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Original Research

Resilience Assessment and Technological Innovation-Driven Pathway Analysis for Coal Mine Environment Safety Risks

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Abstract

To deeply explore the risk factors and evolution paths contained in coal mine accidents and promote the transformation and upgrading as well as high-quality development of the coal industry, this paper adopts text mining and safety risk topic modeling to subdivide the safety risk system of coal mining enterprises into five subsystems: human resource allocation, establishment of scientific research and innovation platforms, technological innovation, policy support, and enterprise system construction. The network analytic hierarchy process and CRITIC weighting method are applied to calculate the comprehensive weights of each risk factor. Taking a certain coal mine in Qinghai as the research object, the system dynamics model is used to construct the causal loop diagram and stock-flow diagram of the safety risk resilience system of coal mining enterprises, and to simulate and analyze the impact of each risk factor on the overall safety risk resilience level of the case coal mine. The key technological innovation factor parameters are regulated to analyze the sensitivity changes of the safety production rate and safety risk resilience level of coal mining enterprises under different scenarios. The results show that: (1) The technological innovation and human resource allocation subsystems have the greatest impact on the safety risk resilience of coal mining enterprises, followed by the enterprise system construction, scientific research and innovation platform establishment, and policy support subsystems. (2) Increasing investment in safety, such as talent cultivation and technological innovation, can enhance the safety risk resilience level and shorten the time required to reach the expected safety value. Conversely, it will reduce the safety risk resilience level and delay the time to reach the expected safety value. (3) Further simulation and evaluation of the technological innovation subsystem reveal that the factors influencing the safety risk resilience of coal mining enterprises in order are construction survey and monitoring, support structure, construction design, mining plan, and engineering technology

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application. (4) The change trend of the conversion rate of technological innovation investment to engineering technology application and construction survey and monitoring is generally in a logistic "S" shape, mainly due to the time delay and lag of the benefits generated by safety investment.

Keywords: coal mine enterprises, environmental safety risks, resilience assessment, technological innovation, pathway analysis

Introduction

As the world's largest producer and consumer of coal, China has coal occupying an irreplaceable core position in its national economy and energy structure. Coal in China has the dual attributes of being a "stabilizer" and a "contradiction in transformation": it makes significant economic contributions and ensures energy security, but the environmental costs and policy constraints force the industry to transform towards high efficiency and cleanliness. In the future energy structure adjustment, the position of coal will shift from "absolute dominance" to "resilient support", playing a transitional role in the energy revolution. Against the backdrop of Chinese-style modernization, studying the safety risk resilience of coal mining enterprises and the path of technological empowerment is not only an urgent need to solve the safety problems of coal mines but also an important support for promoting the green transformation of the energy industry. During the Two Sessions in 2025, the government work report further emphasized the need to "effectively prevent and defuse risks in key areas and firmly hold the bottom line of not allowing systemic risks to occur". The 14th Five-Year Plan clearly requires that coal further play the role of a "stabilizer" and "ballast stone", and "resolutely curb major and extremely serious safety accidents and enhance the capacity for disaster prevention, mitigation, and relief". Therefore, coal mining enterprises must quickly identify various risk factors that affect their social and economic benefits and safety risk resilience levels, find production and operation management models suitable for their own development, and thereby enhance the overall social and economic benefits of coal mining enterprises. Based on this, this paper explores the influence paths and internal mechanisms of different driving factors on the safety risk resilience of coal mining enterprises from five safety investment dimensions: high-end talent cultivation in coal mining enterprises, creation of scientific research and innovation platforms, technological innovation, policy support, and enterprise system construction, with the aim of reducing the risk rate of coal mine accidents through technological innovation, minimizing casualties and economic losses, and scientifically and reasonably assisting in the timely achievement of the "dual carbon" goals.

Resilience was initially a concept in physics, used to describe the ability of an object or system to return to its original state after experiencing positional changes or shape alterations [1]. Later, Holling applied it to the field of ecology, defining resilience as the property that measures the persistence of internal relationships within a system, referring to the system's capacity to absorb changes and disturbances while maintaining the same internal population or state relationships before and after the disturbance [2]. Subsequently, it gradually expanded into fields such as psychology, engineering, economics, and sociology, undergoing an evolution from "engineering resilience–ecological resilience–social resilience". Scholars in various disciplines have shifted their research perspectives on resilience from emphasizing the system's recovery ability to its adaptability. In recent years, resilience has received extensive attention from scholars across different fields, and the definition of resilience has become a hot topic of discussion in the academic community. The most widely cited definition of resilience is that provided by Christopher, who considers resilience as the ability of a system to recover to its original state or transition to a new and more desirable state after being disturbed [3-5].

Safety Risk Resilience is a significant concept in the field of safety science, referring to the comprehensive attribute of a system to maintain or quickly restore to an acceptable safety state through the capabilities of absorption, adaptation, recovery, and optimization when facing internal and external risk shocks, and to enhance its own risk resistance capacity in the process. This concept integrates risk management and resilience theory, emphasizing the system's proactive adaptability and continuous improvement in a dynamic environment. Safety Risk Resilience differs from traditional passive risk management, characterized by dynamism, integrity, and synergy. Research on Safety Risk Resilience mainly focuses on urban fire and traffic [6-8], resilient city construction [9, 10], supply chain and industrial chain resilience construction [11, 12], ecological resilience evaluation of urban agglomerations [13], economic resilience [14, 15], etc. For example, Rajesh studied the technical capabilities that affect supply chain resilience from the perspective of enterprise technical capabilities and identified 11 capability factors that can enhance supply chain resilience, such as the ability to modify supply chain design and supply flexibility [16]. Schloten pointed out in a case study of the food processing industry that supply chain resilience increases with the enhancement of collaborative capabilities such as supply chain information sharing [17]. Rahim et al. explored the views of 47 practitioners in the chemical industry on enhancing risk resilience by combining process safety with process safety risk management. The research results show that the key driving factors for integration include strong leadership, the unification of social values, interdisciplinary training, and comprehensive risk assessment methods. Emerging technologies and regulatory coordination are also regarded as key factors promoting integration [18].

There are relatively few studies on the resilience of coal mine safety. Li et al. analyzed the hierarchical relationships among various influencing factors of miners' psychological resilience in coal mine safety production using the interpretive structural model. The most superficial factors were mainly concentrated at the individual level of miners; the middle-level factors were mainly concentrated at the work level; and the deepest-level factors were all concentrated at the organizational level. Organizational fairness, work pressure, self-efficacy, psychological safety education, and organizational support were the main influencing factors of miners' psychological resilience [19]. Chen and Yang summarized and refined 13 representative influencing factors of psychological resilience from three levels: individual, work, and enterprise management of coal miners. After argumentation, they finally selected 10 influencing factors as indicators for evaluating the psychological resilience of coal miners. Among them, work pressure, organizational fairness, organizational support, and the safety attitude of managers were the fundamental factors for enhancing psychological resilience [20]. Cui et al. explored the driving mechanism of the upward transmission effect of individual psychological resilience among miners on the psychological resilience of coal mine teams, mainly including two paths: emotional transmission and cognitive transmission, and there was a coordinating effect between the paths [21]. These studies mainly focus on how to enhance the psychological resilience of coal mine employees, and there are few papers on the resilience to environmental safety risks in coal mines. Therefore, we select the perspective of coal mine safety risk resilience to conduct in-depth research, explore the paths to enhance coal mine safety risk resilience from multiple influencing aspects, and actively respond to China's "intelligent mine" strategy.

