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From Hidden Risks to State Hazards: Research on the Enhancement of Coal Mine Risk Pre-control Management Pathways

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Abstract

This study focuses on the risk propagation pathways through which state hazards evolve into tangible hidden risks in coal mine production systems, aiming to enhance risk pre-control management. Grounded in the concept of "correlation → causation," a coal mine accident causation network was constructed from 974 accident investigation reports, comprising 16 risk causative nodes and 69 associative pathways. By integrating node centrality measures with associated cause sets, eight potential risk transmission pathways were identified, and a risk transmission structural model for state hazards in coal mine production was proposed. Empirical research was subsequently conducted to validate the hypothesized correlations and path relationships among risk variables. Based on these path relationships, a collaborative control scheme for state hazards was developed. The findings indicate that failures in external management trigger risk transmission within the internal organizational level of coal mining enterprises, initially causing disorder in organizational process activities, which negatively impacts the formulation and implementation of safety production plans. Risks then propagate along the accident chain, leading to defects in the technical environment and ultimately resulting in workers' direct unsafe behaviors.

0 Introduction

In recent years, the safety situation in Chinese coal mines has shown some improvement, with a continuous decline in the total number of accidents and particularly severe incidents within the coal mining industry. However, major and relatively serious accidents still occur intermittently. On January 12, 2024, a coal and gas outburst accident occurred in Henan Province, resulting in 16 fatalities, 5 injuries, and direct economic losses amounting to 21.9729 million yuan. Subsequently, on March 11, 2024, a gas explosion accident took place in Anhui Province, causing 9 deaths and 15 injuries. These successive coal mine accidents reflect that the current coal mine safety production in China has entered a “bottleneck period”, wherein various hidden risks and state hazards are intertwined and superimposed. This situation significantly increases the difficulty of further enhancing risk pre-control management levels [1] and the likelihood of fundamentally preventing major accidents remains relatively low.

From the perspective of management implementation, coal mine safety risk control measures have undergone a transformation from “traditional experience-based management” to “safety system management”, and subsequently to “hazard pre-control management” [2]. Correspondingly, the focus of coal mine safety management has gradually shifted from the initial accident-centered accident management mode to a hidden risk-centered hidden risk management mode [3], and later evolved into a risk management mode centered on hazard management. Against this backdrop, the critical point of risk control has been progressively advanced forward, transitioning towards a pre-control management paradigm. Consequently, various hazard-based risk pre-control safety management systems have emerged [4, 5], including internationally recognized occupational health and safety management systems (OHSMS), the American’s “Operations integrity management system (OIMS)”, South Africa’s “Five star management system”, and their “CAPTM risk management system”. Within the domain of coal mine risk management, some scholars have further explored the extension of coal mine accident prevention mechanisms and the optimization pathways of pre-control methods [6–11]. In recent years, safety management issues in coal mining enterprises based on hazards or risks have attracted considerable attention. For instance, based on the theory of three types of hazards, Jin et al. [12] used path analysis methods to evaluate the probability of coal and gas outburst accidents and revealed its cause mechanism. Wang et al. [13] used “24 model” combined with big data to analyze the risk portrait of miners, which reflected the latest trend from “hazard management” to “accurate pre-control”. Miao et al. [14], aiming at the "hidden danger analysis" and "risk early warning technology" of China coal mine, built a gas safety situation prediction model. Hao and Nie [15] constructed a novel closed-loop management model based on hazard identification, assessment, checking, and action to control risks in mine tunneling systems. Liu et al. [16], from a systems perspective, proposed methods for identifying root hazards and state hazards. Scholars commonly assert that state hazards represent hidden risks under anticipated conditions, while hidden risks are objective manifestations that emerge when the management of state hazards loses control (Fig. 1). The core

emphasis of coal mine risk pre-control management is to prioritize hazard prevention and control, focusing coal mine accident governance on the proactive management of hazards. This approach underscores the importance of comprehensive hazard management measures to promptly detect and effectively mitigate potential hidden risks before they evolve into accidents, thereby preventing incidents before they occur.

Accordingly, this paper advances along the evolutionary trajectory of coal mine accidents by adopting the higher-level conceptual antecedent of “hidden risks”, namely “state hazards”, as the entry point for enhancing coal mine risk pre-control management pathways. It focuses on investigating how state hazards progressively lose control and evolve into tangible hidden risks. By excavating the risk transmission pathways among various state hazards, risks can be identified at their source. Based on this, a risk linkage control scheme tailored to the interaction characteristics of state hazards is developed, aiming to eliminate risks prior to the emergence of hidden risks.

In the domain of coal mine safety, management decision-making scenarios require not only the application of data-driven research paradigms to identify associative patterns among variables but, more importantly, the validation of causal relationships based on these associative patterns. Although data-driven research can reveal correlations between variables, such correlations do not equate to causality. Understanding the causal mechanisms among variables facilitates, on one hand, provides a deeper comprehension of the intrinsic interactive relationships within the coal mine safety system. This understanding enables the optimization of the system by adjusting critical variables to enhance overall safety and stability. On the other hand, it allows for a more precise delineation of key variables influencing coal mine risk prevention and control, thereby providing more accurate guidance for management decisions.

A review of the literature indicates that most existing studies exploring the causal relationships among accident causative factors often rely on spatial and combinatorial assumptions about variables that are directly proposed by researchers through observation or related theories, lacking objective substantiation. Furthermore, the large number of variable combinations results in some combinations remaining untested. Therefore, regarding the methodological selection for analyzing risk transmission pathways of state hazards, the research process of this study primarily comprises two stages (Fig. 2). The first stage is grounded in constructing a classification inventory of coal mine production risk factors and employs a coding set of coal mine accident data to investigate accident causation—that is, the complex network relationships among uncontrolled hidden risks—to elucidate the associative links of state hazards during coal mine production. This approach not only directly generates solutions but also reduces the dimensionality of the variable space and the scale of combinations. Subsequently, by extracting the co-occurrence patterns among strongly associated state hazards, causal hypotheses concerning the interactions between state hazards are proposed. The second stage builds upon the findings of the first stage and utilizes econometric methods under a model-driven paradigm to identify the influence pathways among state hazards. Drawing on systems theory, a risk transmission model of coal mine state hazards is constructed from the complex interactions among various factors. This model provides a systematic theoretical framework for preventing coal mine accidents at their root. The ultimate aim is to integrate traditional safety management models with data analysis techniques to facilitate a transformative shift in coal mine safety management from an “correlation → causation” perspective.

1 Research Methods and Data

1.1 Data sources

The research data in this study comprise two parts. The empirical data in first phase is derived from textual investigation reports on coal mine accidents in China. Specifically, a portion of the samples originates from the official websites of the Ministry of Emergency Management of China, and the safety production supervision bureaus of various provinces and municipalities. The remaining samples were obtained through field investigations conducted at different Chinese coal mining enterprises. After screening and processing, a total of 974 coal mine accident-related textual datasets spanning

nearly a decade were collected, encompassing eight types of accidents: gas, electromechanical, transportation, flooding, fire, blasting, roof, and others. The empirical data in second phase stem from questionnaire surveys administered to coal mine enterprise employees, incorporating both preliminary and formal survey stages.

1.2 HFACS framework

Coal mine accidents typically involve multiple factors, including human errors, organizational deficiencies, adverse working environments, and systemic failures. Among various accident causation models, the Human Factors Analysis and Classification System (HFACS), derived from the Swiss Cheese Model [17], offers a systematic hierarchical classification framework that emphasizes the interaction of human factors with organizational, environmental, and technological systemic elements [18, 19]. Moreover, the HFACS model can be refined and adapted according to the specific characteristics and practical contexts of different industries. It has been extensively applied in large-sample accident analysis across aviation, chemical, construction, and transportation sectors [20–23], demonstrating its effectiveness in analyzing complex accident causation. In addition, the layered structure of the HFACS model provides a logical foundation for quantitative analysis. When integrated with social network analysis, statistical modeling, and other methodologies, it enables an in-depth exploration of the interrelationships and causal pathways among various causative factors, thereby revealing the intrinsic connections and transmission mechanisms underlying accident causation. Therefore, this study adopts the HFACS model as an auxiliary tool for textual analysis of coal mine accidents and, based on this framework, conducts research on the risk transmission mechanisms involving state hazards and hidden risks.

1.3 Complex networks

Complex networks, grounded in graph theory, constitute a mathematical approach employed to investigate the structural and functional characteristics of individual elements and their interrelationships within complex systems [24]. In a complex network, the elements of the system are abstracted as nodes, while the interactions or relationships between nodes are represented as edges, thereby forming a network structure with distinct topological features. The complex network methodology has been extensively applied across disciplines such as social sciences, biology, engineering, and safety science [25, 26], proving particularly effective in elucidating hidden relational patterns and causal chains within complex systems influenced by multifactorial interactions. In this study, the complex network approach is utilized to extract the correlation patterns among accident causal factors within the hierarchical HFACS framework of the coal mining industry.

