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Cause Analysis of Elevator Accidents Based on Complex Network

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Abstract: - In order to excavate the key causes of elevator accidents, 70 elevator accident investigation reports from 2018 to 2023 were collected, and data mining was carried out to extract "4M" unsafe factors. On this basis, based on the complex network, the model of elevator accident causation network is constructed, and the statistical characteristics of this model are analyzed. Finally, the entropy weight-TOPSIS is used to construct a comprehensive evaluation model of network node importance, which comprehensively evaluates the causes of elevator accidents from four indicators, including degree centrality, intermediary centrality, proximity centrality and aggregation coefficient of nodes, and identifies the key factors of elevator accidents. The results show that unsafe factors such as defects of equipment and facilities, illegal operation, improper operation, weak safety awareness, inadequate implementation of safety responsibilities, and inadequate on-site supervision are the key causes of elevator accidents, which need to be controlled and controlled.

Keywords: Complex Network, Elevator Accident, Cause of the Accident, Network Characteristics, Entropy Weight-TOPSIS.

I. INTRODUCTION

Elevators, as specialized equipment, are widely used in residential areas, commercial zones, transportation, and public service areas, closely tied to people's daily lives. Their safety pertains to the protection of people's lives and property. According to the "Announcement on the Safety Situation of Special Equipment Nationwide" released by the State Market Regulatory Authority [1], the proportion of elevator accidents in special equipment accidents was around 20% for 2020-2021, second only to onsite specialized motor vehicle accidents and crane machinery accidents. Therefore, in order to effectively prevent or reduce elevator accidents, strengthening risk control in elevator production and operation, systematically analyzing the factors of elevator accidents, and identifying the key causes are of practical significance for enhancing the safety management level of elevator equipment.

Currently, research on elevator safety incidents primarily focuses on risk assessment, fault prediction, and risk factor analysis. Wang et al. [2] employed the fishbone diagram and AHP methods to evaluate the elevator braking system. Zhang [3] introduced an evaluation method for elevator faults based on FaHA. Tang et al. [4] presented a safety index evaluation method for elevators based on Bayesian networks, addressing the uncertainty in complex electromechanical environments, and enabling maintenance alerts and intelligent responses. Du Ya et al. [5] utilized grounded theory and structural equation modeling to analyze the multifaceted risk factors and their mechanisms for elevator safety and performed a comprehensive assessment of elevator safety risk warnings based on the fuzzy evaluation method. Du Zihao et al. [6] integrated risk levels and grey theory for a holistic assessment of elevator safety.

For accident prediction research, many scholars have utilized big data technologies [7], machine learning techniques [8], light gradient boosting machine [7], decision tree algorithms, etc., to predict elevator equipment failures [9]. Jin Lianghai et al. [10] established a dynamic differential prediction model to forecast the accident occurrence rate of elevators.

Regarding the causes of elevator accidents, based on case analyses, scholars have explored from various aspects including personality factors and safety attitudes [11], human errors [12], component systemic factors [13], and analyzed factors like elevator fault [14], risk elements in elevator inspection processes, and elevator braking system failures, offering safety management recommendations [15,16]. Feng [17] identified three safety issues in aging elevators, including brake spring detachment, non-standard door locks, and broken springs in wire rope connectors causing operational risks. Zhang [18] analyzed the key factors leading to a sudden change in risk perception.

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Most of the aforementioned studies explore risk assessment and prediction from a macro perspective, lacking a systemic analysis of the interactive relationships among elevator accident causes.

Complex network theory has been extensively applied in the field of accident cause analysis. By using complex networks, the interrelations among causes are analyzed in diverse fields like coal mine accidents [19], chemical industry accidents [20], Tower-Crane Accidents [21], and construction accidents [22]. Yet, there are few applications of complex network theory in the domain of elevator safety accidents, considering a systemic analysis of all-rounded causes like humans, objects, environment, and management.