In terms of resilience measurement, methods such as entropy weight-TOPSIS [22], fuzzy comprehensive evaluation [23, 24], and system dynamics [25, 26] are often used. Among them, the system dynamics method is suitable for the research on feedback mechanisms of nonlinear complex system problems and is widely applied in resilience measurement. Ekanayake used the system dynamics method to study the cumulative impact of vulnerability and capability on the resilience of the industrialized construction supply chain in Hong Kong [27]. Li used system dynamics to simulate the changes in the comprehensive resilience of Beijing from 2010 to 2025 [28]. Huang conducted a simulation analysis of the urban flood resilience of Nanjing under four different development scenarios by establishing a system dynamics model and identified key influencing factors through sensitivity analysis [29]. Zhang found, through the use of the progressive difference-in-differences model, that technology supply disruption can significantly enhance the resilience of listed companies by increasing R&D investment and promoting patent output [30]. He used a regression model to find that the application of industrial robots in manufacturing enterprises mainly affects the resilience of the industrial chain and supply chain through capital deepening effect, technological innovation effect, productivity effect, and enterprise digital transformation [31]. This paper combines text mining, security risk topic modeling, and system dynamics simulation to construct a full-chain analysis framework of "risk identification→weight quantification→dynamic evolution". By extracting risk topics from accident reports through text mining, it avoids the subjective bias of the traditional expert scoring method. It combines the ANP and CRITIC weighting methods, taking into account both subjective experience and objective data, to optimize the calculation accuracy of risk factor weights. It subdivides safety resilience into five subsystems and reveals their dynamic interaction mechanism through a system dynamics model. It quantifies key intervention nodes, aiming to provide clear priority action guidelines for enterprises and policymakers, guiding enterprises to focus on key links for optimization.

In research on safety risk management in coal mines, Yan established a comprehensive evaluation model of coal mine safety based on the entropy weight method and grey relational analysis; besides, the practical research was performed on four coal mines in Su County Mine Area, Huabei Mining Group [32]. Niu, based on the theory of disaster causation, deconstructed coal mine safety risk management into three standard links [33]. What's more, the risk management model of coal mine safety, which was integrated with "data perception–data analysis–data service", was built by focusing on coal mine risk factors and combining it with big data technology. By analyzing the advantages and disadvantages of hazard and operability analysis (HAZOP) and layers of protection analysis (LOPA), Zhang constructed the Bayesian model to complete the analysis and calculation of the BN model. This method was applied to coal mine gas explosion accidents [34].

From the perspective of research methodologies, conducting a sensitivity analysis on resilience is an essential step to enhance resilience. Prior studies on the mechanisms influencing resilience predominantly utilized qualitative methods to elucidate the static relationships between resilience and various factors, with limited exploration into the dynamic interactions among internal and external risk drivers within the resilience system of coal mine enterprises. Therefore, building upon existing research and adopting a multidisciplinary cross-theoretical approach, this paper identifies internal and external risk drivers affecting the resilience of coal mine safety risks through text mining and case accident analysis. By leveraging the systematic, dynamic, and nonlinear characteristics of system dynamics models, it constructs causal loop diagrams and stock-flow diagrams of the coal mine enterprise safety risk resilience system. The study conducts dynamic simulations and sensitivity analyses to model the impact of various risk factors on the overall safety risk resilience level of the case coal mine. It also adjusts the numerical values of key technological innovation factors to analyze sensitivity changes in the safety production rate and safety risk resilience under different scenarios, thereby clarifying the risk driver mechanism for enterprises. This aims to provide a more precise basis for risk assessment for the case coal mine enterprise and similar high-risk enterprises.

Materials and Methods

Analysis of Coal Mine Safety Risk Factors

By consulting the accident cases of the National Mine Safety and Supervision Bureau, over 80 cases of coal mine accidents and related accident investigation reports from January 2021 to January 2025 were collected, and text mining tools were used to analyze the relevant literature. According to the analysis, the main types of coal mine safety risk accidents include gas explosion, coal and gas outburst, fire, water inrush, CO poisoning, ground subsidence, roof fall, runaway vehicles, overturning, rock burst, etc. The main risk factors for coal mine accidents mainly include gas over-limit, outdated equipment and facilities, insufficient education and training, lax supervision, profit-driven, unauthorized and illegal production, inadequate supervision and management, failure to install safety monitoring and personnel location detection systems, evasion of supervision, chaotic safety management, and weak safety skills. Among them, improper operation, incorrect use, and violation of operating procedures are the key causes, followed by equipment aging, faults and defects, non-standard placement of warning signs, safety management loopholes, and insufficient emergency response to sudden incidents. Systematically classified, the risks and accidents are mainly caused by the incomplete sub-systems of multi-dimensional factors such as human resource allocation, establishment of scientific research and innovation platforms, technological innovation, policy support, and enterprise system construction.

This paper comprehensively applies the network analytic hierarchy process and the CRITIC weighting method to calculate the comprehensive weights of each risk factor. On the one hand, it makes use of the authority and expertise of experts to determine the weights more reasonably based on the actual problems of coal mine safety accidents. On the other hand, the CRITIC objective weighting method is employed to ensure that the decision-making and evaluation results have a strong mathematical theoretical basis, making the weights closer to objective facts while conforming to subjective intentions. Additionally, since safety investment is the total sum of human, material, and financial resources during coal mine safety production operations, the size of safety investment also directly affects the safety risk resilience level of the system.

System Dynamics Analysis Steps

System Dynamics (SD) was proposed by Professor J.W. Forrester of the Massachusetts Institute of Technology in 1956. It is an interdisciplinary comprehensive discipline for analyzing and studying information feedback systems and solving system problems. It is a computer system simulation method. At present, the idea of system dynamics modeling has been widely used in resource and environment carrying capacity [35, 36], supply chain optimization [37], system coupling [38], power distribution [39], coal mine safety [40, 41], and other fields. System dynamics finds the root of the problem in the internal structure of the system according to the feedback characteristics of the internal components of the system. Therefore, the system dynamics analysis steps can be summarized as follows: (1) Determine the system boundary by means of clear modeling purposes such as case analysis of coal mine safety accidents over the years, field investigation, and literature query; (2) Identify the causal relationship between various factors, determine the feedback loop and the stock-flow diagram, and establish the SD equation; (3) Determine the parameters of each variable, input the equation for simulation, and test whether the model passes. Through the scenario simulation and comparative analysis, the conclusion is drawn. If it does not pass, it will be fed back to the initial state and enter the next round of correction tests. Combining text mining, security risk topic modeling, and system dynamics simulation, a full-chain analysis framework of "risk identification→weight quantification→dynamic evolution" has been constructed. The visualized flow chart steps are shown in Fig. 1.

Basic Assumptions

This paper starts from the direction of safety risk resilience of coal mine enterprises and explores the impact of each subsystem and safety investment on the level of safety risk resilience of coal mine enterprises. According to the actual situation of the case coal mine enterprise, the following assumptions are made:

(1) Human resource allocation, scientific research and innovation platform creation, technological innovation, policy support, and enterprise system construction are taken as the endogenous variables of the safety production system of coal mine enterprises. Only the influence of the interaction of the internal factors of the system is considered, and the remaining factors are not considered as exogenous variables.

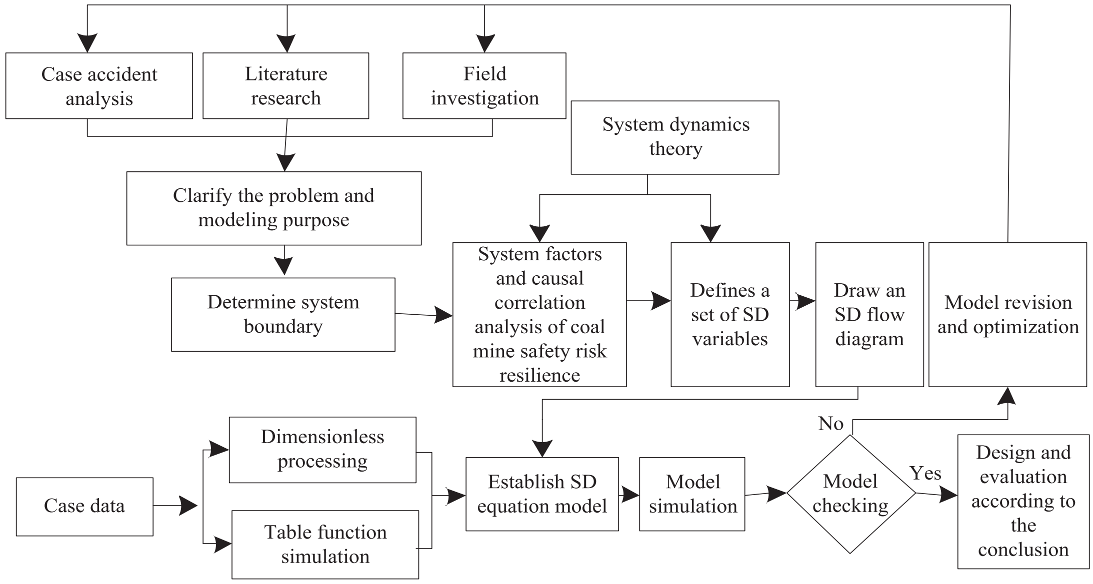

Fig. 1. System dynamics evaluation flow chart.

