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# Analysis of Factors Influencing Fire Accidents in Commercial Complexes Based on WSR-DEMATEL-ISM Model

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**Abstract:** Commercial complexes integrate various business formats, and a fire outbreak can lead to widespread, continuous, and chain-reaction social disturbances, including severe casualties, economic losses, and social impacts. To deeply explore the characteristics and influencing factors of fire accidents in urban commercial complexes in China, this study first analyzed fire accident cases in commercial complexes that occurred from 2002 to 2022. Using mathematical statistics, the analysis examined the year and month of the accidents, their severity, and their causes to identify key risk factors associated with fire hazards in urban commercial complexes. Subsequently, based on the WSR methodology, an index system for assessing the influencing factors of fire accidents in commercial complexes was constructed, encompassing four aspects: personnel, equipment, environment, and management, including 11 cause indicators and 9 outcome indicators. Then, the Decision Experiment and Evaluation Laboratory Method (DEMATEL) was used to quantitatively analyze the relationships among influencing factors, combined with Interpretative Structural Modeling (ISM) to perform a hierarchical categorization of the factors and identify those critically influencing commercial complex fires. This research indicates that critical influencing factors include inadequate regulations, insufficient fire safety inspections, inadequate safety training, careless use of fire during operations, inadequate government supervision, illegal renovations, unimplemented corporate fire safety responsibilities, and poor routine maintenance and management. These results provide a theoretical reference for effectively preventing and controlling fires in commercial complexes.

**Keywords:** commercial complex; fire accident; influencing factors; WSR-DEMATEL-ISM; fire management



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## 1. Introduction

Commercial complexes, as architectural entities that integrate shopping, leisure, entertainment, and culture, boost urban functionality, fulfilling diverse needs for entertainment, consumption, and transportation and promoting an improvement in the standard of living [1]. However, the multifunctionality of commercial complexes results in large building areas, complex structures, high human traffic, and challenges in ventilation and smoke extraction, posing firefighting challenges such as high fire loads, complex origins of fires, multiple pathways for fire spread, and difficult emergency evacuation and rescue [2]. Fire accidents can lead to substantial losses of life and property. In recent years, the safety situation of urban commercial complexes in China has remained severe, with ongoing fire accidents. For example, the 13 June 2022 fire at a shopping center in Dongsheng District, Ordos City, Inner Mongolia, resulted in two fatalities and an affected area of about 1800 square meters [3], and the 6 April 2021 fire at the Tongluowan Commercial Plaza in Chizhou, Anhui, affected about 400 square meters, resulting in four deaths, two injuries, and direct economic losses of 770,088 dollars [4]. The analysis of the patterns of fire accidents in commercial complexes, the summary of the causes, and the exploration of trends in fire accident development are of significant importance for the advancement of urban public safety and urban firefighting management.

To effectively identify fire hazard factors and reduce the risk of fire accidents, scholars have undertaken extensive research on aspects such as building fire safety, primarily employing methods such as Building Information Modeling (BIM) platform [5], uncertain clustering theory [6], fuzzy comprehensive evaluation [7], and grey analysis theory [8] to analyze fire safety risks in general civil buildings, particularly conducting comprehensive studies on the fire risk of high-rise buildings. For instance, Li et al. [9] developed a gray fuzzy hierarchical mathematical model for the fire risk of high-rise buildings and evaluated the fire hazard of five high-rise buildings, providing new references for fire prevention design in high-rise structures. Hansen et al. [10] used the Fire Risk Model (FRM) to assess the safety of Danish high-rise single-staircase residential buildings; Morry [11] developed an evacuation model for high-rise buildings, analyzing the impact of various evacuation routes on fire evolution. However, research on fire risk assessment for commercial complexes, a special type of building, is limited and primarily at the qualitative stage, without a mature and scientific evaluation system yet. Jiang [12] studied the structural safety of the Shanghai Tower during fire accidents. Fang et al. [13] used the basic principles of hierarchical analysis to establish a fire risk assessment index system for shopping malls, and determining the weights of the indexes in the assessment system based on cluster analysis to determine the fire risk level of the building. Liu et al. [14] focused on fire equipment maintenance to establish a fire risk assessment system for large commercial buildings, using the structure entropy weighting method combined with the Analytical Hierarchy Process to evaluate fire risks in four large commercial buildings in Chongqing. EASIR et al. [15] used the fire dynamic simulator (FDS) to simulate mall fires, studying the impact on emergency evacuation of people. Howard [16] explored the relationship between fire damage in large urban complexes and changes in fire temperature, proposing enhancements based on their coupled effects. Nhiwakoti and Moriyama [17,18] conducted live evacuation experiments to study the factors influencing evacuation behavior in commercial complexes. Ahmed et al. [19] analyzed multiple fire scenarios and corresponding evacuation plans in a large shopping center through simulations, showing that the location of a fire significantly affects smoke propagation.

In summary, in the research field of fire accidents in large commercial complexes, scholars have mainly concentrated on fire risk assessment, building fire resistance, fire simulation, and evacuation. Statistical analysis of fire accidents in commercial complexes has been relatively neglected, with a lack of in-depth exploration of the relationships between fire-influencing factors and difficulty in identifying the main and key factors of fire accidents. The importance of statistical analysis lies in its ability to objectively reflect the circumstances and characteristics of accidents [20], playing a pivotal role in the development of accident prevention strategies, such as in road tunnel fire accidents [21], laboratory fire and explosion accidents [22], construction accidents [23], and coal mine accidents [24]. Therefore, this study collected and organized fire accident data in commercial complexes from 2002 to 2022, selected fire influencing factors, and aims to explore development trends and enhance fire prevention and control capabilities [25], laying the foundation for constructing a system of indicators for fire influencing factors. Considering the diversity, uncertainty, and complex interconnections of fire risk factors in commercial complexes, this research utilized the Wuli–Shili–Renli (WSR) methodology to develop an index system for influencing factors, emphasizing the understanding and assessment of fire risks from the physical, logical, and human dimensions [26].

Zio [27] proposed from a systemic perspective that the causes of accidents not only involve the characteristics of the factors themselves but also originate from the relationships among them. In light of this, employing the Interpretative Structural Modeling (ISM) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods, this study further explored the interactions and hierarchical relationships among fire-influencing factors. The ISM method visualizes complex cause-and-effect relationships, constructing logical relationships and hierarchical structures among elements [28]; meanwhile, the DEMATEL method determines the causal relationships and positions between factors, and their integration effectively reveals the influence and interactions of key elements within the system. The DEMATEL-ISM model is still in its initial stages of application in the field of fire safety, but it has been successfully used in areas such as construction [29], urban gas systems [30], highways [28], and coal mining [31], proving its effectiveness in integrating expert knowledge and establishing order, direction, and hierarchical structures among factors, offering valuable insights for fire risk control in commercial complexes. The application of this methodology enhances the scientific validity and rationality of comprehensive assessments of fire risk factors and, simultaneously, by constructing a hierarchical model of influencing factors, offers clear guidance for managing fire risks in commercial complexes.

The remainder of this paper is organized as follows. Section 2 details the two main methods used in this statistical analysis (namely WSR and DEMATEL-ISM). Section 3 develops an index system for the influencing factors of fire accidents in commercial complexes based on the WSR methodology. Numerical calculations and result analysis employing DEMATEL-ISM are detailed in Section 4. The research conclusion and research limitations are in Section 5.

## 2. Materials and Methods

### *2.1. Framework of Methodology*

To thoroughly investigate the factors influencing fire safety risks in commercial complexes, this study proposes the research framework depicted in Figure 1. Initially, utilizing mathematical statistics combined with Origin software (https://www.originlab.com/ 1 June 2024), this study analyzes fire accidents in commercial complexes reported in mainland China from 2002 to 2022. The analysis involves the year, month, and severity of the accidents, subsequently identifying risk factors for urban commercial complex fires. Secondly, a combination of literature review and case studies is employed to identify influencing factors. The WSR theory is then used to establish an indicator system for these influencing factors. Finally, the DEMATEL-ISM method is applied to analyze the interactions among these factors. By constructing a hierarchical model of the influencing factors, key factors in commercial complex fire accidents are identified. The results of this analysis provide theoretical support for the risk management of different subtypes of fires in commercial complexes.

### *2.2. Statistical Analysis of Fire Accident Cases in Commercial Complexes*

To establish a database for quantitative analysis of fire accidents in commercial complexes, this study gathered data from 2002 to 2022 across the country of China (excluding Hong Kong, Macau, and Taiwan) by examining government and media official websites, such as the National Ministry of Housing and Urban–Rural Development Accident Report Website, the State Administration of Work Safety, provincial and municipal Urban Construction Bureaus, the Safety Management Network, and accident reports published by the Ministry of Emergency Management. Each case was assessed for quality, and cases with insufficient or unreliable data were omitted, yielding a selection of 91 typical fire accident cases in commercial complexes.

