making it difficult to comprehensively reflect the complex interaction and feedback relationships between various parts of the system. This makes traditional methods often lack sufficient precision and comprehensiveness in identifying and addressing potential risks to mine safety production [3,13]. With the progress of science and technology, new assessment methods have emerged, gradually making up for the shortcomings of traditional methods. Modern risk assessment techniques can not only effectively identify and quantify potential risks in mine safety production, but also dynamically simulate and predict the evolution of risks. The following are some advanced assessment methods: fuzzy logic methods, artificial intelligence and machine learning [6], Monte Carlo simulation, geographic information system (GIS) and remote sensing technology, etc. These technologies not only improve the accuracy and efficiency of assessment, but also better predict and respond to unexpected risks in dynamic and complex environments, thus helping to improve the management of mine production safety, ensure the safety of miners' lives, and promote the sustainable development of society.

In recent years, Bayesian Network (BN) as a graphical model based on probabilistic inference, where each node represents a random variable and directed edges between nodes represent conditional dependencies between random variables. Using Bayes' theorem, the probability distribution of other unknown variables is inferred with partial information known [16]. With the unique advantages in dealing with uncertainty and complex causality, it has gradually become an important tool for mine safety risk assessment, effectively revealing the correlation between various types of factors in mine safety accidents, and providing more scientific and precise decision support for mine safety management. In mine safety risk assessment, Bayesian network can effectively capture the interrelationships between various types of risk factors in mines, and through probabilistic reasoning, Bayesian network can predict the safety status of the mine system, identify potential risks, and provide a basis for risk control and countermeasures [17]. Some scholars have proposed a Bayesian network model that integrates different risk factors of mines (geological conditions, equipment status and human errors) and applied it to mine risk management. The study validates the effectiveness of the method in the field of mine safety by analyzing data from a variety of mine safety accidents and shows that the method can provide a reliable basis for the assessment of mine safety risks. Similarly, Some researchers have proposed a mine safety risk assessment method based on Bayesian networks. By modeling multiple risk factors involved in mine safety management, a Bayesian network model was constructed so as to effectively assess potential safety risks and propose countermeasures to improve mine safety management [16]. By introducing the time factor, the dynamic Bayesian network can significantly improve the accuracy and predictive ability of mine safety assessment to better cope with the ever-changing mine operation environment [18]. These research results demonstrate the wide application of Bayesian networks in mine safety risk assessment and further promote the in-depth development of innovative Bayesian network-based approaches in the field of mine safety. By flexibly modeling complex causal relationships in mines and considering the effects of multiple factors, Bayesian networks provide more refined and comprehensive risk prediction and decision support for mine safety management.

3.3 Application of Intelligent Control Technology

Intelligent mine is based on the original digital construction, integration of perception technology, transmission technology and information processing and other advanced technologies and modern mining technology, so that the perception and monitoring of the mine can be realized. By doing so, people and people, people and things, things and things of a mine can be closely connected to the network. Through this network, the whole process of mine safety production and operation can be dynamically and comprehensively monitored and controlled, covering all aspects of mine development, extraction, transportation, safety management, production and operation, and ultimately realizing intelligent less manned or unmanned mine operation [19]. As a key technology to solve the problems of mine safety, management and efficiency, smart mine is a cutting-edge research field of multidisciplinary cross-fertilization with broad development potential.

Mining Internet of Things (IoT) technology realizes the intelligent connection of mining equipment and facilities, and can efficiently gather "human-machine-environment" sensory information. With the emergence of various mine big data platforms, it solves the problem of efficient management and storage of mine "human-machine-environment" sensory data. Through the virtual-reality fusion and knowledge generation mechanism, digital twin technology organically combines the existing mine mechanism model, empirical knowledge and mine "human-machine-environment" big data, which provides effective knowledge service for the state identification and intelligent cooperative control of the mine [1,14]. The mine digital twin model and its related intelligent data analysis algorithms will become a key technological breakthrough point for the future development of smart mines.