(2) Safety investment covers human, financial, material, and other inputs. Combined with the actual situation of the research, this paper only considers the safety capital investment, that is, the safety capital investment of the five subsystems of human resource allocation, scientific research and innovation platform creation, technological innovation, policy support, and enterprise system construction.

(3) Safety risk resilience has a certain control effect on the system, but it fails to completely eliminate the influence of other factors.

Construct System Dynamics Model

Causality Diagram

Coal mine safety risk resilience belongs to a dynamic and open risk system, with multiple input and output variables. There are dynamic characteristics such as mutual transmission, derivation, and complexity among variables. When a certain risk variable value increases, new risks may be derived, which will be transmitted to other risk factors or reduce the overall safety level of the system. According to the causal loop and accident causation theory, the unsafe behavior of people and the unsafe state of things are the key causes of risks. The insecurity of people and things is caused by the interaction and coupling of multi-dimensional aspects such as environmental factors and management factors. Therefore, the causal loop diagram of system dynamics is used to describe the complex dynamic correlation of the coal mine safety risk system. "+" indicates positive feedback and "-" indicates negative feedback.

In the causal loop diagram of coal mine safety risk resilience, the total level of coal mine safety risk resilience is taken as the horizontal variable, and the feedback loop of coal mine safety risk resilience is analyzed by Vensim software. According to SD theory, the level of safety risk resilience is more regulated by a negative feedback loop. For example, in the process of risk management and control, using the interactive transmission characteristics between variables in the system and increasing the investment in coal mine safety can improve the frequency of coal mine safety education and training, thus improving the business level and safety management awareness of operators, reducing the rate of personnel errors, and improving the safety behavior probability of personnel, so as to achieve the improvement of the overall level of coal mine safety risk resilience.

A system dynamics causality diagram was constructed for the five subsystems of coal mining enterprises, including human resource allocation, scientific research and innovation platform establishment, technological innovation, policy support, and enterprise system construction, as illustrated in Fig. 2.

SD Flow Stock Diagram of Mining Enterprises

Based on the causal feedback loop and research hypotheses, the flow and stock diagram of the safety risk resilience system for coal mining enterprises (Fig. 3) was constructed. Considering the principles of typicality, comprehensiveness, applicability, and operability of the evaluation indicators, this SD model selected a total of five level variables, five rate variables, fourteen auxiliary variables and fourteen table functions, twenty-six constants, and twenty-four main NYNAMO equations. In Fig. 3, B_1 is the proportion of human resource allocation input, B_2 is the proportion of scientific research and innovation platform construction input, B_3 is the proportion of technological innovation input, B_4 is the proportion of policy support input,

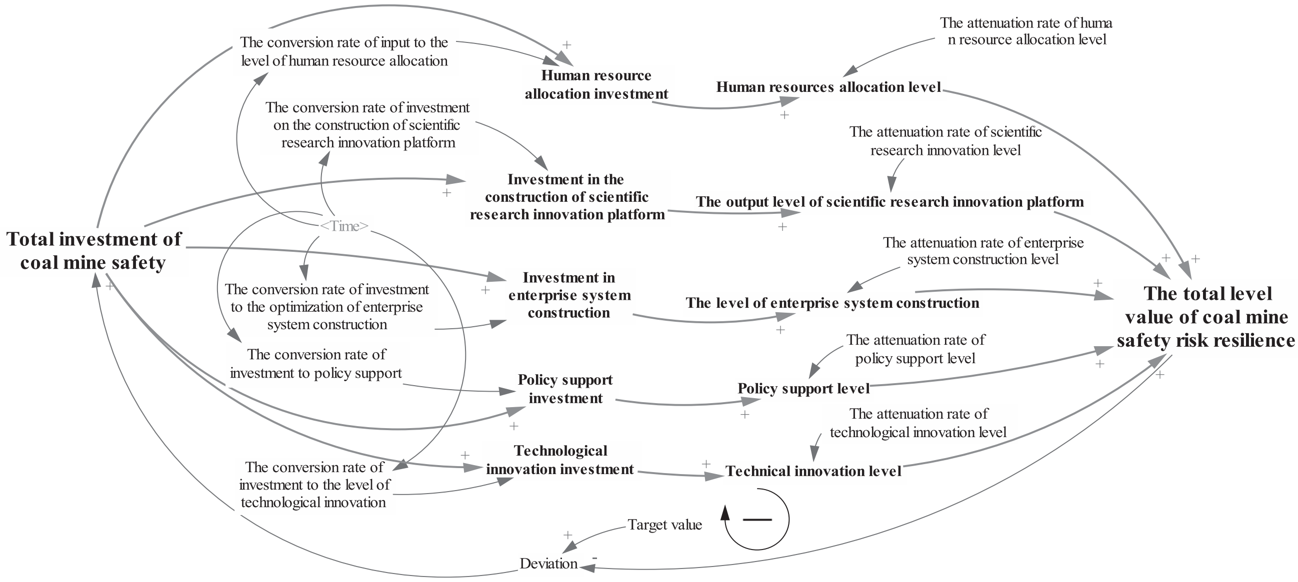

Fig. 2. Causality diagram.

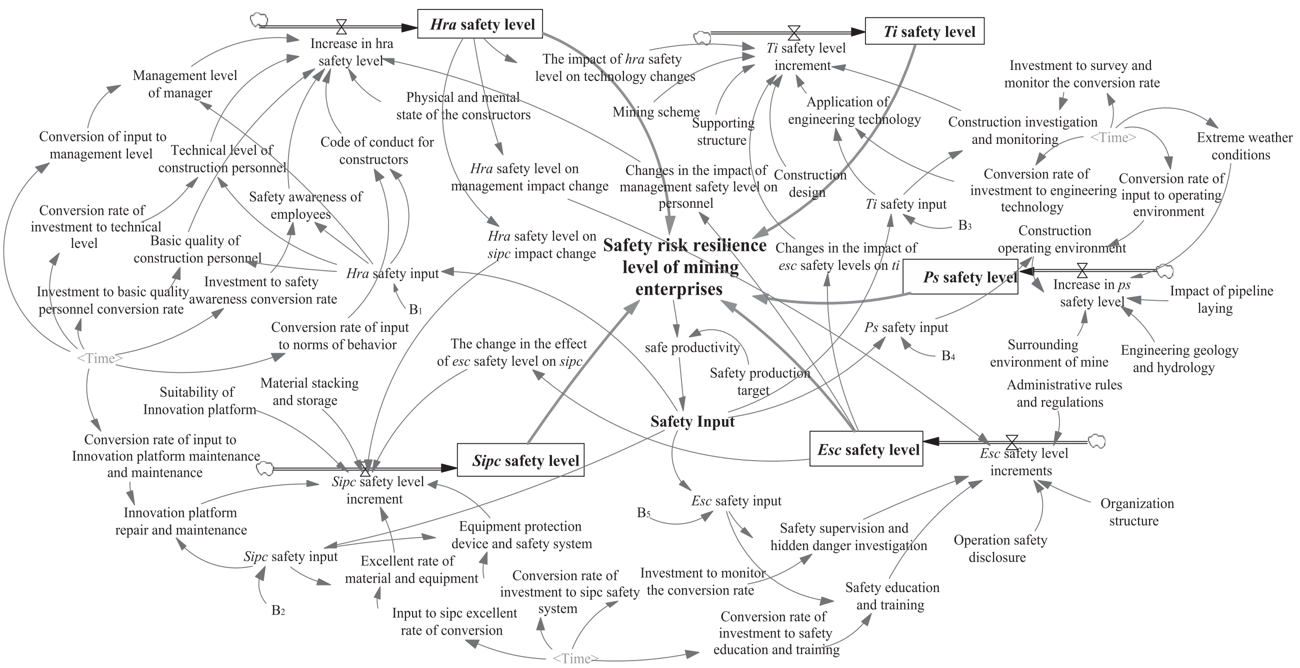

Fig. 3. Stock flow diagram.