1.4 Structural equation model

Structural Equation Modeling (SEM), as a comprehensive statistical analysis method, is widely employed to verify causal relationships among variables and their underlying mechanisms [27]. The core of this method lies in constructing a systematic causal relationship network using observed variables and latent variables, then it evaluates the fit between the theoretical model and empirical data through model fit indices. SEM integrates the characteristics of factor analysis, path analysis, and regression analysis, with the advantage of supporting complex modeling of multivariate and multipath relationships. It is particularly suitable for research scenarios involving multifactor interactions. In the present study, SEM is utilized to validate the causal relationships within the correlation patterns among risk factors contributing to coal mine accidents

1.5 Ethics Statement

All methods were carried out in accordance with relevant guidelines and regulations. The experimental protocols were approved by the Jiangsu University of Architectural Technology Ethics Committee. Written informed consent was obtained from all subjects and their legal guardian prior to their participation in the study.

2 Results and Analysis

2.1 HFACS framework in the coal mining industry

Based on Reason's Swiss Cheese Model and the Human Factors Analysis and Classification System (HFACS) developed by Shappell et al., a text mining analysis was conducted on investigation reports of 974 coal mine accidents. Ultimately, 42 identified coal mine safety risk factors were systematically mapped onto five categories: "unsafe external factors", "unsafe organizational influences", "unsafe supervision", "unsafe preconditions" and "unsafe acts". The comprehensive classification of coal mine production risk factors is presented in Fig. 3. The detailed derivation process of the framework can be found in reference [28].

2.2 Exploration of the correlation and transmission pathways of state hazards in coal mine production

2.2.1 Construction of the causal factor network for coal mine accidents

As illustrated in Fig. 3, the causal system of coal mine accidents primarily comprises 16 categories of causative factors, specifically encompassing 42 accident causative elements. The failure to control one or more of these factors will directly or indirectly affect closely related elements, thereby facilitating the propagation of risk within the system and ultimately resulting in the occurrence of an accident. Given the extensive range of accident causative categories—covering man, machinery, medium, and management, collectively referred to as the 4M elements—exploring the interrelations among these factors sequentially according to the 4M classification without prior knowledge of their interaction mechanisms entails a substantial workload and poses a risk of overlooking critical relational influences among elements. In this context, employing an association rule algorithm to directly extract all strong association rules among accident causative factors, and subsequently constructing a visualized coal mine accident causal network based on these rules, enables the identification of core accident causes and their closely associated cause sets. However, due to the complexity and fine granularity of causative elements within the causal system, and considering the size and complexity of the dataset, directly extracting association rules among accident causative factors from large-scale data may encounter issues such as an explosion in the number of rules and difficulties in ensuring rule quality. Moreover, it becomes challenging to filter out causal pathways that hold significant indicative value for practical problem-solving.

Therefore, this study elevates the granularity of accident causation to the level of accident cause categories, shifting the focus toward higher-level indicators of causative elements. This approach not only reduces the complexity of intricate factors but also provides a clearer perspective for accident analysis. By analyzing accident cause categories, the method identifies high-level risk factors, thereby rendering accident prevention and management more actionable. In accordance with the requirements of the Apriori algorithm, the minimum support threshold was set at 0.1, the minimum confidence threshold at 0.5, the maximum number of antecedents at 1, and the minimum lift threshold at 1. Ultimately, 69 strong association rules among 16 accident cause categories were mined, reflecting the close interrelations among coal mine accident causative factors. Subsequently, based on these strong association rules and Pajek software, a coal mine accident causal network was constructed. The antecedents and consequents of all strong association rules served as nodes within the network, with the relationships between antecedents and consequents represented as edges, and lift values employed as edge weights. The resulting coal mine accident causal network is illustrated in Fig. 4. This network comprises 16 nodes and 69 edges, where the density of connections surrounding a node reflects the complexity of the local region, and the proximity of a node to the network center indicates its influence over other nodes. As shown in the figure, unsafe organizational factors, unsafe supervisory factors, and unsafe environmental factors are relatively closer to the network center, preliminarily indicating that factors such as resource management (D1), organizational climate (D2), organizational process (D3), inadequate supervision (C1), planned inappropriate operations (C2), physical environment (B5), and technological environment (B6) hold greater significance within the overall coal mine risk pre-control system.

2.2.2 Analysis on the correlation network and pathways of the core causative nodes

Core causative nodes play a crucial role within the accident network. When core causative factors are not effectively controlled, risks gradually propagate to closely related nodes. For instance, inadequate internal resource management is often accompanied by risk factors such as “crew management disorder” and “employees’ adverse metal state”. These conditions further facilitate the continued propagation of risk along the accident chain, compelling the state hazards associated with “crew management disorder” and “employees’ adverse metal state” to surpass critical equilibrium points and breach risk thresholds. Consequently, these state hazards sequentially evolve into hidden risks, ultimately exacerbating accident risk and potentially generating new risks. Therefore, in managing state hazards, it is imperative to implement joint prevention strategies targeting their closely associated causative factors, which can interrupt the propagation trend of risk within the network and thereby prevent accident occurrence.

In order to identify the associated risk sets of different state hazards, network analysis was conducted for each core causative factor using Pajek. As previously discussed, the occurrence of accidents results from the joint propagation of multiple unsafe factors along the accident chain. Systematically uncovering the progressive patterns of unsafe factors across various hierarchical levels within risk factors can effectively prevent coal mine accidents. Therefore, to elucidate the risk transmission patterns among state hazards, this study first mined the associated cause sets of state hazards within “external management” and identified their critical risk transmission pathways, followed by a layer-by-layer backward tracing analysis.

Taking “unsafe external management” (E1) as an example, all antecedents and consequents of strong association rules involving E1 were treated as nodes within the network, while the associations between antecedents and consequents were regarded as edges. The lift coefficients related to the association rules were assigned as the weights of each edge. The individual central network of this node is illustrated in Fig. 5. The network graph reveals that risk factors such as organizational process, organizational climate, planned operations, problem correction, supervisory violations, physical environment, and technological environment constitute the associated cause set of E1. These nodes may represent either antecedents or consequents of node E1. To further clarify the risk transmission mechanism centered on “unsafe external management” (E1) and thereby formulate precise joint prevention and control strategies for hazards, the key causative pathways related to E1 must be identified. Since lift reflects the strength of correlation between different factors [29], a lift value of 2 between factors A and B indicates that the probability of occurrence of factor B doubles under the condition of factor A. Accordingly, based on the constructed E1 association network, the longest path was computed using Pajek according to edge weights [30]. Considering the hierarchical relationships among nodes, the critical link in the risk transmission of state hazard E1 was determined as: E1 → D3 → C2, as shown in Fig. 6. The total lift of this risk transmission pathway is 2.39, equal to the sum of the weights of all edges along the key chain. Specifically, when governmental and parent company’s management of coal mining enterprises is inadequate, the likelihood of internal organizational process defects and improper planned operations becomes significantly more pronounced compared to other risk causative factors.

As indicated by the results, the risk associated with node E1 can be transmitted to downstream nodes D3 and C2. Consequently, further analysis was conducted by applying the same procedure to nodes D3 and C2. Individual association networks centered on each node were constructed respectively. The outcomes are presented in Fig. 7. Through computational analysis, the critical pathways for node D3 were identified as D3 → B6 → B5, while for node C2, the critical pathways were D1 → C2 → B6. Given that node B5 exhibits relatively low comprehensive centrality (The detailed calculating is provided in **appendix A**), it was excluded from subsequent analysis. Focus was thus placed on nodes D1 and B6, for which association networks centered on each were constructed, as shown in Fig. 8. The critical pathway for D1 was determined to be D3 → D1 → B3, and for B6, it was C1 → C2 → B6.

2.2.3 Research hypotheses on the risk transmission pathways of state hazards in coal mine production

Due to the presence of multiple risk nodes within the hierarchies of unsafe organizational factors, unsafe supervisory factors, and unsafe preconditions, the identified critical links still remain complex. Therefore, only the top five causal category nodes ranked by network centrality (The detailed calculating is provided in **appendix A**)—namely D1, C3, D3, B6, and C2—were selected from these hierarchies for subsequent path analysis, while redundant nodes within the critical links were removed. Additionally, node B6 belongs to the hierarchy of unsafe preconditions, which is followed by the hierarchy of unsafe behaviors. However, no attribute nodes related to unsafe behaviors appeared among the aforementioned critical links, rendering the risk transmission path from the unsafe preconditions to the unsafe behaviors unclear. By examining all strong association rules involving node B6, it was found that nodes A2 and B6 co-occurred in 51.23% of all coal mine accidents, and when node B6 appeared, the confidence level of node A2 occurring was 57.92%. Therefore, node A2 was regarded as a downstream risk transmission node of node B6.