Based on the analysis of 70 elevator accident cases, this paper, using complex network theory and the entropy-TOPSIS method, builds both the elevator accident causation network model and the elevator accident causation decision model. This helps identify the key factors of elevator accidents, offering a foundation for elevator safety management and comprehensive governance of elevator safety production accidents. The rest of this paper is organized as follows: Section 2 introduces the complex theory and its features; Section 3 presents the construction of the elevator accident causation network model; Section 4 delves into the characteristics analysis of the elevator accident causation network model; Section 5 concludes.

II. Complex Network Theory and its Characteristics

The network constructed by abstracting a complex system can be referred to as a complex network, which exhibits complexity in network structure, node complexity, and the interplay of various complexity factors. Below, we will focus on introducing several statistical characteristics of directed complex networks [23]:

A. Diameter of the Network

The maximum distance between any two nodes in a network is called the diameter of the network, denoted as *D*,

$$D = \max_{i,j} d_{ij} \tag{1}$$

where, d_{ij} represents the number of edges on the shortest path connecting these two nodes v_i and v_j.

B. Average Path Length

It measures the degree of separation between network nodes and reflecting the global characteristics of the network. Its expression is:

$$L = \frac{\sum_{i \geq j} d_{ij}}{N(N-1)} \tag{2}$$

where, N is the number of network nodes; d_{ij} is as mentioned above.

C. Node Degree and Degree Centrality

It is an indicator in the complex network representing the importance of the node.

The in-degree of node v_i represents the causal events for event. The higher the value, the more paths lead to that event, and the more difficult it is to control. Its expression is:

$$D_i^{in} = \sum_{j \in N} e_{ji} \tag{3}$$

where, N is as mentioned above; e_{ji} is the number of edges from node v_j pointing to node v_i.

The out-degree of node v_i represents the number of events triggered by that event. The higher the value, the more severe the consequences caused by the event. Its expression is:

$$D_i^{out} = \sum_{j \in N} e_{ij} \tag{4}$$

where, N is as mentioned above; e_{ij} is the number of edges from node v_i pointing to node v_j.

The total degree of node v_i is the sum of in-degree and out-degree. The expression is:

$$D_i = D_i^{in} + D_i^{out} \tag{5}$$

Degree Centrality (DC_i) is an index measuring the importance and influence of network nodes in complex networks. The expression is: $DC_i = D_i/(N-1)$ where, N is as mentioned above; D_i is the degree of node v_i.

D. Betweenness Centrality

It measures the number of shortest paths passing through node v_i in a network, reflecting the influence of that node in the entire network, its mediating capability, and its bridging role. It is an indicator in complex networks that measures node centrality. The normalized expression is:

$$BC_i = \frac{\sum_{\substack{k \neq m \neq i, \\ k,m,i \in N}} \frac{\delta_{km}(i)}{\delta_{km}}}{(N-1)(N-2)} \tag{6}$$

where, N is as mentioned above; represents the number of shortest paths from node v_k to node v_m passing through node v_i; δ_{km} denotes the number of shortest paths from node v_k to node v_m.

E. Closeness Centrality

It indicates the closeness of node v_i to other nodes. The higher the value, the shorter the minimum distance from that node to other nodes, implying that the event can more easily spread risks to other events. It is an indicator in complex networks that measures node centrality. The expression is:

$$CC_i = \frac{1}{d_i} = [\frac{1}{N-1}\sum_{j=1}^{N} d_{ij}]^{-1} \tag{7}$$

where, N is as mentioned above; d_{ij} is as mentioned above.

F. Clustering Coefficient

It measures the degree of aggregation of node vi. The expression is:

$$C_i = E_i / [D_i(D_i - 1)] \tag{8}$$

where, E_i represents the actual number of edges existing between nodes neighboring node v_i; D_i represents the degree of node v_i.