As a new generation of information technology dedicated to deconstructing, describing and cognizing the physical world, digital twin technology has become a new focus of global information technology development, directly serving key areas such as advanced manufacturing and energy industry in the national strategy of artificial intelligence. With the continuous innovation of information technology, the deep integration of smart mines with digital twin, 5G communication, cloud computing, big data, industrial Internet of Things (IoT), artificial intelligence (AI) and other technologies will provide an important technological support for the intelligent development of coal mines, realize the safe, green, efficient and intelligent mining of coal, and provide new ideas for the exploration of the sustainable development of smart mines [7,13,19]. By proposing the knowledge modeling method of physical entity, virtual space modeling and virtual-reality fusion interaction mechanism, it can effectively solve the problems of accurate control and disaster warning prevention and control in the process of mine production. Mine production scenarios are complex and variable, involving a variety of equipment and facing the coupling problem of the mining environment [8]. Combined with the digital twin five-dimensional model, the construction of a twin model for mine production data requires the integration of cross-domain knowledge, including the deep combination of theories and technologies such as mine operation mechanism, mine safety, CPS, big data analysis and automation control.

4 ACCIDENT ANALYSIS AND PREVENTION

4.1 Analyzing the Causes of Accidents

Accident-Causing Theory (Accident-Causing Theory) is to extract information from a large number of accidents, to analyze the variables and determine and diagnose the causes of accidents, to explore the pattern of events, and to provide a scientific and detailed basis for the prevention of accidents and the improvement of safety management work from the theoretical point of view. The common methods used in causal analysis research are game theory-TOPSIS method, hierarchical analysis (AHP) [10], gray system theory, and explanatory structural model (SIM) [20]. Human factors and the validity and reliability of safety science methods are important criteria for assessing their applicability to accident analysis, but these criteria often lack systematic evaluation. Therefore, the aim of this study is to compare two systematic accident analysis methods, the Accident Map Method (Accimap) and the System Theoretical Accident Model (STAMP), and analyze their performances in four aspects: procedure, level of detail, causal factors, and suggestions for improvement [5], and take the gas explosion accident in the coal mine of Daqing, Heilongjiang, China, as a case study to The validity and reliability of these two methods are discussed in depth. These systematic accident analysis (SAA) methods are based on socio-technical systems, control theory, and resilience engineering [12], and the validity and reliability of the results generated are often considered key criteria for judging their applicability. According to the China Coal Mine Safety Production Network (CMSPN) Accident Express and official data released by provincial coal mine safety supervision bureaus, roof accidents and transportation accidents occur more frequently and cause more fatalities, while the number of gas accidents is much lower than that of transportation accidents, but the number of fatalities is higher than that of transportation accidents, indicating that gas accidents are more dangerous. At present, roof accidents, transportation accidents and gas accidents are still the main causes of mine safety production accidents in China.

On May 23, 2021, a coal mine gas explosion occurred in Daqing City, Heilongjiang Province, China, at the Daqing Longfeng Coal Mine. A large amount of gas leaked from the mine and started a fire (https://www.chinamine-safety.gov.cn/). Investigations showed that about 20 miners were carrying out operations underground at the time of the incident, and that some mine leaders and safety managers failed to perform their duties of emergency warning and ventilation management when the gas explosion occurred, resulting in 24 deaths and 52 injuries. Gas build-up and inadequate ventilation systems were the main causes of the explosion. To this end, we use systems theory applied to accident causation models and identify a range of causal factors. In contrast to related studies such as Underwood and Waterson and Waterson, this study provides a systematic comparative analysis of the results and analytical procedures of four different studies on the same accident through quantitative and qualitative methods. Comparison of the causal factors showed that the reliability based on the STAMP approach (63%) was significantly higher than the Accimap approach (36%), but its validity was lower at 8%. In terms of recommendations for improvement, the STAMP analysis provides broader and covers multiple system levels, whereas the Accimap analysis focuses more on recommendations related to the system as a whole [20]. These findings suggest that the use of more structured analytical methods such as STAMP can help to reveal the nonlinear and coupling relationships in major accidents, and thus have important theoretical significance and practical value for the prevention and control of major accidents in coal mines.