The critical links of attribute nodes across each hierarchy and the specific risk transmission path extraction results are presented in Table 1. Among them, six potential risk transmission paths were extracted from the critical links involving nodes E1 and C2. Four of these paths are directly associated with nodes E1 and C2, namely E1→D3, E1→C2, D1→C2, and C2→B6, all of which have been validated through correlation analysis. Two additional indirectly extracted risk transmission paths, D3→C2 and D1→B6, were further examined by evaluating their lift coefficients. The path D3→C2 exhibited a lift of 1.12, whereas D1→B6 showed a lift of only 1.01. Consequently, the path D3→C2 was retained, and the path D1→B6 was discarded. In summary, this section, based on a data-driven research paradigm, extracted eight potential state hazards risk transmission paths: E1→D3; E1→C2; D3→C2; D3→D1; D1→C2; D3→B6; C2→B6; and B6→A2. These paths serve as the data-supported hypotheses for subsequent studies on the action mechanisms of state hazards in coal mine production.

Table 1
Extraction results of key links and risk transmission pathways of attribute nodes at each hierarchical level

Serial Number	Nodes	Key links (prior)	Key links (subsequent)	Potential risk transmission pathways
1	E1	E1→D3→C2	E1→D3→C2	E1→D3;E1→C2□D3→C2
2	D3	D3→B6→B5	D3→B6	D3→B6
3	C2	D1→C2→B6	D1→C2→B6	D1→C2;C2→B6□D1→B6
4	D1	D3→D1→B3	D3→D1	D3→D1
5	B6	C1→C2→B6	C2→B6	C2→B6
6	/	/	B6→A2	B6→A2

Note: "Key links (prior)" refers to the initial associated path of the core node, while "key links (subsequent)" denotes the associated path after the removal of redundant nodes.

Based on the foregoing analysis, this study constructed a risk transmission structural model of state hazards in coal mine production by systematically delineating the interrelationships among the aforementioned factors (as illustrated in Fig. 9). Concurrently, the research hypotheses are summarized as follows:

H1 External management exerts a significant positive effect on organizational process.

H2: External management exerts a significant positive effect on the planned operations.

H3: The organizational process exerts a significant positive effect on the planned operations.

H4 The organizational process exerts a significant positive effect on resource management.

H5: Resource management exerts a significant positive effect on the planned operations.

H6 The organizational process exerts a significant positive effect on the technological environment.

H7 The planned operations exert a significant positive effect on the technological environment.

H8 The technological environment exerts a significant positive effect on safety behaviors.

2.3 Verification of the causal relationships in the risk transmission pathways of state hazards

2.3.1 Scale design and validation

The design of measurement scales for variables constitutes a critical step in the questionnaire survey method, directly influencing the credibility of data collection and the reliability of research conclusions. In this study, all variables involved are latent variables, which represent abstract constructs. Due to the inherent abstraction and the inability to observe these constructs directly, it is necessary to rely on various indicators to measure them. In the field of coal mine safety, the dimensional composition and number of items in scales developed by different scholars vary. This study posits that such differences primarily reflect divergent understandings and research emphases regarding the concept of coal mine safety management among researchers. Therefore, existing scales cannot be simply adopted in coal mine risk pre-control management research. The initial selection of measurement indicators for the scale should be grounded in the actual conditions of risk pre-control management in Chinese coal mining enterprises. Coal mine accidents, as a direct manifestation of risk management, can serve as a key reference point for the design of measurement scales. Using coal mine accidents as the starting point for indicator selection not only helps ensure that the initial measurement indicators of the scale are more aligned with practical conditions and operationally feasible, but also enables the scale to more accurately reflect the actual risk management needs of coal mining enterprises.

Therefore, in accordance with the objectives of path verification and the data-driven characteristics discussed, the measurement indicators for the variables were all selected from the specific causal factors contained within the coal mine risk categories extracted through text mining algorithms in Fig. 3. For instance, regarding the variable “external management”, the classification of coal mine risk factors indicates that it includes two causal factors: “lack of government supervision” and “ineffective management by parent companies”. Correspondingly, the measurement items are designated as “administrative safety inspection” and “parent company’s safety supervision”, respectively, and so forth. After the initial questionnaire items were generated, to ensure the scientific rigor and readability of the scale, this study successively invited three experts specializing in coal mine safety and risk management to discuss the rationality of the scale and to examine whether all items adequately reflected the actual content of each dimension. On this basis, five frontline managers from different coal mining enterprises were invited to evaluate the readability and comprehensibility of the scale.

After small-scale preliminary test and subsequent revisions, the coal mine production state hazards control scale comprised 19 items, across six dimensions, as presented in **appendix B**. All scale items are self-reported and rated using a five-point Likert scale, where 1 to 5 represent “strongly disagree” to “strongly agree”, respectively. Furthermore, two professors specializing in safety management research and three doctoral candidates in safety management were invited to conduct a comprehensive evaluation of the scale’s format and content. In summary, the large-scale survey yielded a total of 527 questionnaires from five large state-owned coal mine enterprises located in Xinjiang, Guizhou, and Shanxi provinces. Questionnaires exhibiting regularity in response patterns, such as those with nearly identical answers across

all items, were excluded. Ultimately, 431 valid questionnaires were retained, resulting in an effective response rate of 81.78%.

The reliability of the formal scale was primarily assessed using Cronbach's α coefficient. Table 2 presents the results of the reliability analysis for the formal scale. The analysis revealed that the overall Cronbach's α coefficient of the scale was 0.821, while the Cronbach's α values for the individual subdimensions ranged from 0.779 to 0.941. All Cronbach's α coefficients exceeded the threshold of 0.7, indicating that the scale has satisfactorily passed the reliability test. For construct validity assessment, indicators such as the Kaiser-Meyer-Olkin (KMO) test and Bartlett's test of sphericity were employed. Confirmatory factor analysis was utilized to evaluate the scale's convergent validity, while discriminant validity among latent variables was assessed using the comparison between the average variance extracted and the squared correlations. The results indicated that the KMO coefficient for each structural variable of the scale was 0.825, signifying a satisfactory level, and the significance level of Bartlett's test was 0.000, confirming the suitability of the sample data for exploratory factor analysis. Furthermore, the affiliation between 19 items and six factors with eigenvalues greater than one was relatively clear; all factor loadings exceeded 0.7, and no cross-loading phenomena were observed. These findings demonstrate that the scale's validity has passed preliminary verification and possesses robust construct validity.

Table 2
Reliability analysis results of the formal scale

Variables	Overall scale	External management	Organizational process	Resource management	Planned operations	Technological environment	Safety behaviors
N	19	2	5	4	2	3	3
Cronbach's α	0.841	0.810	0.892	0.904	0.781	0.861	0.877

2.3.2 Construction and modification of the structural equation model

The primary objective of this section is to focus on individual miners as the subject, in order to verify the interaction mechanisms among various state hazards in coal mines, thereby establishing a systematic risk transmission analysis model for coal mine state hazards. Subsequently, the study first employed the Amos 17.0 statistical software to construct a structural equation model based on the hypothesized framework. Sample data were inputted, and in accordance with the evaluation and modification principles of structural equation models, the model was appropriately adjusted and refined. Finally, the hypothesized path relationships were tested through the results of the data analysis. The analytical model is illustrated in Fig. 10.

Prior to formally fitting the analysis model, it is essential to determine whether the structural equation model is identifiable. According to the t-rule, the number of freely estimated parameters should be less than the number of observed data points used to generate the covariance structure. Calculations indicate that the model includes 2 exogenous observed variables and 17 endogenous observed variables, yielding a total of $(2 + 17)(2 + 17 + 1)/2 = 190$ sample data points. The number of free parameters t is 65, resulting in positive degrees of freedom. Therefore, the model is identifiable.

Based on the premise that the factor analysis of each dimension within the research model meets the required standards, the degree of fit between the structural equation model data matrix and the sample data matrix was analyzed using the maximum likelihood estimation method. The results indicated a chi-square to degrees of freedom ratio (χ^2/df) of 2.434, which falls within the acceptable range of [1–3]. The RMSEA value was below 0.08, and the goodness-of-fit indices—GFI, IFI, CFI, and TFI—all exceeded 0.9. These findings demonstrate that the constructed risk transmission model of state hazards exhibits a satisfactory overall model fit.

A further path analysis was conducted to verify the correctness of the hypothesized relationships among state hazards proposed in Section 2.2.3. The absolute value of the critical ratio (CR) and the p-value of parameter estimates were employed as the primary criteria for hypothesis testing. Specifically, if the absolute value of CR exceeds 1.96, the path is considered significant at the 0.05 level; if it exceeds 2.58, the path is deemed significant at the 0.01 level. The results (Table 3) indicate that the hypothesized path from the resource management variable to the planned operations variable did not achieve significance at the 95% confidence level. Consequently, this path was removed and the model was refitted. All remaining paths subsequently passed the significance tests, and all unstandardized error terms yielded positive and significant results, indicating no violations in estimation within the research model and all variances were within acceptable normal ranges.