III. Construction of the Elevator Accident Causation Network Model

A. Causation Analysis of Elevator Accident Samples

Based on the accessibility of elevator accident data, this paper selects 70 elevator accidents from 2018 to 2023, including 38 falls, 13 squeezes, 4 object strikes and electric shocks each, 3 collapses and other types of accidents each, 2 entrapments and overshoots each, and 1 shearing accident. The data is sourced from elevator accident investigation reports published on national and local official websites. Combining the "4M" unsafe factors of man, material, environment, and management leading to accident causes, 24 sub-unsafe factors and 9 types of elevator accidents were identified, as shown in Table 1.

B. Establishment of the Elevator Accident Causation Network Model

An elevator accident causation network G (A, S, R) is established based on complex network, where $A = \{A_1, \ldots, A_9\}$ represents the set of accident nodes, $S = \{S_1, \ldots, S_{24}\}$ represents the set of causation nodes, and A and S form the set of network nodes; R represents the set of network edges constituted by the relationships between network nodes. If a particular unsafe factor leads to another unsafe factor, or if an unsafe factor leads to a certain type of accident, there are connections between the unsafe factors or between the unsafe factor and the accident.

Table 1: Elevator Accident Types and Unsafe Factors

Accident Type Nodes		Fall A_1, Squeeze A_2, Object Strike A_3, Electrocution A_4, Collapse A_5, Entrapment A_6, Overshoot A_7, Shearing A_8, Other Accidents A_9
Accident Causation Nodes	Human Factors	Violation of Regulations S_1, Improper Operation S_2, Working Without Certification S_3, Inadequate Emergency Response S_4, Lack of Safety Awareness S_5, Negligence in Supervision S_6, Negligence in Observation S_7
	Material Factors	Lack or Failure of Protective Measures and Safety Devices S_8, Defects in Equipment, Facilities, Tools, or Accessories S_9, Lack or Defects in Personal Protective Equipment S_{10}
	Environmental Factors	Poor Working Environment in Production (Construction) Site S_{11}
	Management Factors	Illegal or Irregular Construction, Contracting, and Subcontracting S_{12}, Failure to Implement Safety Responsibilities S_{13}, Inadequate Implementation of Safety Regulations and Systems S_{14}, Insufficient Qualifications S_{15}, Violation of Command S_{16}, Incomplete Construction Plans S_{17}, Insufficient Safety Education and Training S_{18}, No Safety Technical Briefing S_{19}, Failure to Supervise and Inspect Safety Work S_{20}, Inadequate On-site Supervision S_{21}, Inadequate Maintenance S_{22}, Inadequate Quality and Safety Inspections S_{23}, Failure to Inspect in Time S_{24}

The aforementioned 24 sub-unsafe factors and 9 accident types are taken as nodes of the elevator accident causation network. The association between unsafe factors or between unsafe factors and elevator accidents serves as the edges of the network. Using the Pajek software, an elevator accident causation network model is established, as shown in Figure 1 (in the figure, circles represent network nodes, and arrows indicate the influence relationships between sub-unsafe factors and between accidents).

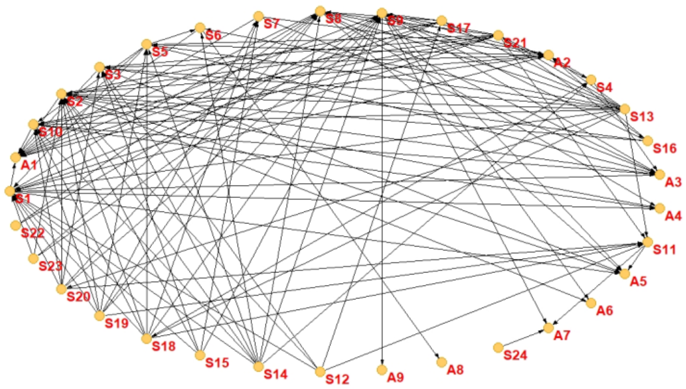

Figure 1: Elevator Accident Causation Network Model

IV. Analysis of the Features of the Elevator Accident Causation Network Model

Based on the model established above, this paper mainly analyzes the model's features from the perspectives of overall characteristics, node degree, betweenness centrality, closeness centrality, and clustering coefficient. Based on this, combined with uncertain multi-attribute decision-making theory, the entropy weighted TOPSIS is established to comprehensively analyze the importance of causation nodes from four indicators: node degree, betweenness centrality, closeness centrality, and clustering coefficient.