This study performed statistical analysis on the number of accidents and fatalities, categorized by year and month, as illustrated in Figures 2 and 3. Additionally, based on the severity of the accidents, we categorized them into four levels: minor, major, serious, and particularly serious accidents. In collecting data on fatal accidents, we primarily concentrated on the number of casualties to reflect the severity of the accidents [32]. The specific classification standards are in accordance with regulations on the reporting, investigation, and disposition of production safety accidents issued by the State Council of

China (2007) [33]. The severity was classified into the following four categories: Ordinary accidents refer to accidents with 1–2 fatalities, serious accidents with 3–9 fatalities, major accidents with 10–29 fatalities, and particularly major accidents with at least 30 fatalities. Statistical results are displayed in Figure 4.

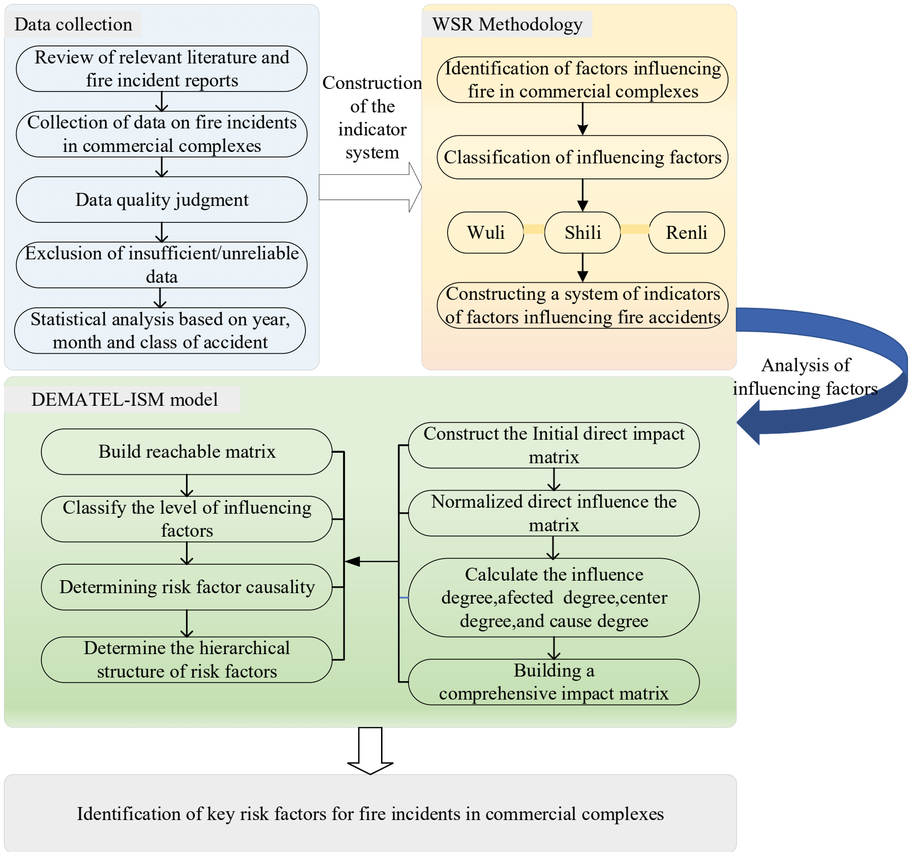


**Figure 1.** The process diagram of the methodology used in the present study.

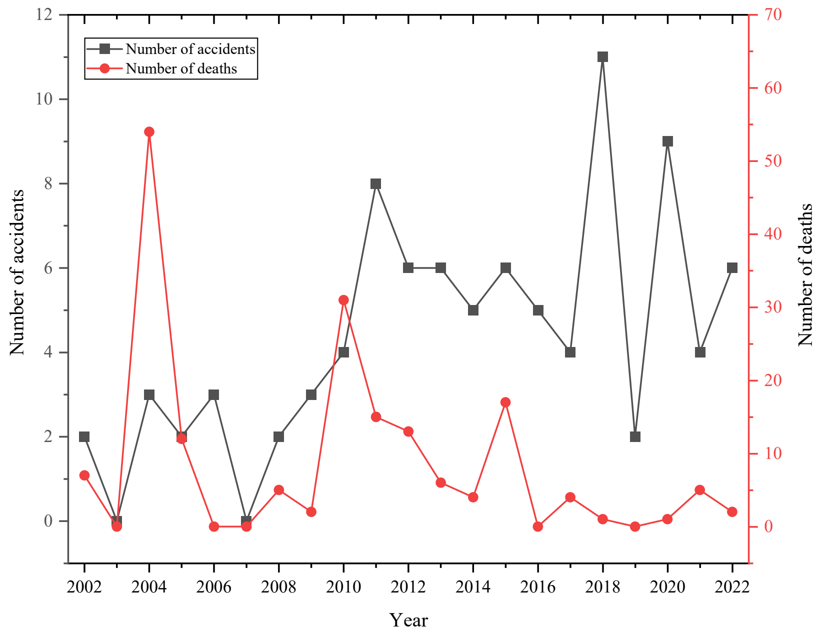


**Figure 2.** Statistics on the number of fire accidents and deaths in commercial complexes from 2002 to 2022.

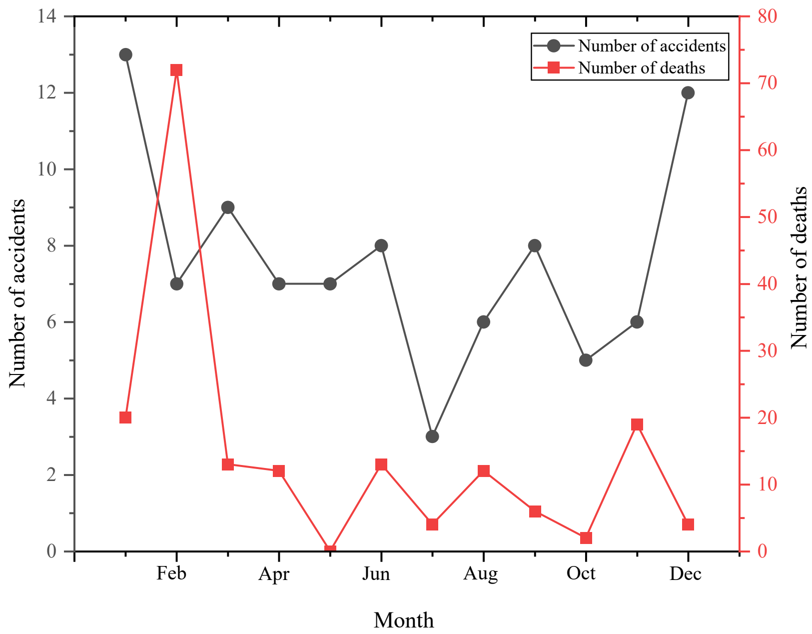


**Figure 3.** Monthly distribution of commercial complex accidents from 2002 to 2022.

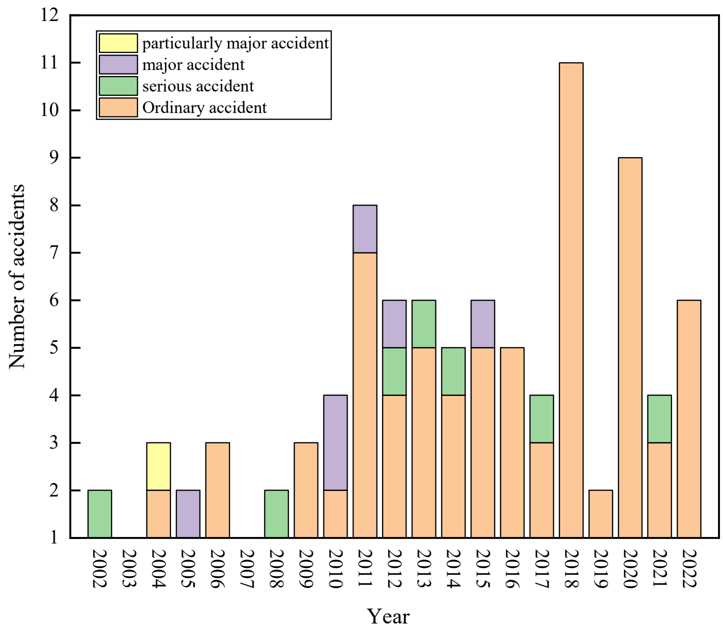


**Figure 4.** Fire accidents in commercial complexes by class from 2002 to 2022.

*2.3. Identification of Influencing Factors in Fire Accidents at Commercial Complexes*

Based on the collected and organized publicly reported accident cases, to comprehensively extract the influencing factors of commercial complex fires, we adopted a combination of literature and case study methods for identifying these factors. Using the literature analysis, this study searched databases such as CNKI, Wanfang, Science Direct, and Web of Science with keywords like “commercial complex fire” and “building fire influencing factors.” In selecting the literature, we focused on the relationship between fire accidents and their influencing factors. Additionally, we conducted interviews with several university experts with extensive experience in architectural design and fire safety management and summarized the influencing factors mentioned in the literature. This process identified 20 clearly articulated fire accident factors, categorized into four dimensions: unsafe conditions of objects, environmental factors, management factors, and unsafe behaviors of people, as shown in Table 1.