Table 3
Path verification of the risk transmission model for state hazards in coal mine production

Pathways	**Non-standardization coefficient**	**Standardization coefficient**	**S.E.**	**C.R.**	**P**
External management → Organizational process	0.139	0.160	0.049	2.817	**
Organizational process → Resource management	0.137	0.112	0.064	2.128	*
External management →→ Planned operations	0.333	0.345	0.061	5.437	***
Organizational process →Planned operations	0.332	0.299	0.062	5.337	***
Resource management →Planned operations	0.059	0.065	0.048	1.231	0.218
Organizational process → Technological environment	0.137	0.139	0.055	2.504	*
Planned operations→ Technological environment	0.345	0.389	0.058	5.997	***
Technological environment → Safety behaviors	0.330	0.327	0.056	5.889	***

The finalized structural equation model, developed to analyze the risk transmission pathways of state hazards in coal mine production, is presented with the fitting results in Table 4. The chi-square value was 351.93; however, due to the large sample size, this indicator was inflated. Therefore, other fit indices were considered: the chi-square to degrees of freedom ratio (CMIN/DF) was 2.427, which falls within the acceptable range of 1 to 3; the goodness-of-fit index (GFI) was 0.919, exceeding the acceptable threshold of 0.80 within the 0 to 1 range; the adjusted goodness-of-fit index (AGFI) was 0.894, also above the 0.80 criterion; the comparative fit index (CFI) was 0.954, surpassing the acceptable standard of 0.90; and the root mean square error of approximation (RMSEA) was 0.058, meeting the criterion of being below 0.08. Collectively, these fit indices demonstrate that the structural equation model exhibits satisfactory goodness-of-fit, thereby supporting subsequent analyses.

Table 4
Fitting indices of the structural equation model

Adaptation index	**CMIN/DF**	**RMSEA**	**GFI**	**AGFI**	**CFI**	**IFI**	**TLI**
Inspection standards	[1–3]	< 0.08	> 0.8	> 0.8	> 0.9	> 0.9	> 0.9
Goodness of fit	2.427	0.058	0.919	0.894	0.954	0.955	0.946

2.3.3 Collaborative control scheme for state hazards

Based on the empirically validated risk transmission pathways of state hazards in coal mines, the failure of external management can propagate risks into the internal organizational components of coal mining enterprises. This initially results in disarray within organizational process activities, subsequently affecting the formulation and implementation of safety production plans. Thereafter, the risks advance along the accident chain, leading to deficiencies in technical environment, and ultimately causing workers to commit direct unsafe behaviors. Therefore, this section focuses on the causal pathways of state hazards identified, transforming the effective information into corresponding collaborative control schemes for state hazards.

(1) Collaborative control scheme for state hazards associated with external management and organizational process

Through the synergistic effect of government inspection and corporate group supervision, effective control is ensured over state hazards such as deficient specialized safety regulations in coal mining enterprises, illegal and non-compliant production, evasion of safety supervision, lax procedural audits, and relaxed routine safety management. Governmental inspection emphasizes regulatory compliance and comprehensive oversight, whereas corporate group supervision focuses on procedural standardization and the enhancement of internal management. The integration of these two approaches forms an organic combination that promotes comprehensive improvement in enterprise safety management. The specific linkage control scheme for state hazards is presented in Table 5.

Table 5
External management × Organizational process state hazards control scheme

External management factors	Organizational process factors	Collaborative control scheme for state hazards interaction
Government supervision	Deficient specialized safety regulations	Implement regular reviews of specialized safety management systems to ensure their scientific rigor and comprehensiveness based on the most recent regulations and standards; Establish an information exchange platform between government authorities and enterprises, and conduct periodic training sessions on specialized safety management systems to facilitate the optimization and updating of enterprises' professional management protocols.
	Illegal organization of production	Strengthen on-site supervision and random inspections by employing advanced monitoring technologies to ensure comprehensive coverage of enterprises' production activities; Establish joint task forces comprising government and law enforcement agencies, and develop a rigorous information-sharing mechanism to achieve precise enforcement actions against illegal and non-compliant production.
	Evasion of safety supervision	Increase the frequency of inspections and enhance the unpredictability of random checks to raise the cost for enterprises attempting to evade regulatory oversight; Establish a safety accountability mechanism whereby the government and enterprises enter into safety contracts that stipulate the legal liabilities and penalties associated with evasion of safety supervision.
Management by parent companies	Lax procedural auditing	Independent audit teams shall be established by parent companies to conduct procedural audits, ensuring the integrity and enforcement of procedures across coal mines; A shared platform for audit results shall be developed between the parent company and its subsidiaries to facilitate cross-level transmission of audit findings and prompt rectification.
	Negligent routine safety management	Develop comprehensive daily safety management assessment indicators to quantitatively evaluate subsidiaries at all levels; Establish a safety management experience exchange mechanism between the group company and its subsidiaries, promoting the sharing and application of successful safety management practices through regular meetings and seminars.

(2) Collaborative control scheme for state hazards associated with organizational process and planned operations

Table 6 presents the integrated control scheme linking organizational process factors, operational planning factors, and their associated state hazards. This scheme effectively addresses state hazards related to production and operational planning, which manifest as "unreasonable task assignment" and "disorganized labor management", through the organic integration of specialized safety regulations, procedural audits, and routine safety management at the organizational process level. The comprehensive management measures contribute to enhancing the overall safety and coordination within the organization.

Table 6
Organizational process × Planned operations state hazards control scheme

Organizational process factors	Planned operations factors	Collaborative control scheme for state hazards interaction
Specialized safety regulations	Unreasonable task assignment	Ensure that professional safety protocols incorporate explicit requirements for the arrangement of production tasks, clearly specifying the safety standards, procedures, and responsibilities involved throughout the production process. Establish an alarm mechanism for anomalies in task scheduling; once deviations from safety standards in task execution are detected, promptly issue warnings and implement emergency response measures.
	Disorganized labor management	Clearly define the labor organization responsibilities of management personnel at all levels within the specialized safety system, ensuring that each management tier comprehends its respective roles and duties in labor organization. Establish a rigorous workforce resource management mechanism within the specialized safety system to guarantee an adequate number of employees, thereby preventing labor organization disorder caused by insufficient staffing.
Procedural auditing	Unreasonable task assignment	Introduce cross-departmental audits whereby mutual reviews are conducted across different departments to ensure coordination and consistency among all units, thereby preventing the formulation of unreasonable production task arrangements. Establish a regular audit schedule for production task arrangements to guarantee comprehensive and systematic reviews of task allocations at all organizational levels.
	Disorganized labor management	Strengthen the collection of data and information related to labor organization during the audit process to more comprehensively assess the rationality, safety, and coordination of the labor organization. Encourage employee participation in the procedural audit of the organization, utilizing objective feedback from practical operational levels to understand the potential complexities and challenges of the labor organization in operational contexts, thereby further optimizing the depth and breadth of the procedural organizational audit.
Routine safety management	Unreasonable task assignment	Strengthen the communication mechanisms across all hierarchical levels to ensure the smooth transmission of information regarding task assignments; regularly obtain updates on task arrangements through periodic meetings, reports, and other means. Establish a dedicated task evaluation team composed of a cross-functional group to conduct regular comprehensive assessments of task assignments and provide recommendations for improvement.
	Disorganized labor management	Introduce digital collaboration tools facilitates to enhance information sharing, task allocation, and progress tracking within teams, thereby improving the efficiency and transparency of labor organization. Strengthen the management and communication capabilities of leadership to ensure that leadership teams can effectively guide and coordinate labor organization, thus preventing the occurrence of disorder and misalignment.

(3) Collaborative control scheme for state hazards associated with operational planning and technical environment

Table 7 presents the integrated control scheme for state hazards concerning operational planning factors and technological environment factors within. In the context of the interplay among multiple factors, the formulation of a clear

coordinated control plan aims to reduce the risk coefficients associated with construction layout, equipment and facilities, as well as monitoring and control systems.

Table 7
Planned operations × Technological environment state hazards control scheme

Planned operations factors	Technological environment factors	Collaborative control scheme for state hazards interaction
Task assignment	Defective construction layout	Establish an on-site inspection mechanism to ensure that the execution of task assignments and construction layouts aligns with the expected standards, and to promptly rectify any identified hidden risks. Develop and maintain comprehensive construction record archives to create a repository of construction experiences, thereby providing a reference for subsequent task planning based on lessons learned from prior construction activities, ultimately reducing defects in construction layouts.
	Equipment and facility defects	Introduce intelligent maintenance systems to enable the early identification of potential equipment issues through data analysis and predictive maintenance, thereby reducing unplanned downtime. Rationally allocate the equipment workload in the scheduling of production tasks to avoid the excessive use of any single piece of equipment, thus mitigating safety hidden risks arising from equipment operation under overload conditions.
	Lack of monitoring and control systems	Establish a regular backup mechanism for monitoring data to ensure that, in the event of a system failure, recovery to the most recent backup state can be promptly achieved. Develop an emergency response plan for monitoring system equipment failures, clearly defining responsible personnel and emergency measures to guarantee a rapid response in the event of system malfunctions.
Labor management	Defective construction layout	Utilize project management tools, such as Gantt charts and schedules, to visually present the construction plan, thereby facilitating the team's comprehension of workflow and task interrelations, and mitigating issues arising in construction layout. Promote collaborative work by fostering a culture of cooperation and information sharing, enabling the team to more effectively address problems encountered during the construction process and prevent the occurrence of chaotic situations.
	Equipment and facility defects	Ensure close coordination between the equipment maintenance team and the production scheduling team. Reasonable production scheduling should take into account the timing and frequency of equipment maintenance to guarantee that the equipment receives adequate upkeep and repairs. Establish a clear responsibility handover process. Personnel newly joining the team or undergoing position changes should receive appropriate training and guidance to ensure the smooth transfer of equipment management responsibilities.
	Lack of monitoring and control systems	Establish dedicated positions within the labor organizational structure specifically for the maintenance of monitoring systems, responsible for the regular upkeep of monitoring equipment and the updating and upgrading of the system. Regularly conduct drills for the monitoring system, including simulations of various faults and emergency scenarios, in order to assess the emergency response capabilities of personnel responsible for the maintenance of monitoring equipment.