A. Overall Network Feature Analysis

In the constructed elevator accident causation network model, calculations show: 22 network nodes and 129 arrows. The network's diameter is 3, indicating that any two factors in an elevator accident can influence each other in a maximum of three steps. L is 1.479, suggesting that the factors on average need about 2 steps to influence each other. The relationships between factors and accidents are relatively close. Overall, the connection between accident causes or between causes and accidents is tight. If any factor in the network fails, the risk of diffusion is high. A rapid emergency mechanism must be established to avoid a chain reaction from the failure of any unsafe factors, making it difficult to control overall.

B. Node Degree Analysis

In-degree Analysis: According to the in-degree formula given in section 1.3, the in-degree values of each node in this network model can be calculated, as shown in Figure 2. The calculated results show that the in-degree values of fall and squeeze accidents are the highest. Many factors lead to such accidents, such as Violation of Regulations S_1, Improper Operation S_2, Working Without Certification S_3, Lack or Failure of Protective Measures and Safety Devices S_8, Lack or Defects in Personal Protective Equipment S_{10}, all pointing to the fall and squeeze accident nodes. This indicates that these factors will cause such accidents. In causation nodes, Violation of Regulations S_1, Improper Operation S_2, and Defects in Equipment, Facilities, Tools, or Accessories S_9 have the highest in-degree values. Followed by Lack or Failure of Protective Measures and Safety Devices S=, Lack or Defects in Personal Protective Equipment S_{10}, Working Without Certification S_3, indicating these factors are influenced by more other factors in elevator accidents. Once an anomaly is detected in any factor, these factors have a higher chance of being affected.

Out-degree Analysis: As seen in Figure 2, since A_1-A_9 are accident nodes and do not point to other accidents or factors, their out-degree values are all 0. In the network model, the causation node with the highest out-degree value is Failure to Implement Safety Responsibilities S_{13}. Followed by Inadequate On-site Supervision S_{21}, Inadequate Implementation of Safety Regulations and Systems S_{14}, Insufficient Safety Education and Training S_{18}, No Safety Technical Briefing S_{19}, indicating these factors influence more other factors to become abnormal and are the root causes of various accident types. These factors are primarily management-related, suggesting the need for improvements at the fundamental management level for elevator safety.

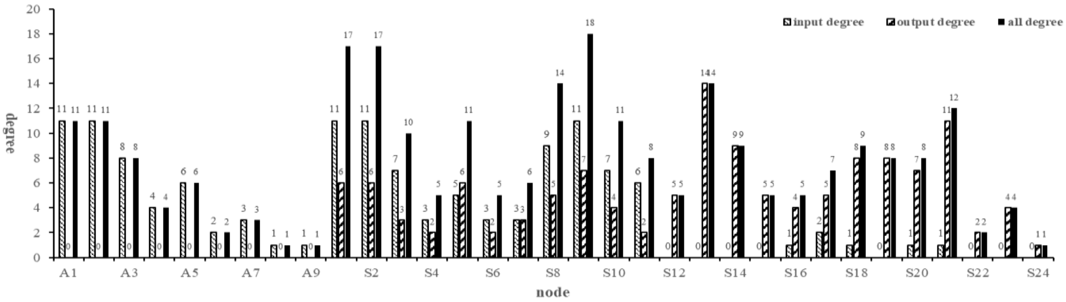

Figure 2: Degree Values (D^{in}, D^{out}, D) of Elevator Accident Causation Network Nodes

Total Degree Analysis: As seen in Figure 2, in the network model, causation nodes such as Defects in Equipment, Facilities, Tools, or Accessories S_9, Violation of Regulations S_1, Improper Operation S_2, Lack or Failure of Protective Measures and Safety Devices S_8, Failure to Implement Safety Responsibilities S_{13}, Inadequate On-site Supervision S_{21} have significantly higher total degree values, indicating that these factors hold core positions in elevator accident factors and should be given priority attention and control.