**Table 1.** Statistics on the causes of fire accidents in commercial complexes from 2002 to 2022.

| Category | Factors Contributing to Accidents | Description of Factors |
|---|---|---|
| The unsafe state of things | Inadequate emergency facilities | Emergency lighting for fire is lacking; evacuation staircases are inadequate or unavailable. |
| | Defective firefighting facilities | Fire extinguishers are insufficient; sprinkler systems have defects; and fire pipelines have defects. |
| | Electrical equipment failure | Aging and deterioration of equipment |
| | Short circuit | Short circuit, shorting, and grounding faults. |
| environmental factors | Unauthorized alterations | Arbitrarily changing the use of certain areas within the mall; altering the building structure without approval; unauthorized construction expansion or addition. |
| | Lack of fire protection design | The configuration of fire barriers is improper; the design of evacuation routes is inadequate. |
| | Impact of surrounding combustibles | Impact of neighboring buildings; trash dumping; storage of items |
| | Blockage of security evacuation routes | Storing debris or piling up objects near evacuation routes or emergency exits; illegally occupying. |
| Management factors | Failure to implement corporate fire safety responsibilities | Companies lack comprehensive fire safety management policies and accountability systems; their fire safety management framework is incomplete; fire safety awareness and education efforts are insufficient. |
| | Inadequate regulations | Lack of clear policies and regulations; the rules and regulations are incomplete; lack of an effective enforcement mechanism. |
| | Poor management of routine maintenance | Equipment breakdowns were not repaired in a timely manner due to a lack of a regular maintenance program for facilities and equipment and deficiencies in routine safety management. |
| | Inadequate safety education and training | Not adhering to relevant safety operating procedures; not familiar with the content and procedures of emergency plans; not conducting evacuation drills on a regular basis; unable to properly use and maintain safety facilities and equipment. |
| | Inadequate fire safety inspections | Inspect the storage and use of combustibles; inspect the emergency lighting and emergency broadcast systems; ensure that the fire safety facilities are intact and operational. |
| | Inadequate government supervision and management | Lax supervision and enforcement; insufficiently rigorous approval checks |
| Unsafe human behavior | Non-compliance with fire regulations | Arbitrarily changing or shutting off the fire alarm system; conducting hot work without approval or failing to report it; not using protective gear as prescribed; not operating equipment as prescribed; not using electrical appliances as prescribed; working without a license. |
| | Careless use of fire in operations | Carelessness with fire during welding and gas-welding operations |
| | Violate labor discipline | Leaving the workstation unauthorized during work hours; disregarding safety operating procedures; and failing to fulfill corresponding job responsibilities. |
| | Lack of fire safety awareness | Personnel have insufficient awareness and concern for fire risks and safety issues. |
| | Inadequate fire safety skills | Deficient in firefighting skills; not proficient in operating fire equipment; insufficient fire emergency response training |
| | human-made fire | Playing with fire, setting off fireworks and firecrackers, committing arson, smoking |

### 2.4. WSR Methodology

WSR theory, proposed by Gu Jifa and Zhu Zhichang in 1994, is a systemic methodology that focuses on the 'physical, logical, and human' dimensions. It addresses various complex issues and can hierarchically organize, rationalize, systematize, and standardize management methods according to the nature of practical activities [34]. This methodology posits that effectively addressing any complex social issue necessitates a thorough understanding of the physical, logical, and human aspects.

'Wuli' (W) investigates 'what it is,' focusing on understanding the laws of the objective world and the elements constituting its objective existence. It popularly defines 'what 'matter' is,' ensuring the study subjects maintain objectivity and reality. 'Shili' (S) evolves from 'Wuli,' integrating operations research and management science to address 'how to do it.' It concerns organizing and managing objective entities to achieve planned objectives. 'Renli' (R) addresses 'what should be conducted,' focusing on the impact of various institutional factors on human behavior. It emphasizes the reliance on individuals to organize and coordinate management processes, effectively utilizing 'matter' to accomplish tasks, and holds a dominant position in WSR methodology [24]. Within these three aspects, 'Wuli' (W) serves as the practical foundation, 'Shili' (S) acts as the normative method, and 'Renli' (R) occupies the core position.

### 2.5. DEMATEL–ISM

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) is a systematic analysis method that utilizes graph theory and matrix tools [29]. The DEMATEL model constructs an impact relation matrix to articulate the knowledge and expert judgments on the relationships among various indicators. Through this matrix, it calculates the centrality and causal relationships of each influencing factor, thereby determining each element's position within the system and identifying key factors. This methodology and its various enhancements have been widely applied in fields such as decision-making [35], risk assessment [36], management science [37], and sustainable technology [38]. In 1973, John Warfield from the United States proposed Interpretative Structural Modeling (ISM), a research methodology that elucidates the relational structure of complex systems. ISM can decompose the entire system into hierarchical subsystems and use a hierarchical-directed graph to elucidate the structure of complex systems, thereby identifying essential, intermediate, and direct factors [28].

By integrating DEMATEL with ISM, the interdependencies among factors are transformed into two causal groups using DEMATEL, which quantitatively analyzes the impacts among system elements through metrics such as degree of cause and centrality. Within complex structured systems, key factors are identified using impact relation graphs. Concurrently, ISM is employed to hierarchically categorize the influencing factors in the system, constructing a bottom-up stepwise model to more clearly delineate the hierarchical relationships among the influencing factors. The integration of both methods not only merges their strengths to grasp the interrelationships among system factors, achieving complementarity in research, but also elucidates the logical and hierarchical relationships among factors related to fire risks in commercial complexes. This ensures a comprehensive and systematic analysis of inter-element relationships, deepens the research, and provides valuable insights for the scientific management and control of fire risks in commercial complexes.

## 3. Construction of Fire Risk Evaluation Index System for Commercial Complexes Based on WSR

The fire risk assessment of commercial complexes is a multi-level, multi-dimensional complex system. This study utilizes the principles of the WSR method, integrating findings from related literature [13,16,18], to select 20 clearly defined fire impact factors in commercial complexes from three dimensions—physical, rational, and human—and four aspects: personnel, equipment, environment, and management. A fire accident impact factor index system for commercial complexes has been developed, as illustrated in Figure 5.