(4) Collaborative control scheme for state hazards associated with technological environment and safety behaviors

Table 8 presents a comprehensive investigation into the integrated control scheme for state hazards arising from the interaction between the technological environment and safety behaviors. It explores countermeasures addressing direct unsafe behaviors—such as decision errors, skill-based errors, and perceptual errors—through technical environment factors including construction layout, equipment and facilities, and monitoring and control systems. By implementing measures such as detailed delineation of construction zones, designing user-friendly human-machine interfaces for equipment, and deploying mobile monitoring applications, the approach aims to mitigate the hazardous impacts that technical environment deficiencies may impose on the state of safety behaviors, thereby interrupting the potential propagation pathways of risk.

Table 8
Technological environment × Safety behaviors state hazards control scheme

Technological environment factors	Safety behaviors factors	Collaborative control scheme for state hazards interaction
Construction layout	Decision errors	Conduct a detailed subdivision of the construction zones based on engineering characteristics, safety requirements, and task types, refining task demands to the specific operational level. This includes delineating precise procedural steps, specifying the tools and equipment to be used, and outlining the requisite safety measures, thereby mitigating decision-making errors among personnel caused by ambiguous information. Establish clear safety signs and warning notices at the construction site, and perform regular inspections of their condition to ensure they remain clearly visible, undamaged, and unobstructed. This practice reduces decision-making errors arising from the absence or inadequacy of safety information.
Equipment and facilities	Skill-based errors	Design user interfaces for equipment that are easy to understand and operate, maintain optimal interface responsiveness, ensure real-time operation, and thereby reduce technical errors caused by delays. Implement regular rotation of equipment operators to cultivate employees' familiarity with multiple devices, enhance their comprehensive operational skills, and consequently mitigate their dependence on specific equipment, reducing technical errors associated with the operation of particular devices.
Monitoring and control systems	Perceptual errors	Develop specialized monitoring and surveillance mobile applications to migrate the monitoring and surveillance systems onto mobile devices, enabling employees to access real-time monitoring information anytime and anywhere. This approach enhances employees' situational awareness efficiency and reduces perception errors caused by the inability to obtain timely information. Establish a flexible and adjustable alarm mechanism that calibrates the sensitivity and mode of alarms according to the specific working environment. This ensures that alarms function optimally based on actual conditions, thereby preventing false alarms that may cause miners to overlook genuine state hazards and root hazards.

3 Conclusions and Discussion

This study employs data-driven outcomes as an objective basis for model-driven approaches and utilizes model-driven methods to validate the intrinsic patterns revealed by data-driven analysis. Progressing from correlation to causation, the coal mine accident causal network is reconstructed by leveraging the underlying safety principles embedded within data. The analysis focuses on the interconnected causal factor sets associated with resource management, organizational process, planned operations, and technological environment. It further explores the critical nodes through which risk is transmitted sequentially from external management levels downward. Based on this, eight hypothesized relationships concerning the roles of state hazards are proposed. Building upon these hypotheses, the study advances structural models regarding the risk transmission mechanisms of state hazards in coal mine production. Measurement items for each variable are developed accordingly. Subsequently, the hypothesized interaction paths among state hazards are

empirically tested via large-sample research, enabling the validation of causal relationships among state hazards from the perspectives of practical operations and work experience, thereby providing novel insights for coal mine safety management research.

While this study provides novel insights into the risk transmission pathways of state hazards in coal mine production, it is important to acknowledge certain limitations that warrant consideration for future research. Firstly, the construction of the coal mine accident causation network relies on 974 accident investigation reports. Although this dataset is substantial, it inherently reflects past incidents and may not fully capture emerging or less frequently reported risk factors. The quality and completeness of these historical reports can also influence the accuracy of the identified associative pathways and causative nodes. Secondly, the proposed risk transmission structural model, while empirically validated, represents a simplification of a highly complex socio-technical system. The dynamic and adaptive nature of coal mine operations means that certain nuanced interactions and feedback loops might not be fully encapsulated within the current static model. Building upon the findings and acknowledging the limitations of this study, future research should focus on developing dynamic, real-time risk monitoring and early warning systems that integrate advanced artificial intelligence and big data analytics to capture the evolving nature of state hazards. Furthermore, exploring the cross-industry applicability of the proposed risk transmission structural model could provide valuable comparative insights and contribute to a more universal framework for industrial safety management.

Declarations

Declarations

The-authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution

Z.F. conceived and designed the study, performed the formal analysis, curated the data, developed the methodology, acquired the resources, prepared the visualizations, and wrote the original draft of the manuscript. X.Z. contributed to resource acquisition, investigation, and visualization. G.X. and Z.F. performed formal analysis and contributed to the conceptualization and methodology. All authors reviewed the manuscript.

Data Availability

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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Figures