C. Betweenness Centrality Analysis

According to the calculation formula of betweenness centrality given in Section 1.4, the betweenness centrality of each causal node in the network model can be obtained, as shown in Figure 3. The calculation results show that the betweenness centrality of various factors ranges from 0 to 0.036. There are 9 factors with a betweenness centrality of 0, namely S_{12}-$S_{15,}$ S_{19}-S_{20} and S_{22}-S_{24}, indicating that these factors do not play a mediating role in the causal network. However, the causal nodes $S_{8,}$ S_9 and other unsafe states of objects, as well as S_1, S_2, S_5, and other unsafe human behaviors, have relatively high betweenness centrality. This suggests that these factors act as bridges in the elevator accident causation network model and have a significant impact on the propagation of unsafe factors in the entire network. They are the key unsafe factors that require special management and control.

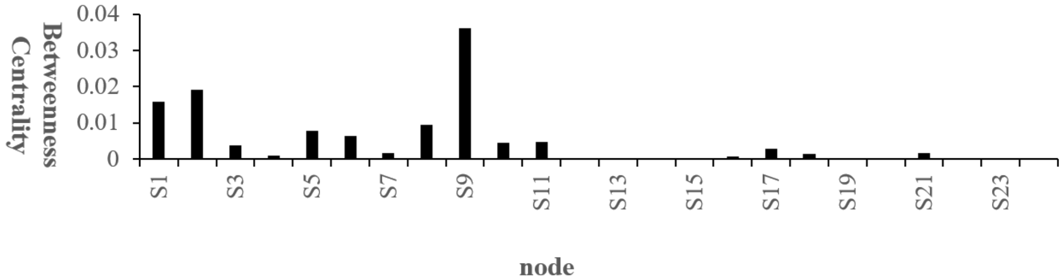

Figure 3: Betweenness Centrality of Causal Nodes in the Elevator Accident Causation Network

D. Closeness Centrality Analysis

Based on the calculation results of the closeness centrality formula provided in Section 1.5 and combined with Figure 4, the closeness centrality of various factors ranges between 0.3 and 0.7. Causal nodes such as defects in equipment, facilities, tools, and attachments (S_9), violation of work rules (S_1), improper operation (S_2), and lack of safety responsibility implementation (S_{13}) have relatively high closeness centrality. This indicates that these causal nodes have short minimum distances to other nodes, occupying central positions in the network. They can influence other factors at a rapid rate. When these causal nodes are at risk, they need to be controlled quickly to prevent the spread of risks.

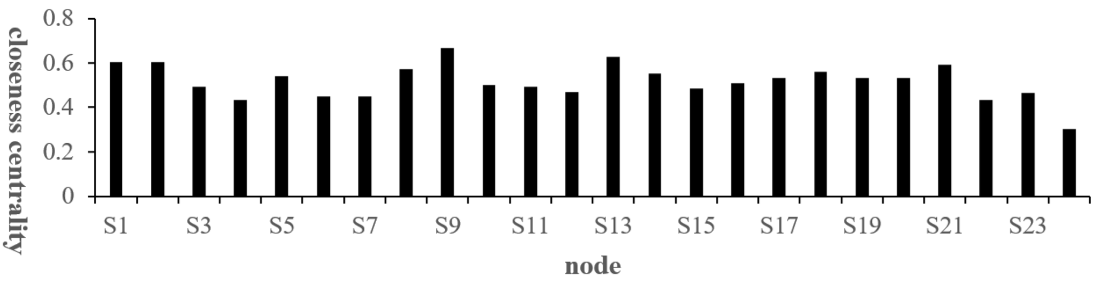

Figure 4: Closeness Centrality of Causal Nodes in the Elevator Accident Causation Network