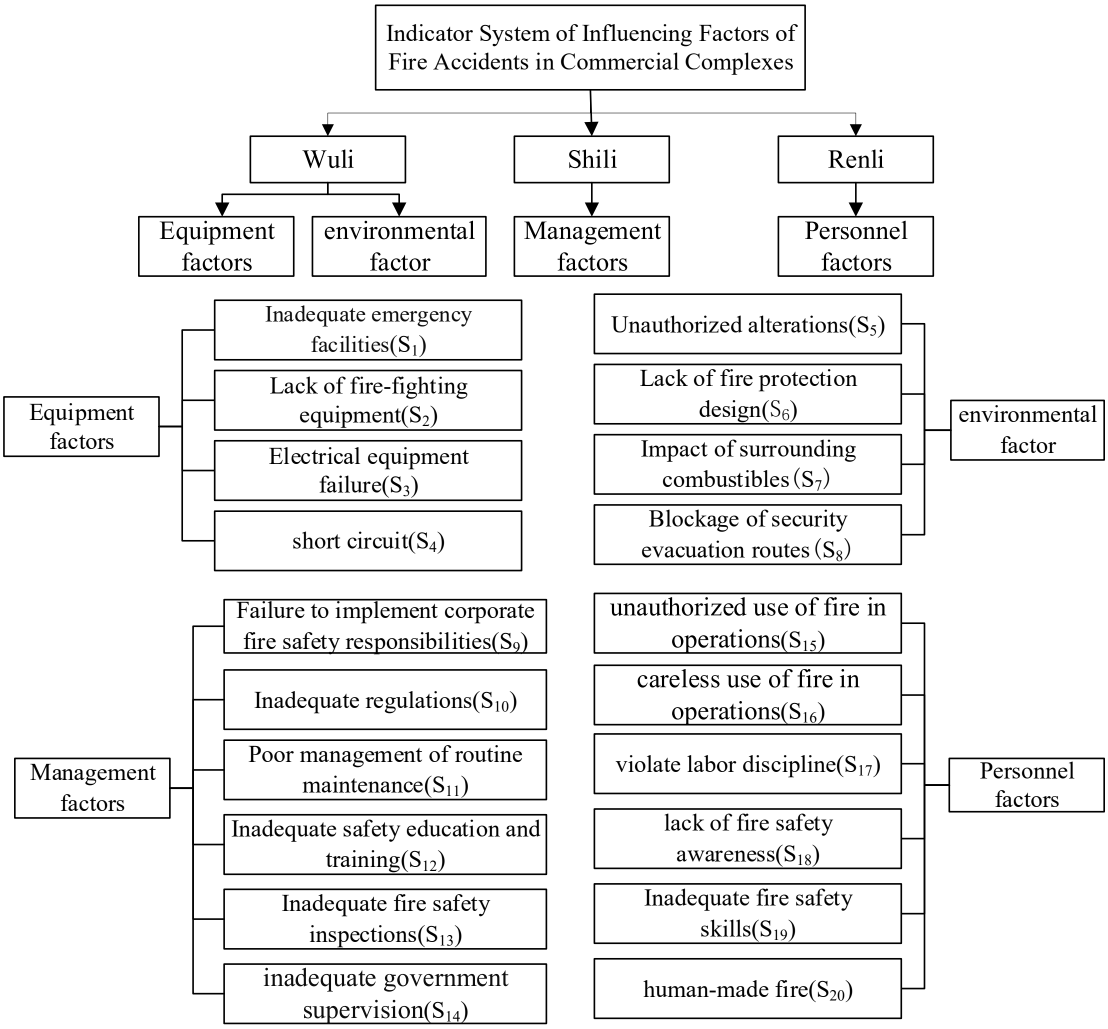


**Figure 5.** Indicator system for influencing factors of fire accidents in commercial complexes.

On the physical level, these factors primarily encompass the use of fire prevention and firefighting equipment, along with environmental elements that support the safe operation of the entire commercial complex. The physical factors leading to fires in commercial complexes primarily manifest in issues such as electrical shorts, electrical equipment failures, insufficient firefighting equipment, and inadequate emergency facilities. The rational dimension primarily reflects management deficiencies in commercial complexes, including unfulfilled corporate fire safety responsibilities, inadequate government supervision, insufficient fire safety inspections, and inadequate safety training. The human dimension emphasizes reliance on individuals to organize and coordinate the daily operations of commercial complexes, where unsafe human behaviors primarily include unauthorized hot work, insufficient fire safety skills, and limited fire safety awareness.

## 4. Modeling and Analysis

### *4.1. Factor Attribute Analysis Based on DEMATEL*

Step 1: Establishment of the direct impact relationship matrix

Based on the analyzed accident cases and the relevant literature, the set of influencing factors, denoted as $S = \{S_1, S_2, \ldots, S_n\}$, was established. Eight experts, each with over five years of experience in fire management or firefighting, were invited to evaluate the impact level of each causal factor on others, assigning scores that represent the intensity of influence from factor $S_i$ to factor $S_j$. We have utilized a 0 to 4 scoring scale, where 0 represents no influence, 1 denotes weak influence, 2 indicates moderate influence, 3 suggests strong influence, and 4 signifies very strong influence [29]. Given the subjective perceptions and individual knowledge differences among experts, an averaging method was utilized to aggregate the evaluation results, thereby obtaining the initial direct influence matrix $A = (a_{ij})_{n\times n}$, as shown in Table 2.

**Table 2.** Direct influence matrix *A*.

| Factors | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ | $S_7$ | $S_8$ | $S_9$ | $S_{10}$ | $S_{11}$ | $S_{12}$ | $S_{13}$ | $S_{14}$ | $S_{15}$ | $S_{16}$ | $S_{17}$ | $S_{18}$ | $S_{19}$ | $S_{20}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $S_1$ | 0 | 3.0 | 3.6 | 2.8 | 1.4 | 3.0 | 2.8 | 3.6 | 1.2 | 1.0 | 3.0 | 0.8 | 2.0 | 2.0 | 0.8 | 1.0 | 0.8 | 1.8 | 1.0 | 1.0 |
| $S_2$ | 3.0 | 0 | 1.2 | 1.0 | 1.0 | 0.8 | 2.6 | 0.8 | 0.8 | 1.6 | 1.0 | 1.0 | 1.0 | 1.6 | 0.6 | 0.6 | 1.0 | 2.0 | 1.4 | 1.8 |
| $S_3$ | 3.4 | 1.6 | 0 | 3.0 | 0.8 | 1.0 | 1.6 | 1.0 | 1.8 | 1.0 | 1.0 | 2.0 | 1.8 | 0.6 | 1.3 | 1.0 | 0.6 | 2.0 | 1.2 | 0.6 |
| $S_4$ | 2.2 | 3.0 | 3.6 | 0 | 1.0 | 2.4 | 0.8 | 2.0 | 1.2 | 0.8 | 1.4 | 2.2 | 1.8 | 2.0 | 1.0 | 1.6 | 1.2 | 2.2 | 1.2 | 1.0 |
| $S_5$ | 3.2 | 1.8 | 2.2 | 1.8 | 0 | 2.4 | 2.6 | 3.2 | 3.4 | 1.8 | 1.2 | 2.2 | 2.0 | 3.2 | 1.0 | 1.0 | 2.2 | 1.6 | 0.8 | 0.8 |
| $S_6$ | 1.2 | 3.2 | 1.8 | 3.0 | 1.4 | 0 | 3.2 | 3.6 | 2.8 | 1.6 | 2.0 | 1.0 | 2.8 | 1.6 | 2.0 | 2.2 | 0.8 | 0.8 | 1.4 | 2.2 |
| $S_7$ | 2.4 | 1.8 | 1.0 | 0.8 | 0.6 | 2.2 | 0 | 3.0 | 2.0 | 0.8 | 0.8 | 1.8 | 1.8 | 2.6 | 1.0 | 1.2 | 1.2 | 1.8 | 0.6 | 1.8 |
| $S_8$ | 2.8 | 1.0 | 1.8 | 0.6 | 2.6 | 0.6 | 2.4 | 0 | 0.6 | 2.2 | 2.4 | 0.8 | 1.6 | 1.8 | 0.9 | 1.0 | 1.2 | 1.8 | 1.6 | 2.0 |
| $S_9$ | 3.2 | 3.0 | 1.0 | 0.8 | 2.0 | 1.8 | 0.8 | 1.2 | 0 | 2.2 | 2.0 | 3.0 | 2.6 | 2.6 | 1.2 | 1.4 | 1.2 | 1.4 | 2.0 | 0.8 |
| $S_{10}$ | 3.0 | 3.4 | 1.8 | 1.3 | 2.4 | 2.6 | 0.6 | 1.6 | 2.0 | 0 | 2.2 | 2.0 | 2.6 | 1.8 | 1.2 | 1.0 | 2.4 | 2.6 | 1.8 | 2.2 |
| $S_{11}$ | 1.2 | 1.8 | 2.6 | 2.8 | 2.0 | 2.0 | 2.4 | 1.8 | 2.2 | 2.6 | 0 | 1.8 | 2.0 | 2.6 | 0 | 1.2 | 0.8 | 1.2 | 1.4 | 0.8 |
| $S_{12}$ | 1.8 | 0.8 | 0.6 | 0.8 | 0.8 | 1.0 | 1.2 | 1.0 | 2.2 | 2.6 | 2.6 | 0 | 2.4 | 2.6 | 3.0 | 2.6 | 3.2 | 3.2 | 2.4 | 3.4 |
| $S_{13}$ | 2.6 | 2.8 | 3.0 | 3.0 | 2.2 | 2.8 | 3.0 | 3.2 | 2.0 | 1.6 | 2.6 | 0.8 | 0 | 1.6 | 1.2 | 1.0 | 1.8 | 2.0 | 1.8 | 1.8 |
| $S_{14}$ | 2.2 | 2.8 | 1.2 | 1.8 | 2.0 | 3.8 | 1.6 | 2.0 | 3.0 | 2.8 | 2.8 | 2.2 | 1.7 | 0 | 1.0 | 1.2 | 2.0 | 1.6 | 1.2 | 1.0 |
| $S_{15}$ | 0.8 | 0.8 | 1.6 | 0.8 | 0.8 | 2.0 | 2.2 | 0.6 | 0.6 | 0.8 | 2.0 | 1.4 | 1.6 | 0.8 | 0 | 1.2 | 2.2 | 3.2 | 2.4 | 1.8 |
| $S_{16}$ | 1.0 | 1.0 | 2.8 | 2.0 | 0.8 | 1.0 | 1.3 | 1.0 | 1.2 | 1.0 | 2.0 | 2.2 | 0.8 | 1.2 | 0.8 | 0 | 1.8 | 2.0 | 1.0 | 1.2 |
| $S_{17}$ | 0.8 | 0.8 | 1.6 | 2.0 | 0.8 | 0.6 | 1.6 | 1.0 | 0.6 | 2.0 | 0.6 | 1.8 | 1.4 | 1.6 | 2.0 | 1.0 | 0 | 3.2 | 1.4 | 1.8 |
| $S_{18}$ | 0.6 | 0.6 | 0.8 | 0.8 | 1.0 | 1.0 | 1.2 | 0.6 | 1.6 | 0.8 | 1.4 | 0.8 | 1.4 | 1.2 | 2.2 | 2.6 | 2.0 | 0 | 2.0 | 2.6 |
| $S_{19}$ | 1.2 | 0.8 | 1.6 | 2.0 | 0.6 | 0.8 | 0.8 | 1.8 | 1.8 | 1.4 | 1.4 | 2.2 | 1.4 | 1.6 | 1.4 | 1.0 | 1.0 | 0.6 | 0 | 1.6 |
| $S_{20}$ | 0.6 | 0.8 | 0.6 | 0.8 | 1.2 | 1.8 | 2.2 | 1.2 | 2.0 | 1.6 | 0.6 | 1.2 | 1.8 | 1.2 | 2.0 | 1.0 | 1.8 | 2.2 | 1.2 | 0 |

Step 2: Establishment of a comprehensive impact matrix

In order to eliminate the effect brought by the difference in magnitude, the direct impact matrix is first normalized according to Equation (1), and the normalized direct impact matrix *B* is obtained, which is calculated as follows:

$$b_{ij} = \frac{a_{ij}}{\underset{1\leq i\leq n}{max} \sum_{j=1}^{n} a_{ij}} \tag{1}$$

The denominator in Equation (1) is the row with the maximum value.