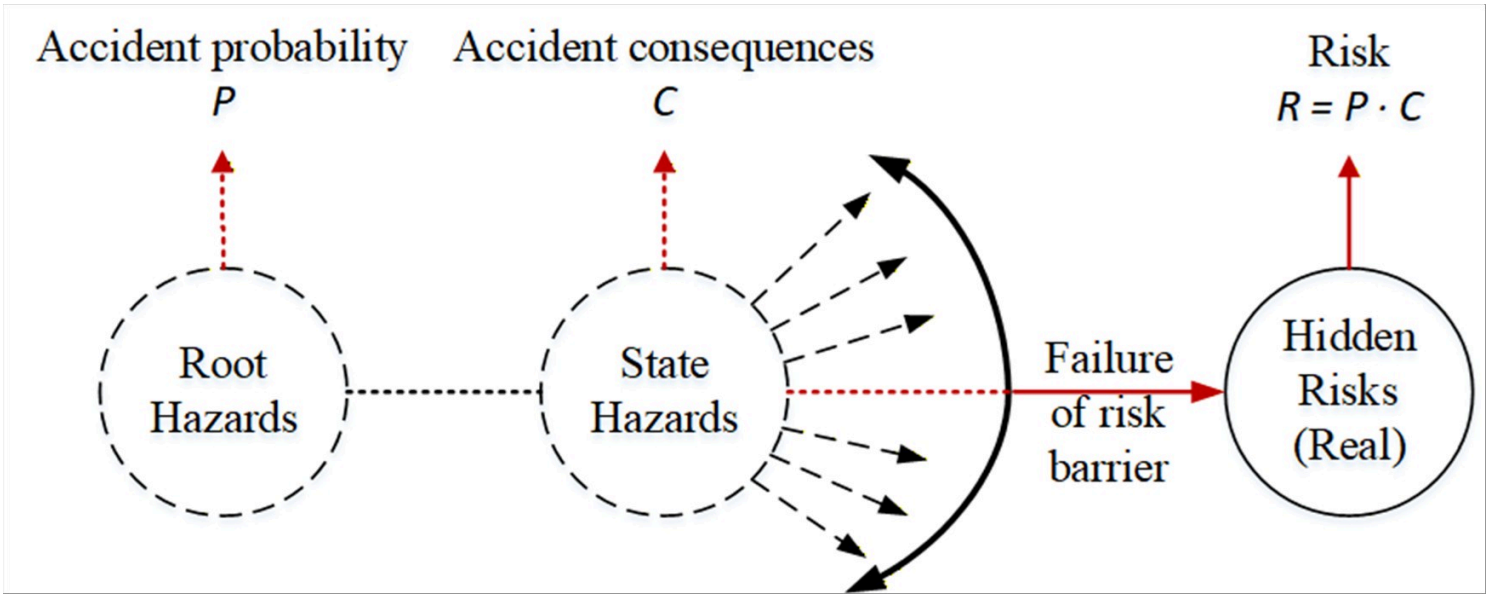


Figure 1

Correlation diagram among hazards, hidden risks, and accidents

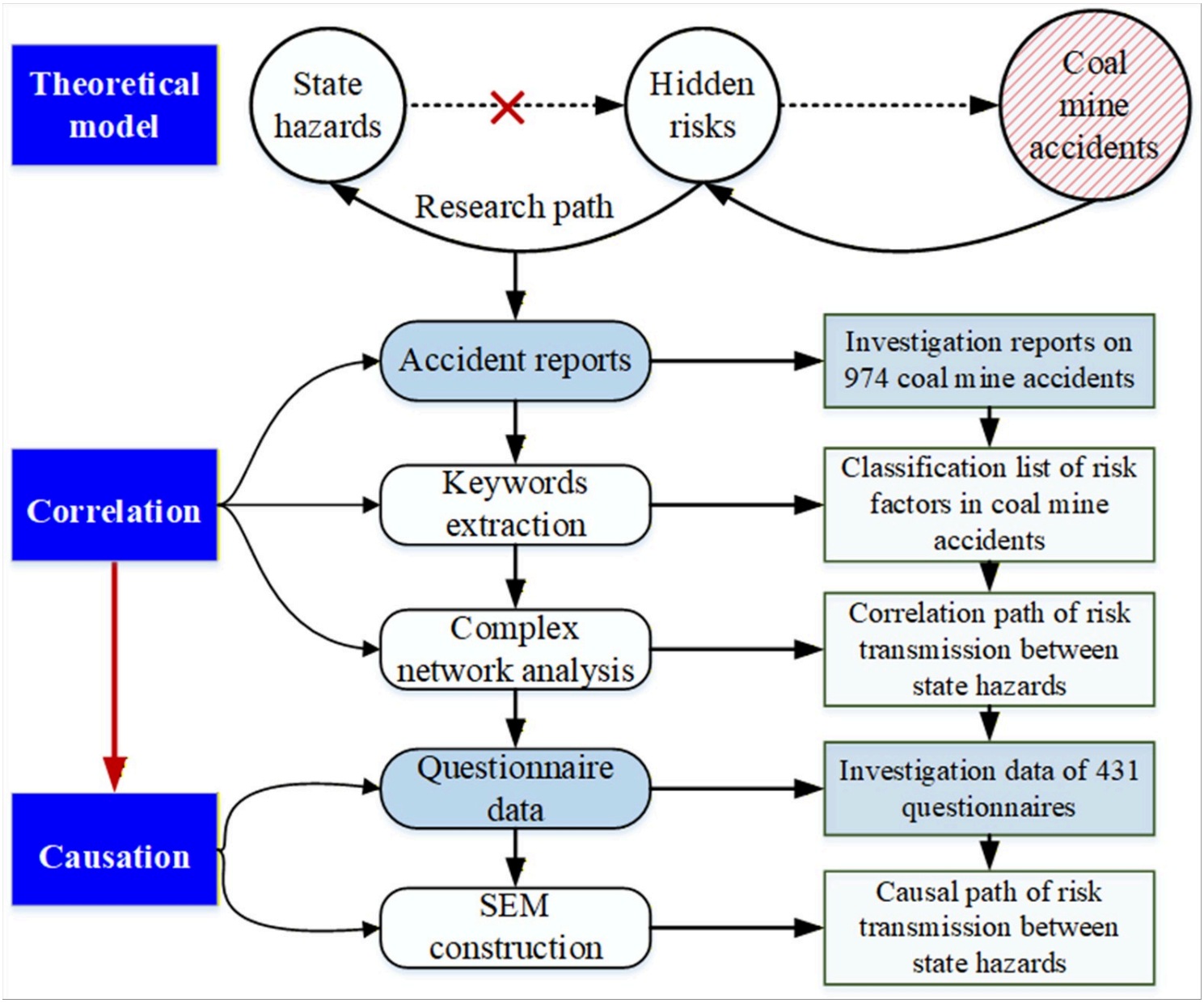


Figure 2

Research framework

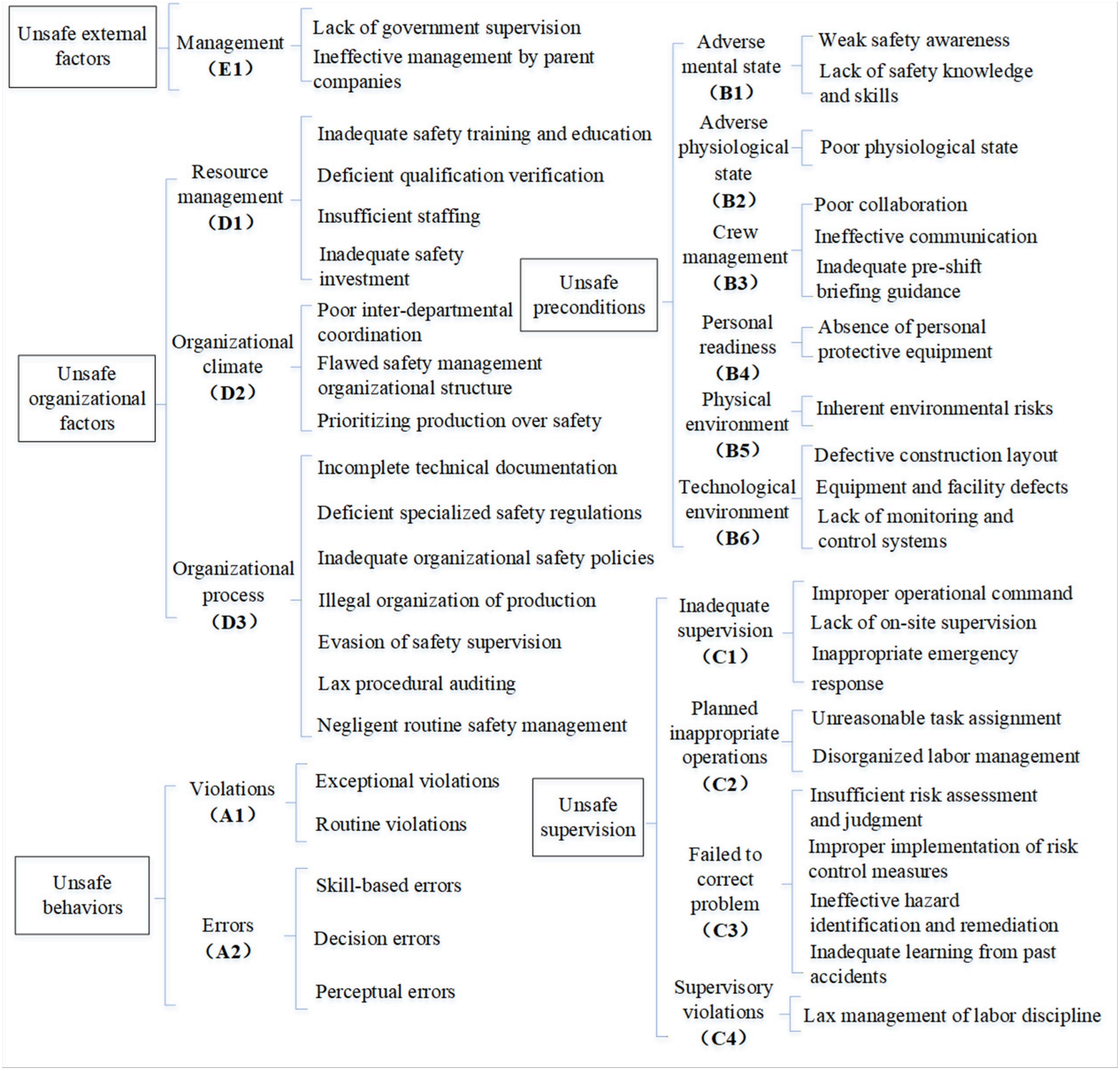


Figure 3

Classification of risk factors in coal mine production

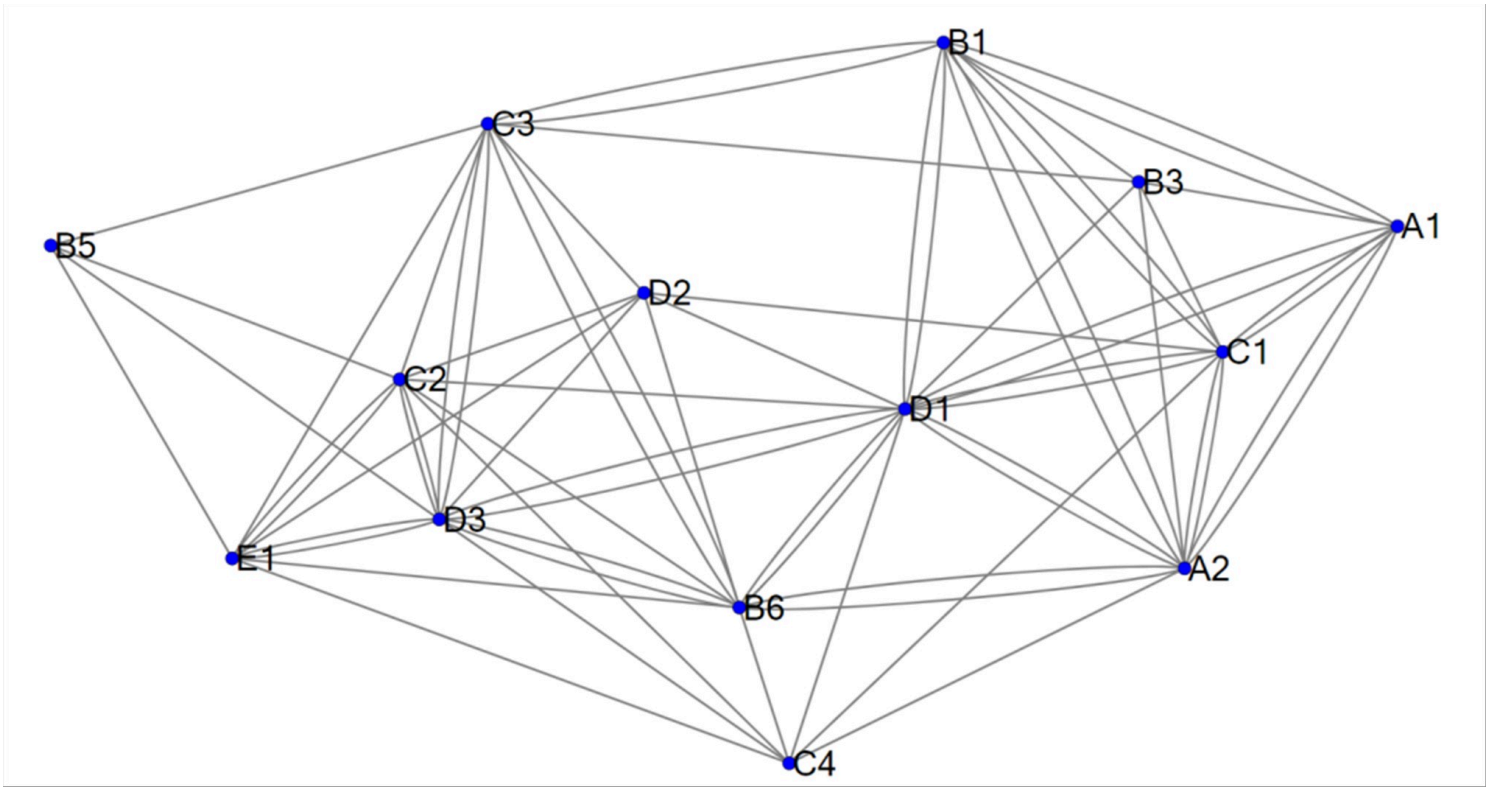


Figure 4

Causal network of coal mine accidents