E. Clustering Coefficient Analysis

Based on the calculation results of the clustering coefficient formula provided in Section 1.6 and combined with Figure 5, the clustering coefficients of various factors range from 0 to 0.3. Notably, the clustering coefficient of the failure to inspect on time (S_{24}) is 0. This is because this node only has one adjacent point with a degree value of 1. Therefore, the Pajek software displays the result as 999999998 (error value). In this study, it is set to 0. Causal nodes like violation of command (S_{16}), incomplete construction plans (S_{17}), weak safety awareness (S_5), lack of safety responsibility implementation (S_{13}), and inadequate on-site supervision (S_{21}) have relatively high clustering coefficients. This suggests that the factors connected to these unsafe factors are closely linked and can easily influence each other. Therefore, when managing and controlling these kinds of factors, special attention should be paid to the chain reactions caused by the control of one unsafe factor, which could affect the safety of the entire system.

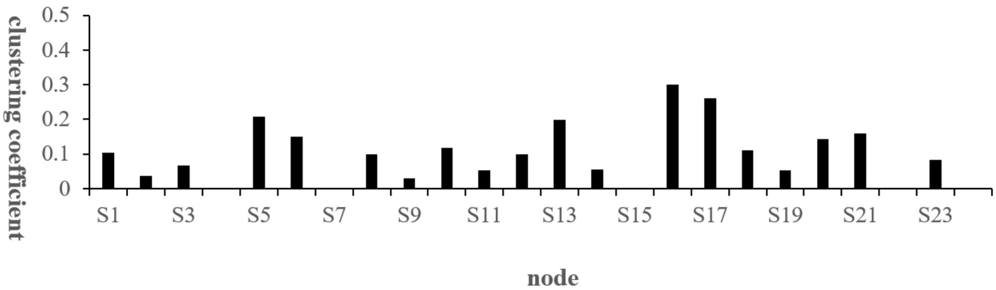

Figure 5: Clustering Coefficient of Causal Nodes in the Elevator Accident Causation Network

F. Comprehensive Analysis of the Importance of Unsafe Factors in Elevator Accidents

In the complex network model, centrality indicators (DC_i, BC_i, CC_i) are metrics used to determine the influence or importance of network nodes. Although these indicators measure the influence and importance of network nodes, the focus of measurement standards is different: node degree centrality mainly uses the local characteristics of the network to measure the importance of a node without considering the information of its neighboring nodes; both node betweenness centrality and closeness centrality use the characteristics of the entire network, reflecting the degree of connection and the connectivity ability of the node in the network between nodes.

Since the aforementioned centrality indicators only reflect the importance and influence of network nodes from a single perspective and cannot fully reflect the importance of nodes, using clustering coefficient 、 the 3 types of centralities of network nodes and the entropy weight-TOPSIS, a comprehensive importance evaluation model for unsafe factors of the elevator accident causation network is constructed to comprehensively rank the causes of elevator accidents.

(1) Constructing the Network Node Evaluation Matrix

Assuming there are m evaluation nodes in the elevator accident causation network and n evaluation indicators, x_{ij} is the attribute value of the ith network node regarding the jth indicator. After standardization and normalization, the original form of the network node evaluation matrix is expressed as:

$$X=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \xrightarrow{x_{ij}=\frac{x_{ij}-x_{\max}}{x_{\max}-x_{\min}}} X'=\begin{bmatrix} x'_{11} & x'_{12} & \cdots & x'_{1n} \\ x'_{21} & x'_{22} & \cdots & x'_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x'_{m1} & x'_{m2} & \cdots & x'_{mn} \end{bmatrix} \xrightarrow{p_{ij}=\frac{x'_{ij}}{\sum_{i=1}^{m} x'_{ij}}} P=\begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ p_{m1} & p_{m2} & \cdots & p_{mn} \end{bmatrix} \quad (9)$$

(2) Determining Indicator Weight Using the Entropy Method

E_j of the jth indicator is expressed as:

$$E_j=-\frac{1}{\ln m}\sum_{i=1}^{m} p_{ij}\ln p_{ij}, \quad j=1,2,...,n \quad (10)$$

Then the entropy weight W_j can be represented as:

$$W_j=\frac{1-E_j}{\sum_{j=1}^{n}1-E_j}, \quad j=1,2,...,n \quad (11)$$

(3) Determining the Comprehensive Importance Evaluation Value of Network Nodes Using the TOPSIS Method

The weighted normalized matrix $Z=PW_j$ can be obtained by the normalized evaluation matrix P of network nodes and the weight W_j of each indicator.