Based on the calculated normalization matrix *B*, the integrated impact relationship matrix *C* is calculated according to Equation (2), as shown in Table 3.

$$C = \left(C_{ij}\right)_{n\times n} = B^1 + \cdots + B^{\mathrm{k}} = B\frac{I - B^{\mathrm{n}-1}}{I - B} = B(I - B)^{-1} \tag{2}$$

In Equation (2), *I* is the unit matrix.

Step 3: Calculation of Influence, Influenced, Centrality, and Causality

Upon obtaining matrix *C*, the influence degree ($D_i$), the affected degree ($G_i$), the centrality degree ($M_i$), and the cause degree ($R_i$) of each fire evacuation factor are calculated sequentially according to Equations (3) to (6). $D_i$ is the sum of the elements in each row of the comprehensive influence matrix *C*, representing the total influence of each row's corresponding factor on other factors. $G_i$ is the sum of the elements in each column of matrix *C*, indicating the total influence received by the column's corresponding factor from other factors. The centrality degree ($M_i$) is derived by summing the influence degrees of all factors, reflecting the importance of the factor in the system of influence factors; a higher value denotes greater importance. The cause degree ($R_i$) is determined by the difference between the influence degree and the affected degree. If the cause degree is positive, the factor is deemed a cause element, exerting significant influence on others; conversely, if it is negative, it is considered an effect element, being significantly influenced by others. The calculation results are displayed in Table 4. A causality diagram is plotted with the centrality degree ($M_i$) as the horizontal axis and the cause degree ($R_i$) as the vertical axis, as illustrated in Figure 6.

$$D_i = \sum_{j=1}^{21} C_{ij} (i = 1, 2, 3, \cdots, 21) \quad (3)$$

$$G_j = \sum_{i=1}^{21} C_{ji} (j = 1, 2, 3, \cdots, 21) \quad (4)$$

$$M_i = D_i + G_i \quad (5)$$

$$R_i = D_i - G_i \quad (6)$$

**Table 3.** Comprehensive influence matrix *C*.

| Factors | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ | $S_7$ | $S_8$ | $S_9$ | $S_{10}$ | $S_{11}$ | $S_{12}$ | $S_{13}$ | $S_{14}$ | $S_{15}$ | $S_{16}$ | $S_{17}$ | $S_{18}$ | $S_{19}$ | $S_{20}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $S_1$ | 0.1944 | 0.2514 | 0.2589 | 0.2300 | 0.1662 | 0.2406 | 0.2460 | 0.2614 | 0.1960 | 0.1775 | 0.2372 | 0.1738 | 0.2220 | 0.2201 | 0.1416 | 0.1508 | 0.1609 | 0.2249 | 0.1635 | 0.1760 |
| $S_2$ | 0.1996 | 0.1238 | 0.1476 | 0.1354 | 0.1138 | 0.1390 | 0.1829 | 0.1420 | 0.1346 | 0.1419 | 0.1393 | 0.1298 | 0.1443 | 0.1569 | 0.1005 | 0.1019 | 0.1234 | 0.1735 | 0.1288 | 0.1477 |
| $S_3$ | 0.2238 | 0.1761 | 0.1354 | 0.1939 | 0.1186 | 0.1554 | 0.1727 | 0.1590 | 0.1677 | 0.1387 | 0.1536 | 0.1643 | 0.1756 | 0.1471 | 0.1258 | 0.1219 | 0.1248 | 0.1881 | 0.1362 | 0.1316 |
| $S_4$ | 0.2220 | 0.2291 | 0.2382 | 0.1471 | 0.1406 | 0.2066 | 0.1795 | 0.2022 | 0.1769 | 0.1561 | 0.1836 | 0.1885 | 0.1976 | 0.1991 | 0.1357 | 0.1518 | 0.1568 | 0.2160 | 0.1544 | 0.1609 |
| $S_5$ | 0.2819 | 0.2388 | 0.2380 | 0.2170 | 0.1437 | 0.2418 | 0.2523 | 0.2652 | 0.2582 | 0.2090 | 0.2121 | 0.2185 | 0.2364 | 0.2617 | 0.1579 | 0.1609 | 0.2068 | 0.2363 | 0.1708 | 0.1840 |
| $S_6$ | 0.2315 | 0.2633 | 0.2254 | 0.2381 | 0.1725 | 0.1797 | 0.2616 | 0.2676 | 0.2383 | 0.1983 | 0.2228 | 0.1872 | 0.2477 | 0.2197 | 0.1750 | 0.1830 | 0.1704 | 0.2131 | 0.1803 | 0.2110 |
| $S_7$ | 0.2106 | 0.1889 | 0.1642 | 0.1508 | 0.1238 | 0.1913 | 0.1469 | 0.2134 | 0.1824 | 0.1459 | 0.1588 | 0.1668 | 0.1850 | 0.2012 | 0.1263 | 0.1327 | 0.1469 | 0.1925 | 0.1300 | 0.1683 |
| $S_8$ | 0.2227 | 0.1726 | 0.1868 | 0.1506 | 0.1702 | 0.1591 | 0.2041 | 0.1478 | 0.1550 | 0.1782 | 0.1946 | 0.1476 | 0.1825 | 0.1865 | 0.1234 | 0.1278 | 0.1486 | 0.1944 | 0.1526 | 0.1722 |
| $S_9$ | 0.2587 | 0.2448 | 0.1928 | 0.1783 | 0.1751 | 0.2096 | 0.1929 | 0.2000 | 0.1627 | 0.2017 | 0.2125 | 0.2188 | 0.2299 | 0.2290 | 0.1489 | 0.1559 | 0.1702 | 0.2117 | 0.1836 | 0.1686 |
| $S_{10}$ | 0.2702 | 0.2688 | 0.2262 | 0.2046 | 0.1957 | 0.2412 | 0.2060 | 0.2241 | 0.2239 | 0.1634 | 0.2293 | 0.2095 | 0.2456 | 0.2255 | 0.1613 | 0.1586 | 0.2094 | 0.2557 | 0.1918 | 0.2140 |
| $S_{11}$ | 0.2121 | 0.2150 | 0.2241 | 0.2184 | 0.1717 | 0.2095 | 0.2213 | 0.2091 | 0.2105 | 0.2053 | 0.1584 | 0.1898 | 0.2122 | 0.2244 | 0.1172 | 0.1478 | 0.1553 | 0.2007 | 0.1643 | 0.1622 |
| $S_{12}$ | 0.2305 | 0.2004 | 0.1916 | 0.1855 | 0.1547 | 0.2004 | 0.2095 | 0.2002 | 0.2222 | 0.2189 | 0.2332 | 0.1603 | 0.2349 | 0.2363 | 0.2001 | 0.1919 | 0.2267 | 0.2664 | 0.2029 | 0.2377 |
| $S_{13}$ | 0.2737 | 0.2655 | 0.2636 | 0.2508 | 0.1977 | 0.2545 | 0.2685 | 0.2711 | 0.2315 | 0.2070 | 0.2453 | 0.1912 | 0.1942 | 0.2303 | 0.1650 | 0.1641 | 0.1999 | 0.2499 | 0.1968 | 0.2105 |
| $S_{14}$ | 0.2548 | 0.2594 | 0.2135 | 0.2159 | 0.1886 | 0.2697 | 0.2279 | 0.2353 | 0.2480 | 0.2300 | 0.2447 | 0.2164 | 0.2281 | 0.1861 | 0.1562 | 0.1643 | 0.2005 | 0.2330 | 0.1787 | 0.1876 |
| $S_{15}$ | 0.1551 | 0.1482 | 0.1641 | 0.1402 | 0.1144 | 0.1711 | 0.1824 | 0.1434 | 0.1388 | 0.1318 | 0.1688 | 0.1475 | 0.1665 | 0.1462 | 0.0949 | 0.1245 | 0.1593 | 0.2109 | 0.1609 | 0.1578 |
| $S_{16}$ | 0.1587 | 0.1501 | 0.1884 | 0.1634 | 0.1117 | 0.1443 | 0.1557 | 0.1463 | 0.1474 | 0.1334 | 0.1655 | 0.1632 | 0.1442 | 0.1514 | 0.1097 | 0.0921 | 0.1462 | 0.1801 | 0.1249 | 0.1381 |
| $S_{17}$ | 0.1539 | 0.1461 | 0.1611 | 0.1618 | 0.1129 | 0.1381 | 0.1634 | 0.1473 | 0.1349 | 0.1560 | 0.1354 | 0.1541 | 0.1588 | 0.1606 | 0.1398 | 0.1175 | 0.1076 | 0.2101 | 0.1363 | 0.1554 |
| $S_{18}$ | 0.1389 | 0.1327 | 0.1359 | 0.1288 | 0.1114 | 0.1387 | 0.1478 | 0.1308 | 0.1501 | 0.1229 | 0.1454 | 0.1260 | 0.1504 | 0.1442 | 0.1372 | 0.1468 | 0.1466 | 0.1262 | 0.1428 | 0.1643 |
| $S_{19}$ | 0.1620 | 0.1451 | 0.1593 | 0.1601 | 0.1075 | 0.1396 | 0.1426 | 0.1636 | 0.1588 | 0.1417 | 0.1521 | 0.1611 | 0.1563 | 0.1588 | 0.1212 | 0.1133 | 0.1267 | 0.1456 | 0.0997 | 0.1452 |
| $S_{20}$ | 0.1488 | 0.1465 | 0.1363 | 0.1333 | 0.1222 | 0.1642 | 0.1777 | 0.1532 | 0.1660 | 0.1468 | 0.1344 | 0.1395 | 0.1675 | 0.1519 | 0.1380 | 0.1158 | 0.1477 | 0.1843 | 0.1303 | 0.1114 |