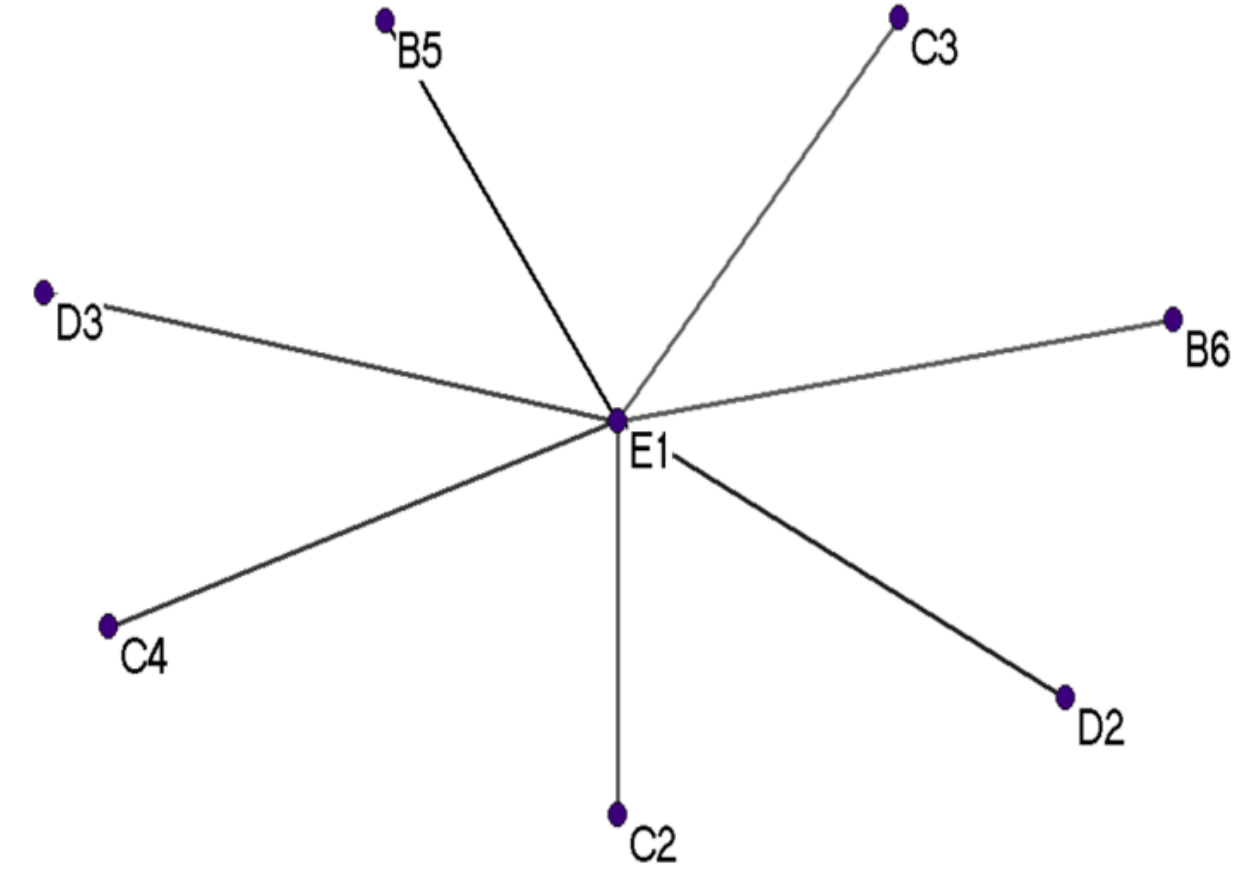


Figure 5

Correlation network of coal mine risk causative node E1

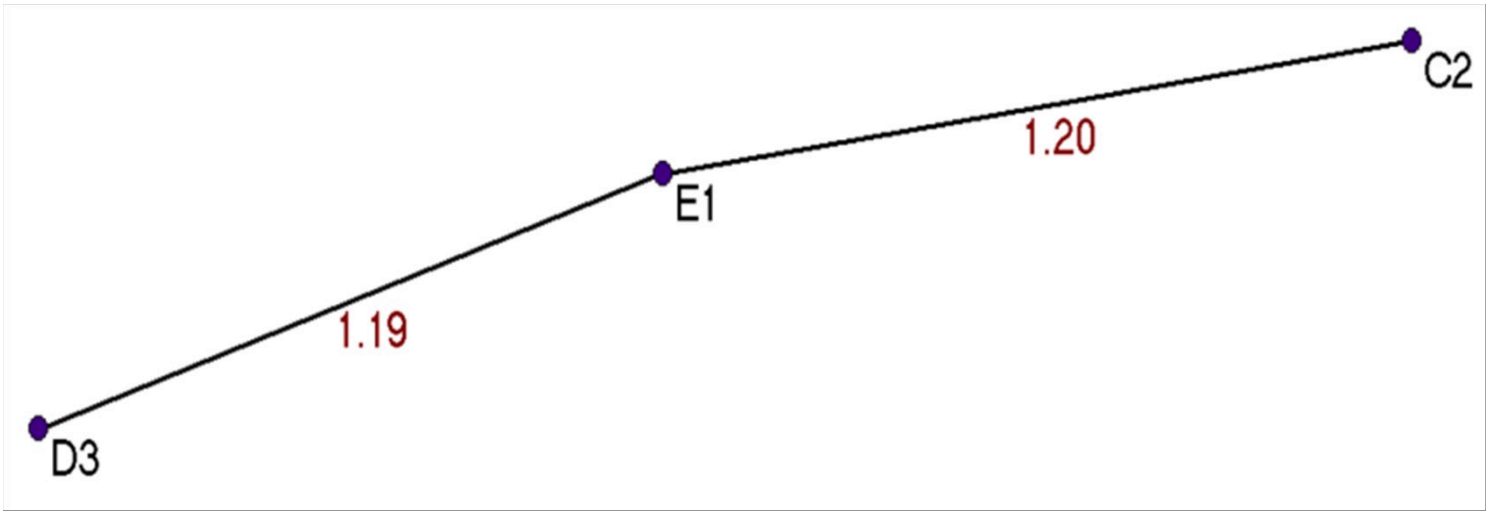


Figure 6

Strongly associated path of risk causative node E1

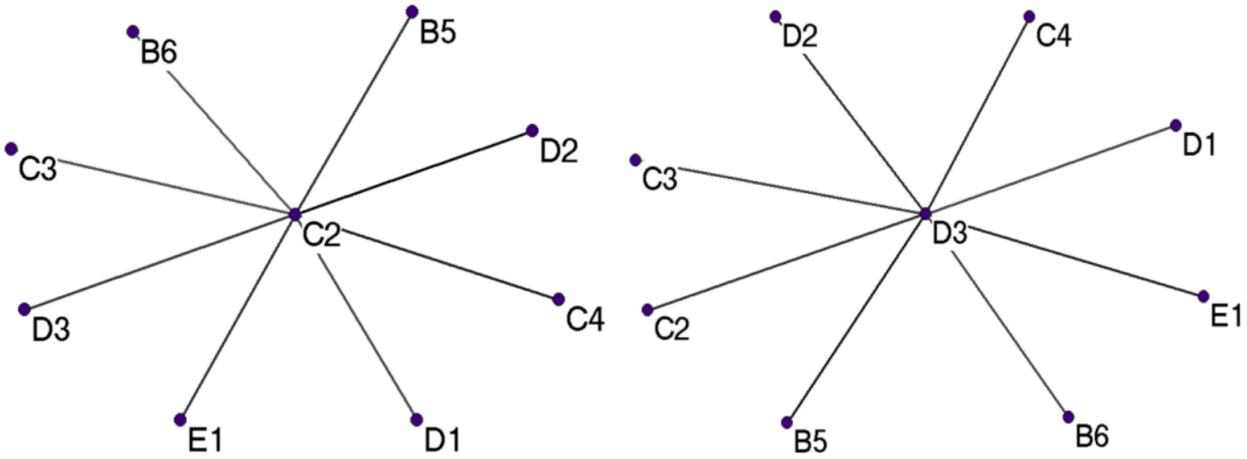


Figure 7

Correlation network of coal mine risk causative nodes C2 and D3

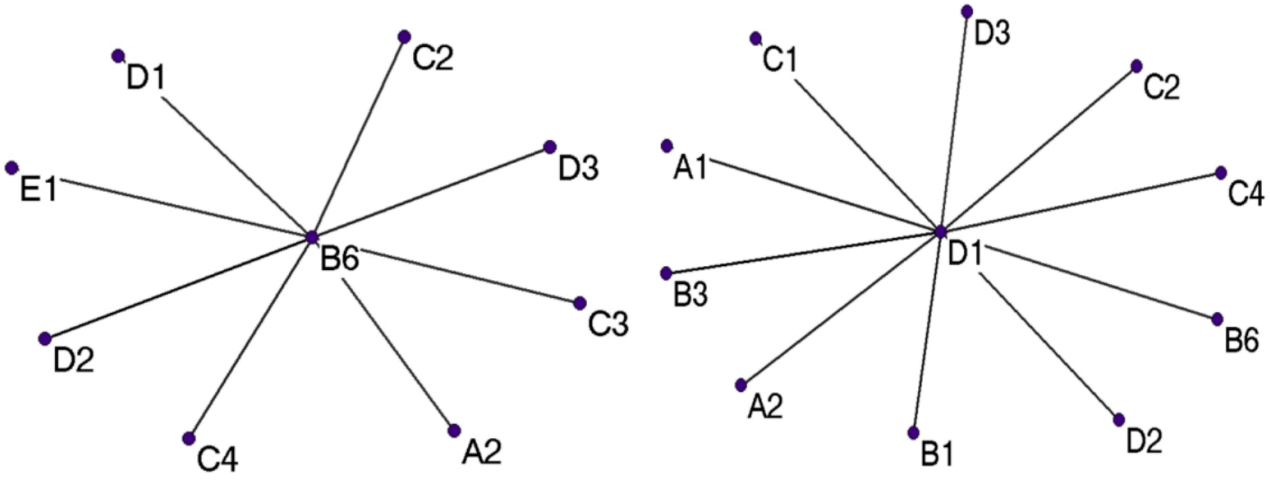


Figure 8