and B_5 is the proportion of enterprise system construction input. Assuming that the construction period of a certain stage of coal mine production is twenty-four months, the model is set in units of months. Each variable can truly and objectively reflect the actual safety status of each subsystem, such as human resource allocation (*hra*), scientific innovation platform construction (*sipc*), technological innovation (*ti*), policy support (*ps*), and enterprise system construction of coal mining (*esc*), and accurately characterize the logical relationship and dynamic correlation between each indicator variable.

Based on the influencing factors of coal mine safety risk resilience and the stock flow diagram of system dynamics, the weight of each factor is selected as the variable coefficient, and the SD equation of the case coal mine safety risk resilience system dynamics model is established. The SD equation of the main variables is shown in Table 1.

Model Sensitivity Test

Sensitivity testing is the core part of system dynamics model validation, which is used to evaluate

Table 1. Main variables equation in the SD model.

Variable name	Design ideas
Technological innovation (ti) safety level	INTEG (*ti* safety level increment, 0.3)
Technological innovation (*ti*) safety level increment	The impact of *hra* safety level on *ti* changes+Mining plan*0.021 + Engineering technology application*0.019 + Supporting structure*0.024 + construction exploration and monitoring*0.027 + Construction design*0.018 + Changes in the impact of *esc* safety levels on *ti*
Safety productivity	Safety production target*Safety risk resilience level of mining enterprises
Safety risk resilience level of mining enterprises	*hra**0.286 + *sipc**0.145 + *ti**0.109 + *ps**0.083 + *esc**0.377
Safety input	With Lookup (Time, ([(0,0)-(1,10)],(0,0),(0.2,2),(0.4,5),(0.6,8),(0.8,9),(1,10)))
Technological innovation (*ti*) safety input	Safety input*B_3 (B_3 is the investment proportion for *ti*)
Changes in the impact of *esc* safety levels on *ti*	*esc* safety level*0.18

Table 2. Control parameters and schemes.

Programme	*hra* safety level	*sipc* safety level	*ti* safety level	*ps* safety level	*esc* safety level
Original scheme	0.25	0.2	0.2	0.1	0.25
Scheme1	0.325	0.2	0.2	0.1	0.25
Scheme2	0.25	0.26	0.2	0.1	0.25
Scheme3	0.25	0.2	0.26	0.1	0.25
Scheme4	0.25	0.2	0.2	0.13	0.25
Scheme5	0.25	0.2	0.2	0.1	0.325

the sensitivity of the model output to changes in input parameters, equation structure, or initial conditions [42]. The purpose of the sensitivity test is mainly reflected in three aspects: first, identify the key parameters: determine which parameters have the greatest impact on the model results; Second, verify the robustness of the model: verify the stability of the model under parameter fluctuations; Thirdly, optimize the model structure: find redundant or overly sensitive equations and improve the model reliability. In this paper, single-factor sensitivity analysis is used to verify the rationality of the model. Only one parameter is changed each time (other parameters are fixed), and the changes in the output results are observed, which is convenient to quickly locate the key variables. The control scheme is shown in Table 2.

Vensim software was used to regulate and control the parameters and impact factors of different schemes in Table 2 one by one. The simulation results of safety productivity under the six schemes before and after parameter changes were compared and observed, as shown in Fig. 4. The effect was optimized compared with the original model in terms of amplitude. The overall model is still running smoothly, and the evolution trend is similar before and after. It can be seen that the safety risk resilience system of the coal mine enterprise has passed the parameter sensitivity test. This model can reflect the actual situation of each sub-system of coal mine enterprises and can also be used to simulate the development trend of the safety risk resilience level of coal mine enterprises.

Results

Coal Mine Safety Risk Resilience Simulation Results Analysis

This paper selects a certain coal mine in Qinghai as the research object. Through data statistical analysis, the corresponding parameters are brought into the system dynamics equation. After simulation, the changing trend of the safety risk resilience level of the coal mine enterprise can be obtained, as shown in Fig. 5. Within the research period, the safety risk resilience level of the coal mine enterprise roughly experienced an initial slow growth, a mid-term accelerated growth, and a late-term decelerated saturation development trend with the increase of safety investment, which describes the dynamic equilibrium process under limited resources. This is in line with the actual changing trend of the limited growth of the coal mine enterprise, indicating that the model is relatively reliable.

During the daily mining process of the case coal mine, with the safety investment accompanying the risk management at the construction site, the safety

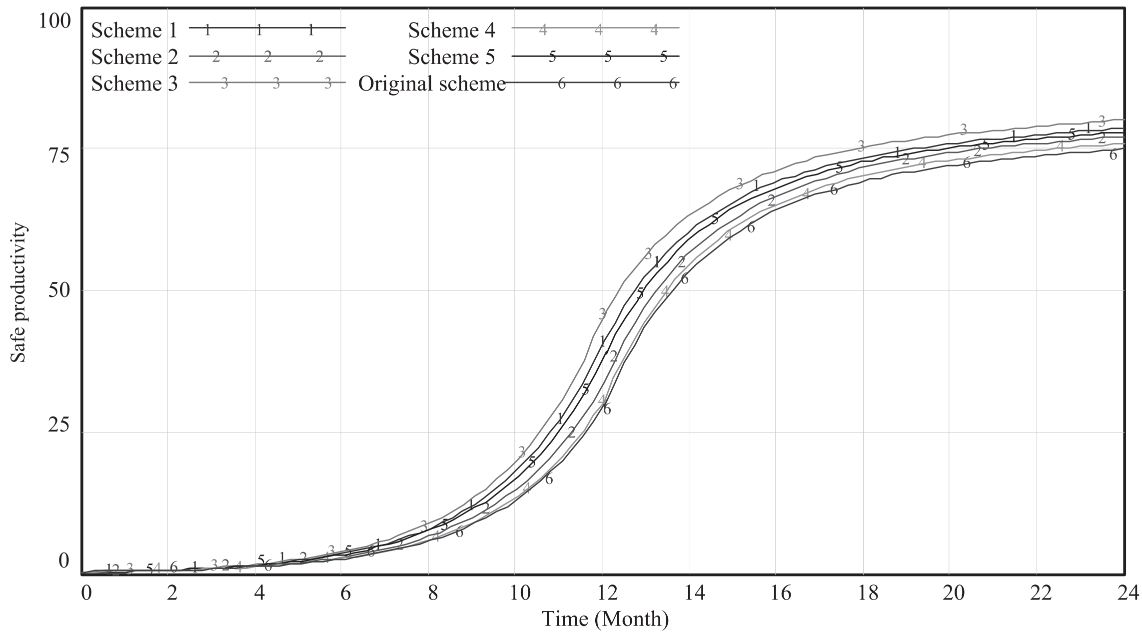

Fig. 4. Model sensitivity test.