**Table 4.** Results of DEMATEL analysis.

| $S_i$ | $D_i$ | $G_i$ | $M_i$ | $R_i$ | $M_i$ Sort | Factor Properties |
|---|---|---|---|---|---|---|
| $S_1$ | 4.0932 | 4.2038 | 8.2970 | −0.1106 | 2 | Resulting factors |
| $S_2$ | 2.8067 | 3.9667 | 6.7734 | −1.1600 | 15 | Resulting factors |
| $S_3$ | 3.1102 | 3.8514 | 6.9617 | −0.7412 | 13 | Resulting factors |
| $S_4$ | 3.6428 | 3.6041 | 7.2468 | 0.0387 | 12 | Causal factors |
| $S_5$ | 4.3914 | 2.9132 | 7.3046 | 1.4782 | 9 | Causal factors |
| $S_6$ | 4.2866 | 3.7944 | 8.0809 | 0.4922 | 4 | Causal factors |
| $S_7$ | 3.3267 | 3.9417 | 7.2684 | −0.6150 | 10 | Resulting factors |
| $S_8$ | 3.3772 | 3.8830 | 7.2602 | −0.5058 | 11 | Resulting factors |
| $S_9$ | 3.9457 | 3.7038 | 7.6495 | 0.2420 | 7 | Causal factors |
| $S_{10}$ | 4.3246 | 3.4044 | 7.7290 | 0.9202 | 5 | Causal factors |
| $S_{11}$ | 3.8290 | 3.7270 | 7.5560 | 0.1020 | 8 | Causal factors |
| $S_{12}$ | 4.2043 | 3.4540 | 7.6583 | 0.7504 | 6 | Causal factors |
| $S_{13}$ | 4.5312 | 3.8798 | 8.4111 | 0.6514 | 1 | Causal factors |
| $S_{14}$ | 4.3389 | 3.8371 | 8.1759 | 0.5018 | 3 | Causal factors |
| $S_{15}$ | 3.0268 | 2.7756 | 5.8024 | 0.2512 | 19 | Causal factors |
| $S_{16}$ | 2.9148 | 2.8234 | 5.7382 | 0.0913 | 20 | Causal factors |
| $S_{17}$ | 2.9513 | 3.2348 | 6.1861 | −0.2835 | 17 | Resulting factors |
| $S_{18}$ | 2.7678 | 4.1133 | 6.8811 | −1.3454 | 14 | Resulting factors |
| $S_{19}$ | 2.8604 | 3.1294 | 5.9899 | −0.2690 | 18 | Resulting factors |
| $S_{20}$ | 2.9156 | 3.4045 | 6.3202 | −0.4889 | 16 | Resulting factors |

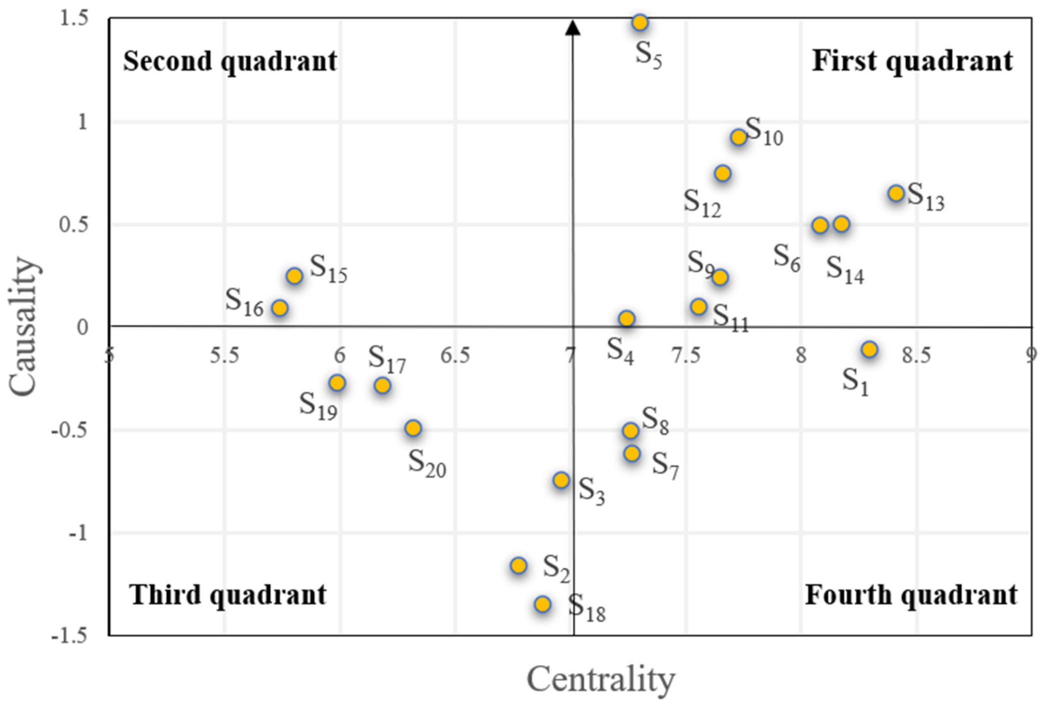


**Figure 6.** Cause-effect diagram of risk factors for fire accidents in commercial complexes.

## *4.2. Hierarchy of Factors Using ISM*

Step 1: Establish the overall influence matrix $H$.

Calculate the overall impact matrix $H$ according to Equation (7).

$$H = T + C \tag{7}$$

Step 2: Establish reachability matrix

In order to realize the simplification of the system structure, the threshold value $\lambda$ is introduced, and different values of $\lambda$ will form different hierarchical recursive models. The calculation of the mean and standard deviation based on statistical distribution can make causal factor logic grading more objective. The formula is as follows:

$$\lambda = \alpha + \beta \tag{8}$$

$\alpha$ and $\beta$ are the mean and standard deviation, respectively, of all the factors in the composite impact matrix $T$, and $\lambda \in [0, 1]$.

The overall impact matrix $H$ is transformed into a reachability matrix $K$. If $h_{ij} \geq \lambda$, then in the reachability matrix, $k_{ij}$ = 1; conversely, $k_{ij}$ = 0. The calculation results are shown in Table 5.