Based on the weighted normalized matrix Z, the positive (negative) ideal value Z^+ (Z^-) are obtained,

$$D^{+}=\left\{\max\left|z_{i1},z_{i2},\ldots,z_{in}\right.\right\},\quad i=1,2,...,m$$
$$D^{-}=\left\{\min\left|z_{i1},z_{i2},\ldots,z_{in}\right.\right\},\quad i=1,2,...,m \tag{12}$$

The comprehensive importance level I_i of each node in the elevator accident causation network is expressed as:

$$I_i=\frac{D_i^-}{D_i^+ + D_i^-},\quad i=1,2,...,m \tag{13}$$

Where, $D_i^-=\sqrt{\sum_{j=1}^{n}(D^- - z_{ij})^2},\quad i=1,2,...,m,\quad D_i^+=\sqrt{\sum_{j=1}^{n}(D^+ - z_{ij})^2},\quad i=1,2,...,m$.

Based on the value of the comprehensive importance degree I_i, the importance levels of the nodes are ranked. The larger the value, the stronger the comprehensive importance of the corresponding network node.

Through the above steps, the ranking results of the importance of each node are as follows: $S_9 > S_1 > S_2 > S_5 > S_{16} > S_{17} > S_8 > S_{13} > S_{21} > S_{10} > S_6 > S_{20} > S_{18} > S_3 > S_{11} > S_{14} > S_{19} > S_{12} > S_{23} > S_7 > S_{15} > S_4 > S_{22} > S_{24}$. The calculation results show that the top 10 in comprehensive importance are defects in equipment, facilities, tools, and accessories S_9, violations of regulations S_1, improper operation S_2, weak safety awareness S_5, violation of commands S_{16}, incomplete construction plans S_{17}, lack of protective measures or malfunction of safety devices S_8, failure to implement safety responsibilities S_{13}, inadequate on-site supervision S_{21}, and lack or defect of personal protective equipment S_{10}.

Overall, in the causation of elevator accidents, human unsafe behavior and management defects play a dominant role. Although the importance of equipment and facilities is ranked first, it is considered a potential factor behind human unsafe behavior. During the entire elevator operation process, human involvement is indispensable. Direct factors in elevator accidents mainly include violations of regulations, improper operations, and weak safety awareness. The root cause of human unsafe behavior is inadequate safety management. Management defects such as failure to implement responsibilities and inadequate on-site supervision lead to unsafe situations for people and objects, resulting in elevator accidents. Therefore, focusing on elevator safety management factors, adopting safety measures, and promptly identifying potential safety hazards are vitally important from the root causes of elevator accidents.

V. CONCLUSIONS

Based on the elevator safety accident investigation report, by constructing an elevator accident causation network model and a network node importance comprehensive evaluation model, a comprehensive analysis of unsafe factors in elevator accidents was conducted, leading to the following conclusions:

(1) The elevator accident causation network exhibits scale-free network characteristics. This network has a relatively short L, a high clustering coefficient for most nodes, and closely related nodes. Nodes with high C_i are more susceptible to rapid spread between factors, triggering chain reactions, leading to various elevator accidents.

(2) In elevator accidents, human-management factors relatively dominate. Apart from defects in equipment and facilities, unsafe factors like violations of regulations, improper operations, weak safety awareness, failure to implement safety responsibilities, and inadequate on-site supervision are key causes of elevator accidents, which need to be a focal point of control.

(3) By extracting unsafe factors and their interrelationships from elevator accident reports, the results obtained have a certain subjectivity. Further utilization of more objective text data mining techniques is needed to enhance the objectivity of computational results.

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