Correlation network of coal mine risk causative nodes B6 and D1

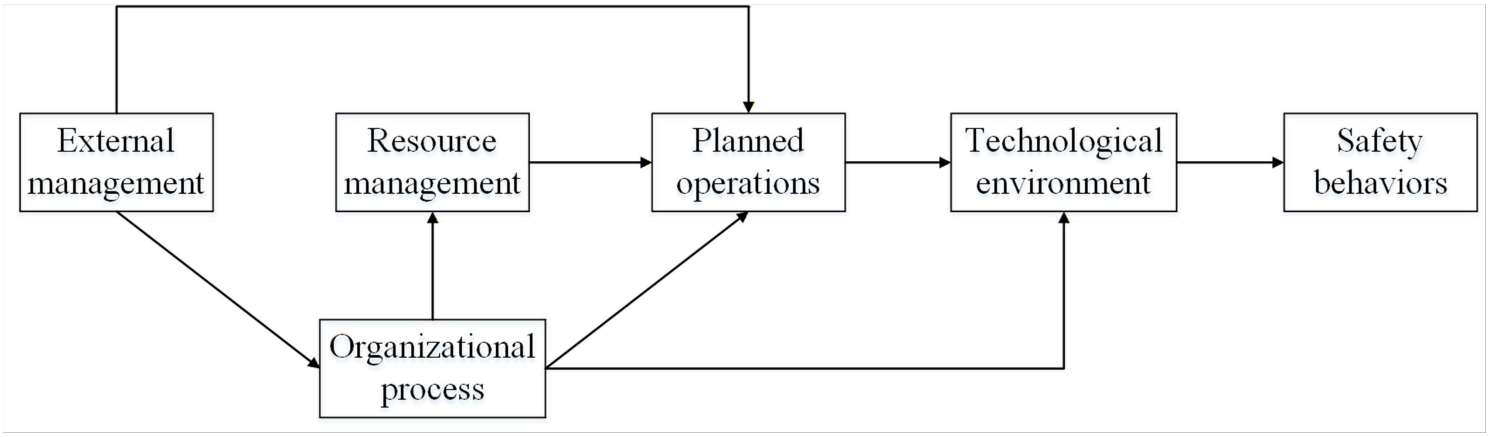


Figure 9

Risk transmission structural model of state hazards in coal mine production

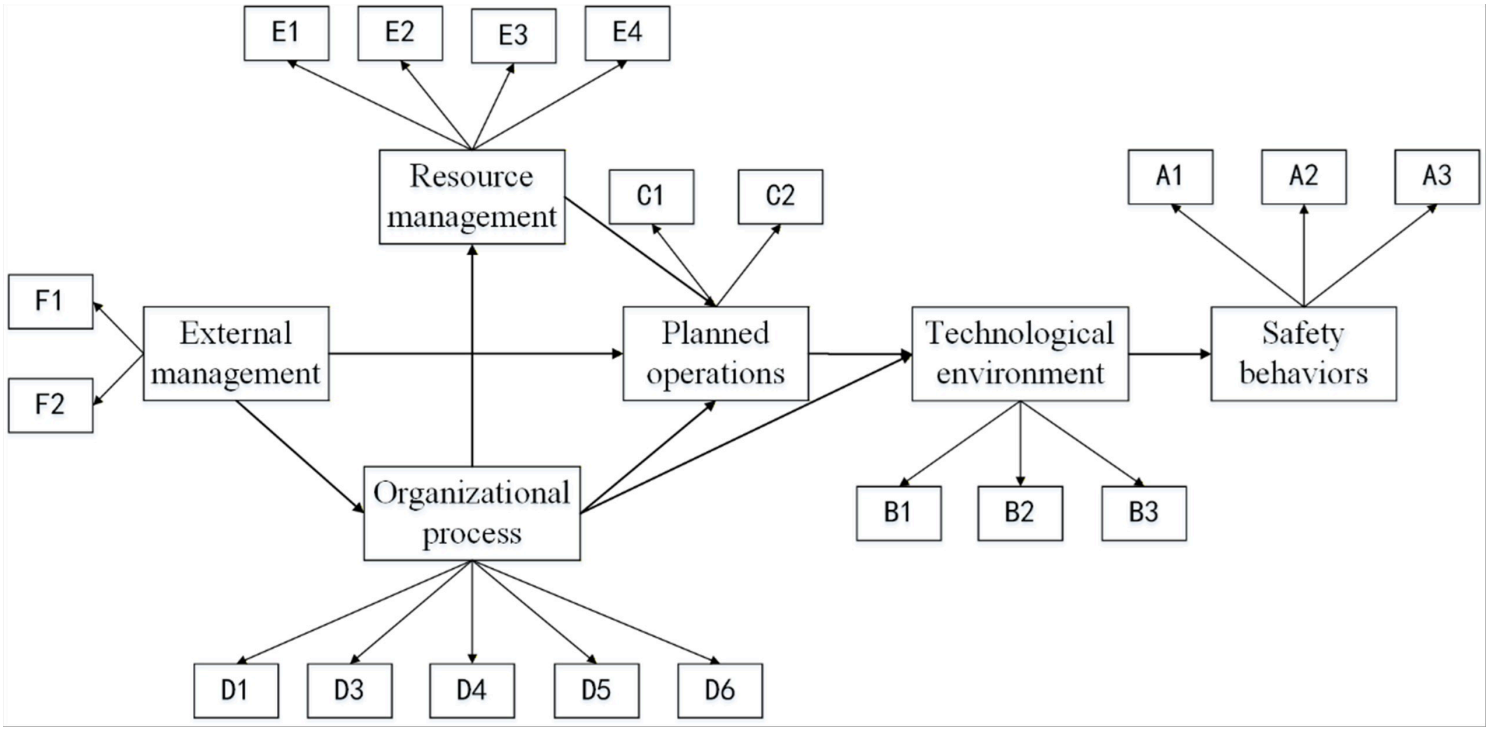


Figure 10

Risk transmission analysis model of state hazards in coal mine production

Supplementary Files

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- Appendix.docx