**Table 5.** The reachable matrix.

| **Factors** | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ | $S_7$ | $S_8$ | $S_9$ | $S_{10}$ | $S_{11}$ | $S_{12}$ | $S_{13}$ | $S_{14}$ | $S_{15}$ | $S_{16}$ | $S_{17}$ | $S_{18}$ | $S_{19}$ | $S_{20}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $S_1$ | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| $S_2$ | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $S_3$ | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $S_4$ | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $S_5$ | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| $S_6$ | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $S_7$ | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $S_8$ | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $S_9$ | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| $S_{10}$ | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| $S_{11}$ | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| $S_{12}$ | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 |
| $S_{13}$ | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| $S_{14}$ | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| $S_{15}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| $S_{16}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| $S_{17}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| $S_{18}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| $S_{19}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| $S_{20}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

Step 3: Construct multi-level hierarchical structural models

From the reachable matrix K, the reachable set L ($S_i$), the prior set P ($S_i$), and the common set Q ($S_i$) of the influencing factors can be found according to the following formulas, which are shown in Equations (9) to (11). According to the principle of hierarchical division, the factor that satisfies L ($S_i$) = Q (Si) is extracted as the first hierarchical factor; then, the rows and columns corresponding to this factor are deleted from the reachable matrix, and this process is repeated to divide the reachable matrix K into structural levels, so as to determine the reachable set L ($S_i$), prior set P ($S_i$), and common set Q ($S_i$) of the factor $S_i$, and the results are shown in Table 6. The multilayer recursive order structure model of commercial complex fire accidents is constructed by the hierarchical division of influencing factors through ISM, as shown in Figure 7. Through the constructed multilayer hierarchical structure model, the hierarchical structure relationship between the factors in the system is determined, and the deep causative factors, surface causative factors, and transition causative factors of the commercial complex fire accident are clarified.

$$\mathrm{L}\ (\mathrm{S_i}) = \left\{\mathrm{S_i} \middle| a_{ij} = 1\right\} \tag{9}$$

$$\mathrm{P}\ (\mathrm{S_i}) = \left\{\mathrm{S_i} \middle| a_{ij} = 1\right\} \tag{10}$$

$$\mathrm{Q}\ (\mathrm{S_i}) = \mathrm{L}\ (\mathrm{S_i}) \cap \mathrm{P}\ (\mathrm{S_i}) \tag{11}$$

**Table 6.** Hierarchy analysis calculation results.

| Levels | Factor | L ($S_i$) | P ($S_i$) | Q ($S_i$) |
|---|---|---|---|---|
| L1 | $S_2$ | 2 | 1,2,4,5,6,9,10,13,14 | 2 |
| | $S_3$ | 1,3 | 1,3,4,5,6,10,11,13 | 1,3 |
| | $S_7$ | 7 | 1,5,6,7,11,13,14 | 7 |
| | $S_{16}$ | 16 | 16 | 16 |
| | $S_{20}$ | 20 | 12,20 | 20 |
| | $S_{15}$ | 15 | 15 | 15 |
| | $S_{17}$ | 17 | 12,17 | 17 |
| | $S_8$ | 1,8 | 1,5,6,8,10,13,14 | 1,8 |
| | $S_{18}$ | 18 | 1,5,10,12,13,14,18 | 18 |
| | $S_{19}$ | 19 | 19 | 19 |
| L2 | $S_4$ | 1,2,3,4 | 1,4,6,13 | 1,4 |
| | $S_{11}$ | 3,7,11,14 | 1,6,10,11,12,13,14 | 11,14 |
| L3 | $S_1$ | 1,2,3,4,6,7,8,11,13,18 | 1,3,4,5,6,8,9,10,12,13,14 | 1,3,4,6,8,13 |
| | $S_{13}$ | 1,2,3,4,6,7,8,9,11,13,14,18 | 1,5,6,9,10,12,13,14 | 1,6,9,13,14 |
| L4 | $S_9$ | 1,2,9,13,14 | 5,6,9,10,12,13,14 | 9,13,14 |
| L5 | $S_6$ | 1,2,3,4,6,7,8,9,11,13 | 1,5,6,10,13,14 | 1,6,13 |
| L6 | $S_{10}$ | 1,2,3,6,8,9,10,11,13,14,18 | 10,14 | 10,14 |
| | $S_{14}$ | 1,2,6,7,8,9,10,11,13,14,18 | 5,9,10,11,12,13,14 | 9,10,11,13,14 |
| L7 | $S_5$ | 1,2,3,5,6,7,8,9,13,14,18 | 5 | 5 |
| | $S_{12}$ | 1,9,11,12,13,14,17,18,20 | 12 | 12 |

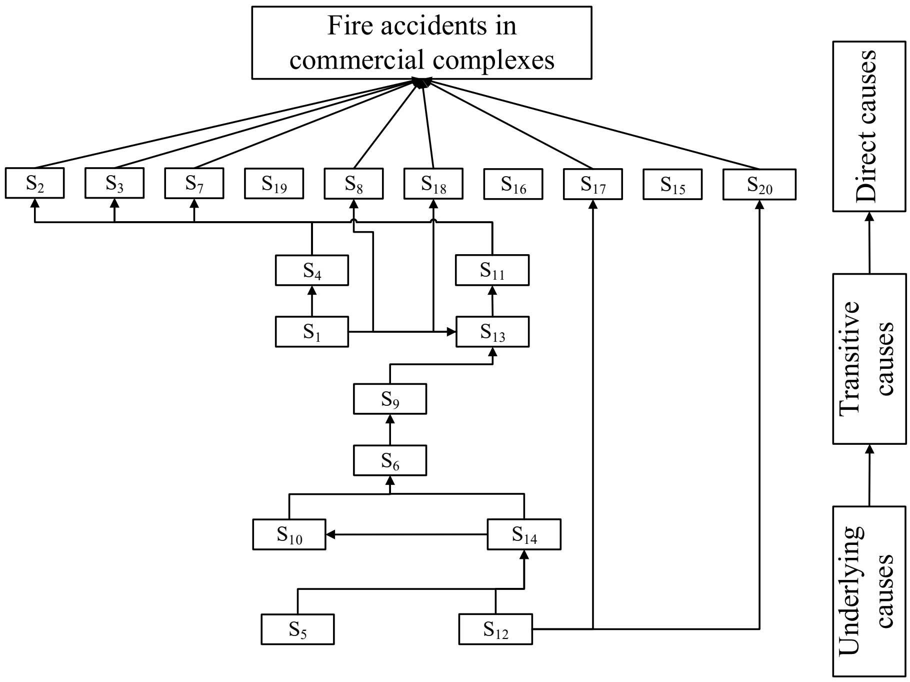


**Figure 7.** Multilayer hierarchical structure model of fire accident in commercial complex.

## *4.3. Results and Discussion*

### 4.3.1. DEMATEL Analysis Results

(1) Centrality analysis

The relationship diagram of factors affecting fire in commercial complexes calculated by DEMATEL (Figure 6) shows that the factors affecting fire in commercial complexes can be categorized into four groups. The first category is the set of strong causal factors (first quadrant). The close relationship and complex interactions between these types of factors can have a significant impact on commercial complex fires. The second category is the set of weak causal factors (second quadrant). These types of factors also have an impact on commercial complex fires, as well as some impact on other outcome-type factors. The third category is the set of weak outcome factors (third quadrant). This type of factor is the result of a combination of other cause-based factors that have an impact on the risk of fire in commercial complexes. The fourth category is the strong outcome factor set (fourth quadrant). This type of factor is the result of the combined effect of other cause-type factors.

According to Table 4, factors such as $S_1$ (inadequate emergency facilities), $S_6$ (lack of fire protection design), $S_{13}$ (inadequate fire safety inspections), and $S_{14}$ (inadequate government supervision) have relatively high centrality values, significantly influencing the occurrence of fire accidents in commercial complexes. This reflects significant deficiencies in the government and enterprises' implementation of fire safety responsibilities, particularly in critical areas like fire prevention design and safety management, directly increasing the risk of fire accidents. Therefore, it is crucial to strengthen management and monitoring in these areas to enhance safety measures in urban commercial complexes.

According to the WSR theory, at the physical level, $S_1$ (inadequate emergency facilities) and $S_2$ (defective firefighting facilities) show high centrality, followed by $S_5$ (unauthorized alterations) and $S_7$ (impact of surrounding combustibles). This suggests that preventing fire accidents in commercial complexes hinges on ensuring adequate emergency facilities and optimizing the safety management coordination mechanism. Concurrently, relevant departments should intensify their technical reviews of fire prevention designs. At the logical level, $S_{13}$ (inadequate fire safety inspections) and $S_{14}$ (inadequate government supervision) exhibit high centrality, indicating the need for governments and fire systems to strengthen fire safety inspections and supervision in commercial complexes. This ensures adherence to fire safety responsibilities and fundamentally reduces the risk of fire accidents in urban complexes. At the human level, $S_{18}$ (lack of fire safety awareness) is the primary influencing factor. Ying [39] suggests the need to develop and rigorously enforce effective safety management regulations, enhance fire safety education for employees, address safety hazards promptly, and foster a safe operating environment through integrated education and publicity efforts. This comprehensive approach aims to address the underlying issues related to fire safety awareness and ensure a safer environment for all occupants of urban complexes.