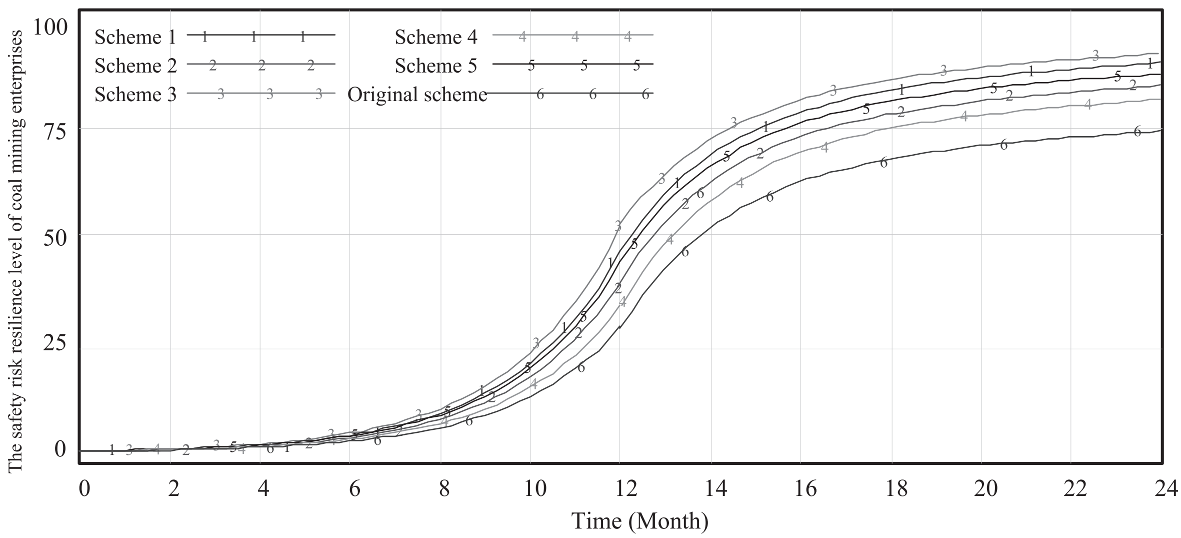

Fig. 5. The change trend of mine safety risk resilience level under each scheme.

risk resilience level of the coal mine enterprise initially grows at a relatively slow pace. This indicates that the technical empowerment, application of results, economic or social benefits generated by safety investment have certain time delays and lags, such as underutilization of resources. After reaching a certain threshold, the growth rate reaches its peak (near the inflection point). As it approaches the environmental carrying capacity limit (saturation value) of the coal mine enterprise, the growth rate gradually decreases and eventually stabilizes. This also reflects the feedback relationship between the safety risk resilience level of the coal mine and safety investment, and safety investment is a long-term investment process. During this period, it is necessary to continuously optimize and adjust the allocation of various resources to achieve high-quality development of coal mine safety resilience in the reality of limited growth.

According to the regulation scheme in Table 2, the safety level change values of the five subsystems of human resource allocation, scientific research and innovation platform establishment, technological innovation, policy support, and enterprise system construction were regulated one by one. The initial values of each subsystem were increased by 30%. Observing the change trend in Fig. 5 and Fig. 6, it can be seen that the safety risk resilience level change trends of the technological innovation and human resource allocation subsystems are relatively significant, the change of the enterprise system construction subsystem

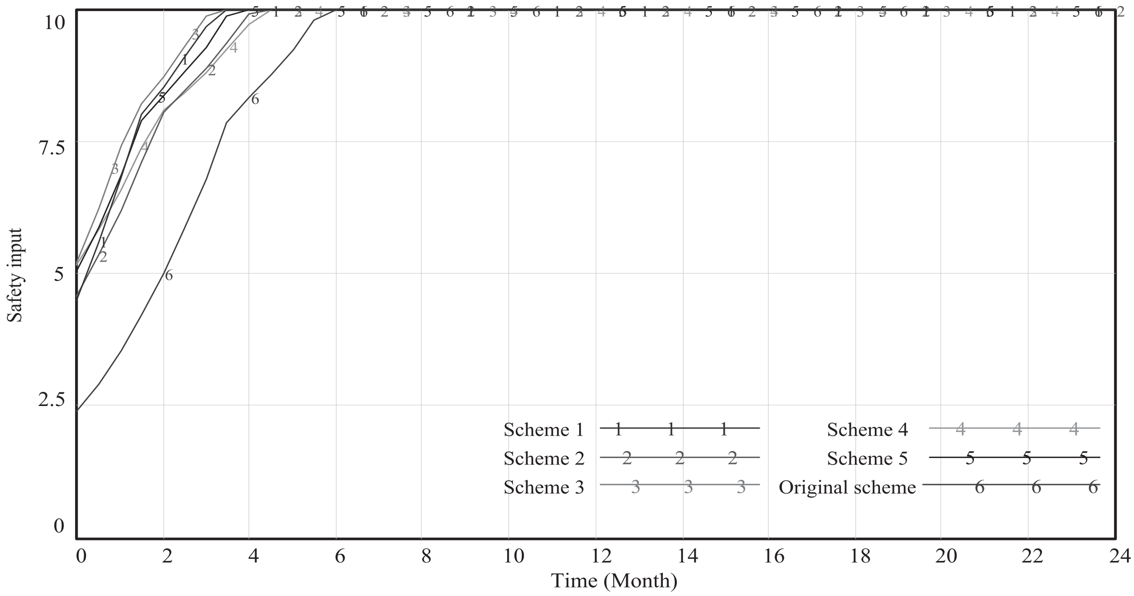

Fig. 6. The change trend of safety input under each scheme.

is moderate, and the changes of the scientific research and innovation platform establishment and policy support subsystems are relatively slow.

By choosing Table Time, the rate of change for each subsystem was calculated. The average value of each group was subtracted from the average value of the Scheme and then divided by the average value of each group to obtain the corresponding rate of change. The safety risk resilience change rates of the five subsystems, namely human resource allocation, scientific research and innovation platform establishment, technological innovation, policy support, and enterprise system construction, were 45.25%, 27.68%, 48.08%, 17.32%, and 36.16%, respectively. Ultimately, the degree of influence of the five subsystems on the safety risk resilience level of coal mining enterprises was determined to be technological innovation, human resource allocation, enterprise system construction, scientific research and innovation platform establishment, and policy support in sequence.

Technological Innovation (*ti*) Subsystem Simulation Results Analysis

The "14th Five-Year Plan for Scientific and Technological Innovation in the Energy Field" points out that, focusing on major demands such as green and intelligent coal mining, major disaster prevention and control, and multi-quality and multi-level conversion, as well as pollutant control, a technology system for the green, intelligent, and efficient development and utilization of coal should be formed. As one of the main energy sources in China, in the process of transforming from "Made in China" to "Intelligently Made in China", the coal mining field has been constantly emphasizing technological innovation, fully applying various intelligent technologies to improve the quality of coal mining and enhance China's economic and social benefits. Therefore, this paper extracts the technological innovation subsystem for simulation and emulation again, deeply analyzes the reasons for the fluctuation of the technological innovation subsystem, and conducts a causal tracking analysis of the technological innovation subsystem.

Causality Diagram of the Technological Innovation Subsystem

The technological innovation risk factors of safety production in mining enterprises mainly refer to the unsafe factors caused in the process of mining design, construction, exploration, and monitoring. The technological innovation subsystem is not only affected by its own system, but also by the interference of other risk system factors. The causal feedback loop of the technological innovation risk subsystem is shown in Fig. 7.

Fig. 7 and Fig. 8 show the Causes Tree and Uses Tree of the technological innovation risk. The Causes Tree shows that technological innovation risk is not only affected by its own system factors, but also by other subsystems such as environment and personnel. The Uses Tree shows that when technological innovation risks lead to accidents, compensation strategies should be adopted according to the results.