4.2 Measures for the Prevention of Accidents

Preventive measures for mine safety accidents are crucial, not only to maximize the safety of miners' lives, but also to work to reduce the occurrence of mine disasters and ensure the safety and stability of mine operations. Effective preventive measures can greatly reduce the risk of accidents, improve the safety of mine production, and create a safer working environment for miners. Below are some common and critical mine safety accident prevention measures:

1.In order to strengthen the new safety management system, it is necessary to improve the ventilation system and strictly implement the mine safety production responsibility system. Regular safety inspections and hidden dangers are carried out to identify potential risks and take effective preventive and control measures in a timely manner. In underground mining operations such as coal mines, it is necessary to ensure sufficient ventilation to prevent the accumulation of gas and other harmful gases, so as to avoid the occurrence of explosions and other major safety accidents, and at the same time, it is necessary to strengthen the safety training of miners and the construction of a safety culture [21], the miners are the first line of defense for mine safety, so they should be organized regularly to carry out safety training, to improve their safety awareness and emergency response capabilities, and to create a safe, healthy and positive working atmosphere, and encourage employees to take the initiative to participate in safety management.

2.A risk matrix (high risk, medium risk, low risk) is used for hierarchical management based on a comprehensive assessment of the probability and consequences of risks, and appropriate control measures are taken based on the results of the assessment, prioritizing high-risk areas to ensure safe production. At the same time, detailed emergency plans for mining disasters are formulated and emergency drills are organized regularly [13] to ensure that mine staff can react quickly and take effective rescue measures when disasters occur.

3.Scientific geological investigation is carried out to assess the stability of the mine, especially during the extraction process, to ensure the structural safety of the mine and prevent the occurrence of geological disasters such as landslides and landslides. At the same time, the introduction and application of advanced safety technology equipment, such as gas monitoring instruments, explosion-proof equipment and automated control systems [22], real-time monitoring of environmental changes in the mine through technical means, timely warning of potential dangers, to ensure that mining operations are carried out safely.

5 CONCLUSIONS AND OUTLOOK

Aiming at the model construction of smart mines, mine production safety problems and solutions, this paper analyzes the current status of smart mine research and development, and points out that digital twin technology is the inevitable trend of the future evolution of smart mine technology. From the perspective of system architecture, smart mines need to realize their optimization and enhancement by deriving and constructing physical entities and smart twin digital bodies. On the basis of applying the actual needs, this paper discusses how to solve the key objectives of safety management system, risk assessment and control, and accident analysis and prevention in the process of realizing smart mine technology. Based on the current research status and existing gaps, this paper puts forward the following suggestions: 1) the establishment of an intelligent control system based on dynamic risk assessment as the core guarantee of mine safety, 2) increasing R&D investment in cutting-edge technologies, such as AI and digital twin, to promote technological innovation and application, and 3) the application of deep learning in mine risk assessment and accident prediction, to further improve mine safety management's Intelligent level. In the future, the mine safety management system will make more significant progress with the help of intelligent, digital and automation technology, which is no longer limited to static monitoring and after-the-fact response, but will be transformed to dynamic, real-time intelligent management. Through big data analytics, IoT, digital twins and other means, risk prediction and control in mines will be more accurate, and accident prevention and emergency response will be more efficient. With the in-depth promotion of safety culture and the continuous improvement of industry standardization, the overall safety management level of mines is expected to be steadily improved and the frequency of accidents gradually reduced, creating a safer working environment for miners. Overall, the core development direction of mine safety management in the future should focus on intelligent, data-based management methods, while strengthening the cultivation of safety awareness of the whole staff and cultural construction, so as to realize the transformation from post-response to forward-looking prevention.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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