(2) Causality analysis

The impact of various factors on fire accidents in commercial complexes is quantified by their causality degree. If this value is greater than zero, it denotes that the factor is causative. According to Table 4, factors such as $S_5$ (unauthorized alterations), $S_6$ (lack of fire protection design), $S_4$ (short circuit), $S_9$ (failure to implement corporate fire safety responsibilities), $S_{10}$ (inadequate regulations), and $S_{11}$ (poor management of routine maintenance) are identified as causative, significantly impacting urban complex fire accidents. Notably, $S_5$ (unauthorized alterations), $S_{10}$ (inadequate regulations), and $S_{12}$ (inadequate safety education and training) are the primary causes of these accidents. If the causality degree of a factor is less than zero, it indicates that the factor is resultant. Factors such as $S_1$ (inadequate emergency facilities), $S_2$ (defective firefighting facilities), $S_3$ (electrical equipment failure), $S_7$ (impact of surrounding combustibles), $S_8$ (blockage of security evacuation routes), and $S_{17}$ (violate labor discipline) are identified as resultants. Notably, $S_1$ (inadequate emergency facilities) is heavily influenced by other factors, necessitating further investigation into its causes and enhanced control measures. The condition of these factors evolves with the functional structure of causative factors, contributing to the complex dynamics of evolving fire risk factors in commercial complexes.

Factors located in the first quadrant, with high causality and centrality, are identified as key factors [26]. According to Figure 6, the key factors influencing fire accidents in commercial complexes include $S_5$ (unauthorized alterations), $S_{10}$ (inadequate regulations), $S_{13}$ (inadequate fire safety inspections), $S_{12}$ (inadequate safety education and training), $S_{16}$ (careless use of fire in operations), $S_{14}$ (inadequate government supervision), $S_9$ (failure to implement corporate fire safety responsibilities), and $S_{11}$ (poor management of routine maintenance), which should be prioritized in preventive strategies. $S_{15}$ (unauthorized use of fire in operations) and $S_{16}$ (careless use of fire in operations) are in the second quadrant, characterized by high causality but low centrality, suggesting these factors strongly influence other factors and should be taken seriously. $S_7$ (impact of surrounding combustibles) and $S_8$ (blockage of security evacuation routes) are positioned in the fourth quadrant, exhibiting high centrality but negative causality, marking them as key factors in the fire accident influence system of commercial complexes, which are readily influenced by other factors.

#### 4.3.2. ISM Analysis Results

In the multi-level hierarchical structure model for fire accidents in commercial complexes, higher structural levels warrant increased attention. According to Table 6, the interactions between factors affecting fire accidents in commercial complexes are organized into seven hierarchical levels, illustrating the complex interdependencies and indicating their management priorities. Figure 7 shows that factors such as $S_2$ (defective firefighting facilities), $S_3$ (electrical equipment failure), $S_7$ (impact of surrounding combustibles), $S_8$ (blockage of security evacuation routes), $S_{17}$ (violate labor discipline), $S_{18}$ (lack of fire safety awareness), and $S_{20}$ (human-made fire) are positioned at the first level, representing direct influencers of fire accidents in commercial complexes. Consequently, governmental and fire safety departments must rigorously enforce safety responsibilities, develop and implement building fire safety regulations, conduct regular inspections of fire safety equipment and measures in commercial complexes, and ensure strict compliance with relevant building and fire safety standards. Moreover, businesses should enhance fire safety awareness among employees and management, strengthen emergency drills and training, and boost their self-protection and emergency response capabilities. Additionally, businesses should enhance internal safety monitoring and patrols within malls to promptly identify and mitigate fire hazards, thus reducing the risk of fire accidents due to human factors. Factors such as $S_{15}$ (unauthorized use of fire in operations), $S_{19}$ (inadequate fire safety skills), and $S_{16}$ (careless use of fire in operations) are not significantly influenced by other factors, indicating their potential to directly cause fire accidents. These factors are classified as unsafe human behaviors; thus, fire prevention and management strategies should particularly emphasize human factors. L2, L3, L4, L5, and L6 represent intermediary layers comprising eight factors. Although factors in intermediary layers are not direct causes, their complex interactions significantly influence the evolution of fire accidents. Consequently, enhancing fire safety supervision and guidance for merchants, along with strengthening on-site inspections and safety checks, is essential to ensuring fire safety. $S_5$ (unauthorized alterations) and $S_{12}$ (inadequate safety education and training) are positioned at the highest level as the fundamental factors in causing fire accidents. Businesses must enhance the planning and design management of commercial complexes, rigorously enforce relevant building codes and fire regulations to prevent fire hazards caused by unauthorized reconstructions, and consistently organize fire safety training and drills, as well as promote fire safety education to elevate the fire safety awareness and skills of employees and property management staff. These fundamental factors can indirectly influence the development of fire accidents through interactions with intermediary and surface-level factors and thus require close monitoring.

#### 4.3.3. DEMATEL-ISM Integrated Analysis

The comprehensive analysis of DEMATEL-ISM reveals that direct influencing factors such as $S_2$ (defective firefighting facilities), $S_3$ (electrical equipment failure), $S_7$ (impact of surrounding combustibles), and $S_{18}$ (lack of fire safety awareness) are strong resultant factors in DEMATEL. The fundamental factors in ISM analysis, $S_5$ (unauthorized alterations) and $S_{12}$ (inadequate safety education and training), are identified as causal factors in

DEMATEL analysis. The factor with the lowest nodal degree in the ISM model is locational advantage, which is consistent with the lowest centrality value in the DEMATEL analysis.

From the above analysis, it is evident that the two methods exhibit a high degree of consistency in the importance and classification of fire risks in commercial complexes, further validating the scientific effectiveness and accuracy of the model analysis.

These findings contribute to a more comprehensive understanding of the mechanisms underlying fire risks in commercial complexes and provide scientific recommendations for prevention and control. Based on the aforementioned analysis, a series of measures can be implemented to effectively prevent and control fires in commercial complexes. These measures include enhancing firefighting infrastructure, conducting regular fire safety inspections, raising safety awareness among personnel, and improving monitoring and early warning systems.

Such efforts will help reduce the probability of fire accidents, enhance the scientific and targeted nature of fire prevention and control in urban commercial complexes, safeguard lives and property, and promote the sustainable development of urban commercial complexes.

## 5. Conclusions

Fire statistics are crucial for understanding the trends of fire accidents in commercial complexes, enhancing fire control capabilities, and preventing such accidents. Fire accidents are the result of the combined effects of factors including personnel, equipment, the environment, and management. This study offers a statistical analysis of fire accidents in mainland China's commercial complexes from 2002 to 2022, summarizes the causes, establishes an index system for fire impact factors, and explores the interaction mechanisms among these factors. Here are the main conclusions:

(1) From 2002 to 2022, the number of accidents generally exhibited a fluctuating upward trend, with January recording the most accidents and July the fewest; February had the highest fatality rate.

(2) Based on a combination of literature studies and case studies, incorporating the principles of the fundamentals of security accident generation and integrating the basic elements of safety accidents, this study analyzed accident causes from four perspectives: unsafe human behaviors, unsafe conditions of objects, environmental factors, and management factors. Employing the WSR methodology and using physical, logical, and human perspectives as a foundation, it categorized 20 fire risk impact factors into four dimensions: personnel, equipment, environment, and management. This classification led to the creation of a scientifically sound system for evaluating and controlling fire risks in commercial complexes, marking a significant advancement in fire safety management.

(3) The DEMATEL model was applied to calculate and rank the degrees of influence, effect, centrality, and causality of causal factors. Based on these metrics, eight key factors were identified as critical to causing fire accidents in commercial complexes: $S_5$ (unauthorized alterations), $S_{10}$ (inadequate regulations), $S_{13}$ (inadequate fire safety inspections), $S_{12}$ (inadequate safety education and training), $S_{16}$ (careless use of fire in operations), $S_{14}$ (inadequate government supervision), $S_9$ (failure to implement corporate fire safety responsibilities), and $S_{11}$ (poor management of routine maintenance).

(4) Using ISM, a multi-level hierarchical structure model was established to analyze fire accident factors in commercial complexes, categorizing them into seven levels and dividing them into direct, intermediary, and essential factors. The direct factor layer includes ten impact indicators, which directly cause accidents and are the most easily perceived in accident analysis. Measures should be intensified to enhance safety monitoring and promptly identify fire hazards. The intermediary factor layer comprises eight indicators, representing significant factors between direct and essential factors that require effective intervention. $S_5$ (unauthorized alterations) and $S_{12}$ (inadequate safety training) are positioned at the highest level, constituting fundamental factors in fires within commercial complexes. This study employed the DEMATEL–ISM method

to examine the impact and extent of the influence of these factors on fire accidents, further exploring their interactions. The findings offer valuable insights for scientifically managing fire risks in commercial complexes and contribute to enhancing their sustainable development.

However, several significant challenges emerged during the research process. These challenges are necessary and can be addressed in future research for improvement. Firstly, due to the limitations in calculating the matrix workload, this study only extracted 20 risk factors, resulting in the generalization of some factor indicators. Future research needs to be more detailed and extensive. Secondly, in the DEMATEL method, the degree of mutual influence between factors is determined by experts, fully reflecting the experts' judgment based on their many years of experience in the field. However, this method also has subjective limitations. Additionally, the number of experts participating in the survey and their level of expertise should be considered, as this will help better identify the key factors contributing to fire risks in commercial complexes and their different structural relationships.

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