Causal Tracing Analysis

According to Fig. 9, the causal tracing analysis results (a) of the mine technological innovation subsystem safety level show that the increment in the technological innovation safety level has a great impact on the technological innovation safety level, and it is found that the increment in the technological innovation safety level

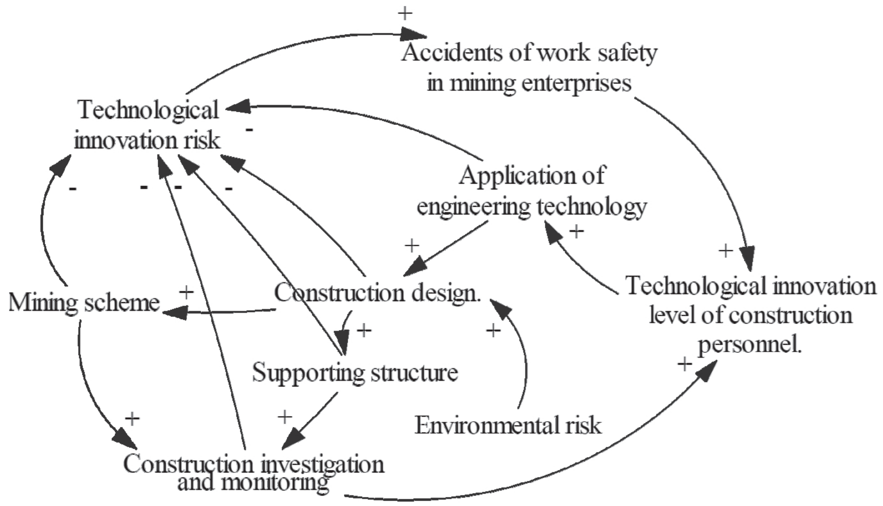

Fig. 7. Causality diagram of technological innovation subsystem.

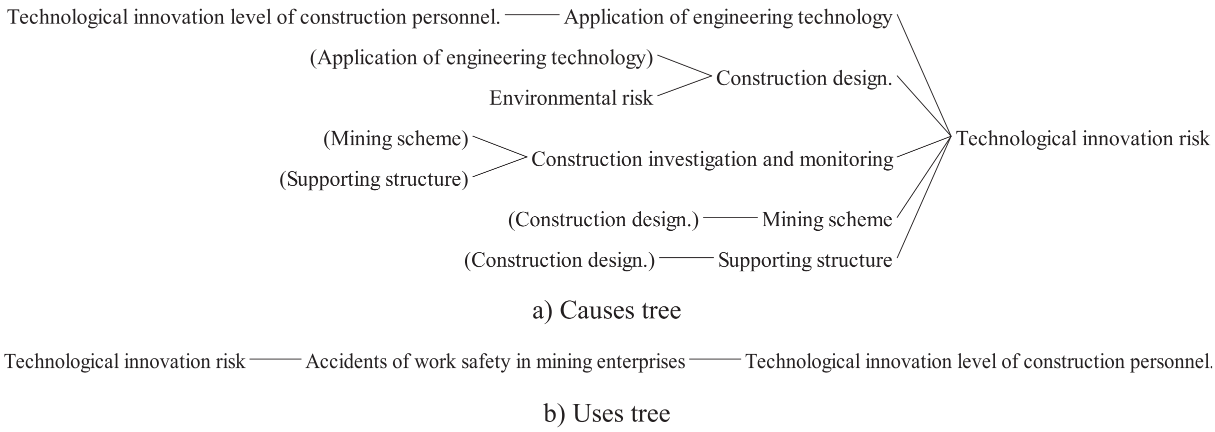

Fig. 8. Technological innovation subsystem cause and effect trees.

has an overall upward trend. Then, the causal tracing of the technological innovation safety level increment (b) shows that the engineering technology application and construction exploration and monitoring have a great impact on the fluctuation of the technological innovation level increment. Further causal tracing is carried out for engineering technology application (c) and construction exploration and monitoring (d), and it is concluded that engineering technology application is mainly affected by the input on the conversion rate of engineering technology and technological innovation safety input, and construction exploration and monitoring is mainly affected by the input on the conversion rate of construction exploration and monitoring and technical safety input. It is found from Fig. 9c) and d) that the change trend of the conversion rate of the input to the engineering technology application and construction exploration and monitoring is in a "W"-shaped development state of decline-rise-slow-decline-slow rise. The main reason is that the benefits generated by the safety input have a certain time delay and lag, resulting in a reverse change relationship between the safety input and the conversion efficiency at the initial stage, but this relationship will not last for a long time. In the later stage, with the increase in the maturity of relevant intelligent technologies and the improvement of the operation level of construction technicians, the conversion rate of technological innovation input will gradually increase to a stable state.

Determination of Parameter Value and Equation

According to the risk factor value of the technological innovation subsystem calculated in the previous article, the key technological innovation factors are further adjusted, and the changes in the safety level of the technological innovation subsystem are simulated. The assignment is shown in Table 3.

Technological Innovation Subsystem Simulation Analysis

The safety level of the technological innovation subsystem is simulated by adjusting the key risk factors

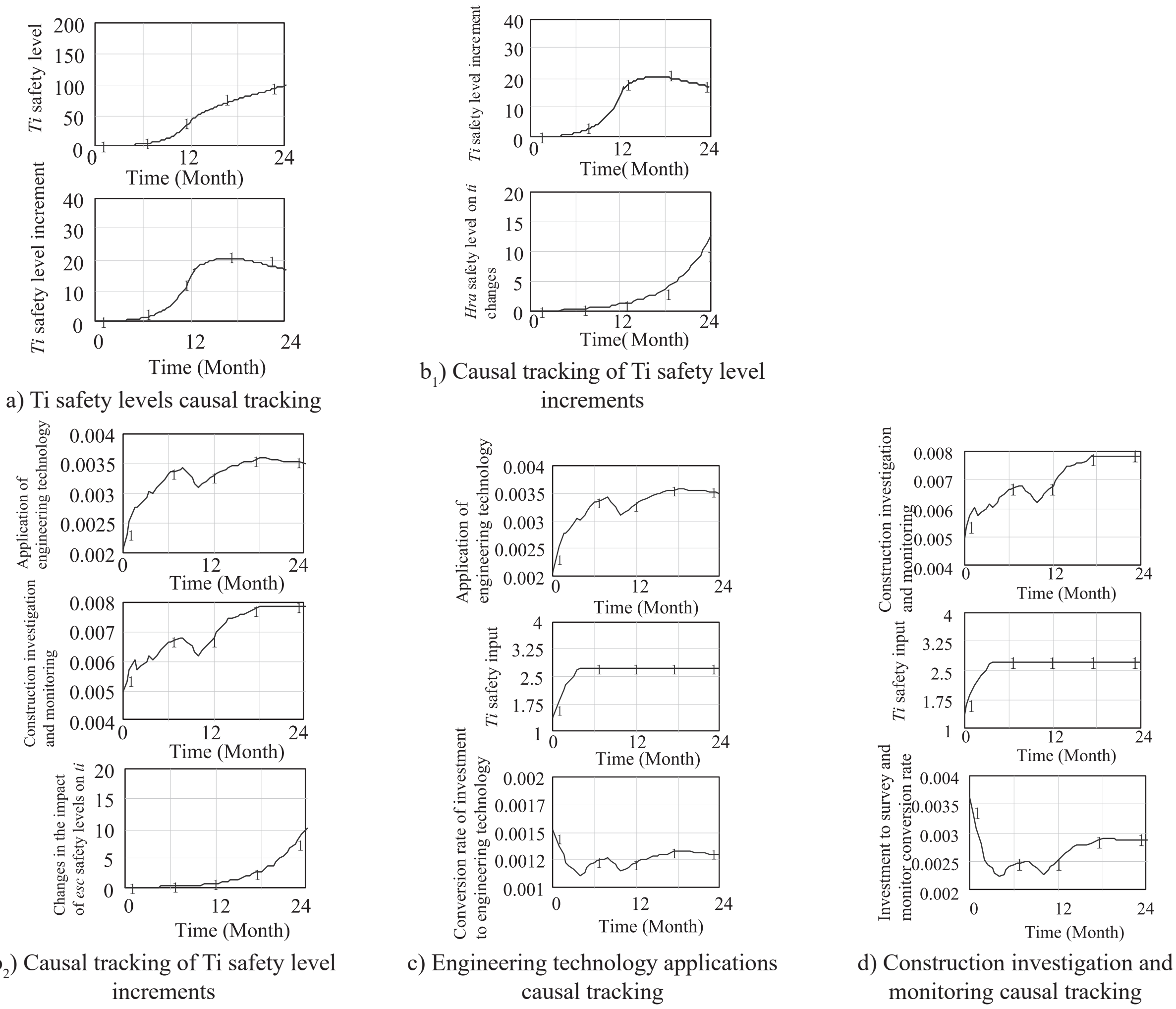

Fig. 9. Causal tracking analysis of technological innovation safety level.

of the technological innovation subsystem. The other four subsystems remain unchanged, and the initial value of each risk factor of the technological innovation subsystem is increased by 25% successively. Scheme represents that the initial value of each factor of the technological innovation subsystem remains unchanged; Scheme1 indicates that the initial value of the support structure increases by 25%; Scheme2 indicates that the initial value of the mining plan increases by 25%; Scheme3 indicates a 25% increase in the initial construction design value; Scheme4 indicates that the initial value of engineering technology application increases by 25%; Scheme5 represents a 25% increase in the initial value of construction investigation and monitoring, and its technological innovation safety level change trend is shown in Fig. 10.

Table 3. Weight and initial value of each factor of the technological innovation subsystem.

Risk factors	Weight	Initial value
Support structure	0.024	0.053
Mining scheme	0.021	0.057
Construction design	0.018	0.064
Engineering technology application	0.019	0.059
Construction survey and monitoring	0.027	0.063

By solving the change rate of each risk factor of the technological innovation subsystem, subtract the Scheme average from the average of each group, and then divide by the average of each group to obtain the corresponding change rate. The results show that the change rate of five risk factors of the support structure, mining scheme, construction design, engineering technology application, construction investigation, and monitoring to the safety level of the technical subsystem are 10.19%, 6.67%, 9.46%, 5.06%, and 16.49%. According to the SD simulation results, the influence degree of internal factors of the technological innovation subsystem is successively: construction design, support structure, construction investigation and monitoring, mining scheme, and engineering technology application. The influence degree of the internal factors

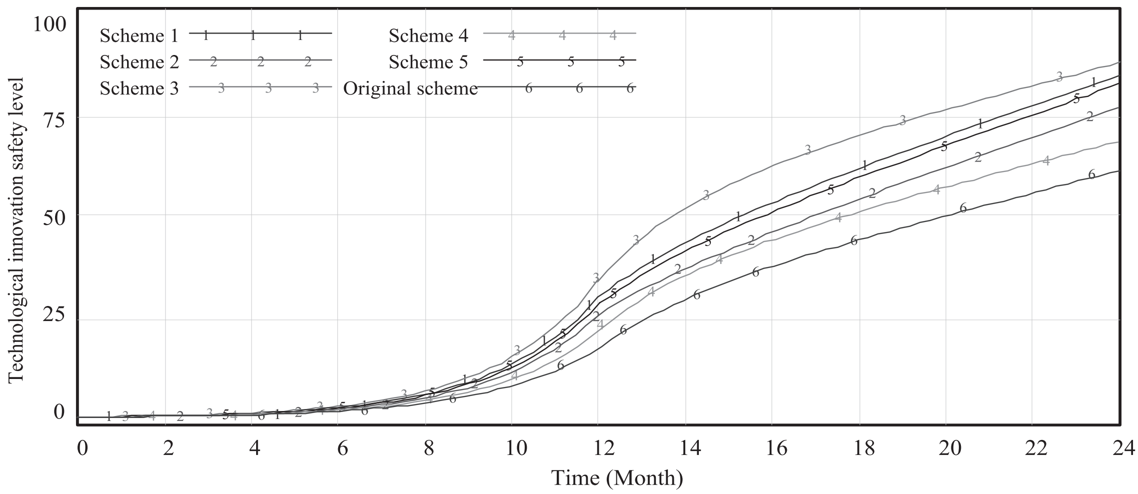

Fig. 10. Technological innovation safety level change trend.

of the technological innovation subsystem is measured by the comprehensive weight, which is successively construction investigation and monitoring, support structure, mining scheme, engineering technology application, and construction design. This is slightly different from the SD simulation results, indicating that the internal factors of the technological innovation subsystem or the external factors will interact with the internal factors, resulting in differences.

Discussion

This study developed a comprehensive framework for evaluating and analyzing the evolution of safety risk resilience in coal mining enterprises by integrating text mining, topic modeling, combined weighting (ANP-CRITIC), and system dynamics (SD) simulation. An empirical investigation was conducted using a coal mine located in Qinghai Province as a case study. The research outcomes not only identified the key factors influencing the safety risk resilience of coal mining operations and their causal pathways but also provided valuable decision-making support for enhancing the intrinsic safety level of coal mines and promoting sustainable development within the coal industry.

The Hierarchical Influence of Core Subsystems: The Pivotal Roles of Technological Innovation and Human Resource Management

The research demonstrates that technological innovation and human resource management are the two primary drivers for enhancing the safety risk resilience of coal mining enterprises. This conclusion aligns closely with contemporary safety management theories and practices. Technological innovation, encompassing intelligent mining equipment, advanced monitoring and early warning systems, and efficient support technologies, acts as the fundamental force for directly improving the inherent safety of production processes, thereby reducing both the likelihood and severity of accidents. Concurrently, human resource allocation, including the quantity, structure, skill level, and training effectiveness of professional personnel, constitutes the foundation for the effective deployment of technologies, the rigorous implementation of management systems, and the assurance of emergency response capabilities, which echoes the safety resilience evaluation theory proposed by Guo in 2025 [43]. It further discovers that the synergy between technological innovation and human resources dominates the enhancement of resilience, which is consistent with the scenario prediction made by Liu et al. in 2025 [44]. A well-trained and competent workforce serves as the "active agent" in mitigating risks and achieving resilience.

In comparison, enterprise system construction, the establishment of scientific research and innovation platforms, and policy support, although exerting a relatively secondary influence, represent the foundational environment and enabling mechanisms that underpin the effective functioning of the two core subsystems. A robust institutional framework provides the structure for standardized operations, while a well-developed research platform serves as the source of continuous innovation. Strong policy support functions as an external catalyst, encouraging enterprises to increase their investment in safety measures. Collectively, these elements form a multi-tiered, interdependent network that supports risk resilience.

Dynamic Effects and Time Delays Associated with Safety Investment: Nonlinear Pathways to Resilience Enhancement

The impact of safety investment, especially in talent cultivation and technological innovation, on safety risk resilience shows nonlinear characteristics and a significant time delay effect. The research indicates that increased investment does not yield immediate results; rather, its benefits follow a logistic "S"-shaped growth curve. This observation underscores the complexity and long-term nature of building safety resilience. The "S"-shaped benefit curve of safety investment confirms the nonlinear characteristics of complex system intervention (He's system dynamics principle, 2010) [45], quantifying the lag period in the coal mine safety field (for instance, technological innovation investment takes 6 to 12 months to show effects) and providing a time threshold reference for dynamic decision-making.

The delay can be attributed to multiple factors: the time required for research, development, adoption, and internalization of new technologies; the learning and adaptation period needed for employees to effectively utilize new equipment and processes; the gradual integration and internalization of safety management systems and culture; and the fact that the benefits of safety investment (such as reduced accident rates and improved emergency response capabilities) typically become evident only after reaching a certain threshold. These insights caution managers to adopt a long-term strategic perspective and avoid reducing critical safety investments due to the absence of immediate visible outcomes. Doing so may result in diminished resilience, prolonged recovery periods, and potentially a vicious cycle of "underinvestment→increased accident risk→reactive remediation→short-term improvement→renewed underinvestment→recurring risk escalation". This paper echoes the research of Majernik (2023) and Yuan (2015) on increasing the intensity of safety science and technology research in the coal industry and exploring innovative paths in terms of mechanisms and systems, policies and regulations, talent cultivation, and scientific research [46, 47].

Priority of Internal Factors within the Technological Innovation Subsystem: From Exploration and Monitoring to Engineering Application

The research, which ranks the internal factors within the technological innovation subsystem (construction survey and monitoring > support structure > construction design > mining plan > application of engineering technology), carries significant practical implications. This ranking indicates that:

Risk perception and early warning capabilities are foundational: Accurate construction surveys and real-time monitoring systems serve as the "eyes and ears" for identifying potential hazards and issuing timely risk warnings, making them essential for accident prevention. Without reliable risk information, subsequent decision-making and response actions may be ineffective or misguided.

Structural safety acts as a direct protective barrier: An effective support structure functions as a physical safeguard against potential hazards, playing a critical role in maintaining operational safety.

Design and planning are the key to source control: Scientific construction design and mining plans are crucial steps in avoiding major risks and optimizing production layouts from the source.

The application of technology is the manifestation of effectiveness: The application of engineering technology is the concrete implementation and effectiveness demonstration of the aforementioned survey, design, and plans. Its outcome depends on the accuracy and reliability of the preceding steps.

This ranking provides a clear direction for coal mining enterprises to optimize the allocation of technical resources: priority should be given to ensuring the accuracy of geological exploration, the coverage and reliability of monitoring systems, and the advancement and reliability of support technologies. Then, design and plans should be optimized in sequence, ultimately achieving the effective application of engineering technologies.

At the methodological level, this study successfully integrates qualitative text mining (identifying risk subsystems), quantitative combined weighting (ANP considering network relationships, CRITIC highlighting objective differences), and dynamic simulation (SD depicting nonlinearity and delayed feedback) methods, constructing a more comprehensive and dynamic framework for assessing the resilience of coal mine safety risks. This comprehensive research paradigm of "qualitative identification – quantitative assessment – dynamic simulation" provides a valuable reference for coal mine risk management research on complex socio-technical systems, which is conducive to enhancing safety risk resilience awareness across the entire industry.

Research Limitations and Future Directions

This study is based on a single coal mine in Qinghai. Coal mines in different regions, with different geological conditions, scales, and management levels, may have different risk factor weights and resilience evolution paths. Future research can expand the sample size and conduct multi-case comparisons or regional studies.

The SD model is a highly abstract and simplified representation of reality. The relationships between variables, delay times, and functional forms set in the model, although based on literature and expert opinions, may still contain biases. In the future, more precise data can be used to calibrate and validate the model parameters.

The data sources for text mining (such as accident reports and policy documents) may have incomplete information or expression biases. The expert judgment in ANP has a certain degree of subjectivity. In the future, it is possible to explore the integration of more diverse data sources (such as sensor data and employee behavior data) and adopt more robust group decision-making methods.

The model mainly focuses on the internal risk subsystem of the enterprise. The impact of external environmental factors (such as sharp market fluctuations, extreme climate events, and major policy changes) on resilience has not been fully incorporated. In the future, these external disturbances can be considered as external variables or shock scenarios in the model for simulation.

This study mainly focuses on resilience related to safety risks. In the future, it is possible to further explore the comprehensive resilience of coal mining enterprises in the face of multiple pressures such as production disruptions, market changes, and environmental constraints.

In light of the above analysis, this study systematically identified and quantified the key subsystems and internal factors influencing the safety risk resilience of coal mining enterprises, dynamically simulated the long-term effects of safety investment, and particularly emphasized the core status of technological innovation and human resources, as well as the time lag in the generation of safety benefits. The research findings provide a scientific basis for coal mining enterprises to implement precise policies and enhance their intrinsic safety levels, and also contribute theoretical and methodological support for the coal industry to balance safety and development during its transformation and achieve high-quality growth. Future research could be further deepened in aspects such as model refinement, case universality, inclusion of external environments, and comprehensive resilience dimensions.

Conclusions

The main purpose of simulating the safety risk resilience level of coal mining enterprises is to study the fundamental causes of accidents, explore the changing patterns of the complex coal mine system, and use system dynamics to display the internal interaction relationships of the system with dynamic numerical values. The safety risk resilience system of coal mining enterprises is divided into five subsystems: human resource allocation, scientific research and innovation platform creation, technological innovation, policy support, and enterprise system construction. Based on the identification of risk factors, the system dynamics software is used to define the interrelationships among the internal factors of the coal mine system, forming the causal relationship diagram and flow diagram of the safety risk resilience system of coal mining enterprises. On this basis, sensitivity tests are conducted, and the safety investment levels of each subsystem are adjusted one by one to compare and analyze the contribution rates of each subsystem to the safety risk resilience system of coal mining enterprises. A causal trace analysis is also conducted on the technological innovation subsystem to visually display the causal feedback chain of the safety risk resilience system of coal mining enterprises, with the aim of providing theoretical references for coal mine managers and related coal mine researchers to conduct dynamic risk resilience research.

(1) Formulate a reasonable safety investment allocation plan. The safety investment of coal mining enterprises is mainly used for technology introduction, mechanical equipment, safety education and training, etc. By establishing a system dynamics simulation model, the safety risk resilience level of coal mining enterprises under different safety investment allocation schemes can be simulated and analyzed. Then, the optimal safety investment plan can be formulated based on the actual situation. The system dynamics simulation results of the case coal mine show that increasing safety investment can improve the safety risk resilience level of coal mining enterprises and shorten the time required to reach the expected safety value. Conversely, it will reduce the safety level, delay, and increase the time to reach the expected safety level. Therefore, when funds are sufficient, it is appropriate to consider increasing the amount of safety investment to enhance the safety risk resilience of coal mining enterprises.

(2) The safety of coal mining enterprises is influenced by various internal and external factors. Among them, the regulation and control of technological innovation and human resource allocation subsystems have the most significant impact on the safety risk resilience of coal mining enterprises. Therefore, coal mining enterprises should further focus on the needs of the country and local areas, promote the precise alignment of technological research and development with the demands of mining areas, safeguard the safety of miners, and lead sustainable development. Moreover, the coal industry and related coal universities should pay attention to talent cultivation, focus on attracting and nurturing talents, foster an innovative ecosystem, and rely on university resources to create a "dual-mentor" model to deliver compound talents with both theoretical knowledge and practical skills, contributing talents, technology, and wisdom to ensuring national energy security and promoting high-quality industry development. They should jointly promote the deep integration of the innovation chain, talent chain, and industrial chain in the coal industry, and accelerate the formation of new productive forces.

(3) Among the five risk factors in the technological innovation subsystem, namely, support structure, mining plan, construction design, engineering technology application, and construction investigation and monitoring, their respective rates of change on the safety level of the technological subsystem are 10.19%, 6.67%, 9.46%, 5.06%, and 16.49% in sequence. Construction investigation and monitoring, and support structure, have the greatest impact on the safety level of technological innovation. Consequently, prior to the preparation of a construction plan, coal mining enterprises should conduct precise surveys of the mine construction environment. Through drilling and geophysical exploration, data such as coal seam

occurrence conditions (thickness, dip angle, burial depth), geological structures (faults, folds), gas content, and hydrogeological conditions should be obtained. Based on these exploration results, recoverable reserves and mining technical conditions are assessed, and the economic value of resources is evaluated. Potential disaster risks, including gas outbursts, rock bursts, water hazards, and fires, are identified. Specialized monitoring plans are developed, and an automatic monitoring system is established to implement dynamic, real-time monitoring throughout the construction process. This includes continuously monitoring the stability of supporting structures during roadway excavation and formulating corresponding emergency prevention and recovery measures. In summary, given the complexity and variability of the mine environment, scientific planning and thorough evaluation before executing a coal mine construction plan can minimize construction risks, enhance the safety resilience of coal mines, and ensure the efficient and safe operation of the mine throughout its entire life cycle.

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Conflict of Interest

The authors declare no conflict of interest.

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