Journal of Engineering Science and Technology Review 16 (3) (2023) 173 - 180

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Fire Risk Assessment of High-Rise Residential Buildings Based on Catastrophe Theory

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Received 2 April 2023; Accepted 19 June 2023

Abstract

Fire risk control in high-rise residential areas has become the core issue of modern urban safety management. How to effectively evaluate the fire risk of high-rise residential buildings and then put forward scientific risk control measures is the focus of current academic and fire research. To reduce the probability of fire disasters in high-rise residential buildings and effectively evaluate their fire safety level, a total of 11 index factors affecting the fire risk level of high-rise residential buildings were identified in this study from three dimensions—residential conditions, property management, and community safety system. Furthermore, taking a high-rise building in Chinese Haikou City as an example, the fire risk level was determined, and the key factors affecting the fire risk level were clarified by combining the entropy weight model and the catastrophe series theory. Results show that the fire risk value of the high-rise residential buildings is 0.979, being relatively low, which coincides with the actual result obtained by the fire safety inspection department. The fire risk level of the high-rise building is significantly affected by the indexes of the automatic alarm system, with a weight value of 0.2839. The obtained conclusions provide a decision-making reference for comprehensively elevating the risk management level of high-rise residential buildings.

Keywords: Fire risk assessment, High-rise residential building, Catastrophe theory, Fire safety management

1. Introduction

The continuous progress of social and economic development and accelerating urbanization have led to a gradual concentration of the population in cities and increased the building density in urban areas. As human needs and lifestyles evolve, low-rise spaces are no longer sufficient. This has led to the necessary development of high-rise spaces [1]. In China, high-rise residential buildings have become increasingly popular due to advancements in building materials and construction technology. However, these buildings have large volumes, complex functions, and high population densities, which can make fire incidents particularly challenging. In such situations, personnel may face physical exhaustion, and staircases can become crowded and blocked, causing conflicts between personnel evacuation and rescue. The number of floors, people, and long vertical evacuation distances can further complicate the situation [2]. The incidence of high-rise residential building fires has continued to increase in recent years, which causes huge negative impacts and losses to society. Attaching importance to the fire safety management of high-rise buildings and adopting reasonable and effective fire risk assessment for high-rise buildings are important in reducing the risk of fire and promoting the development of urban and rural construction [3-4]. With the rise of modern high- and super-high-rise buildings, general owners also need to pay fire insurance for their purchased buildings. Scientific and reasonable fire risk assessment is the theoretical basis for insurance companies to determine appropriate insurance rates, which provides support for the insurance industry.

Many scholars are currently conducting extensive research on the methods and theories of fire risk assessment for high-rise residential buildings. However, a unified standard evaluation system has not yet been established. Some of the evaluation indicator systems in the research are also too broad, and their operability is weak in practical evaluation. Subjectivity has always existed in the calculation of evaluation indicator weights by scholars as well, which has a certain impact on the evaluation results [5]. Therefore, this work reviews relevant research on fire risk assessment for high-rise residential buildings at home and abroad. An evaluation indicator system is established based on the characteristics of high-rise residential communities and in combination with knowledge of real estate operation and management. This study uses statistical principles and methods to construct a fire risk assessment model for high-rise residential buildings, evaluates the fire risk level of a high-rise residential building in Zhengzhou as an example, finds the weak links in its fire risk, and proposes corresponding improvement suggestions. This work provides a new method and idea for fire risk assessment of high-rise residential buildings and enhances the scientific rationality of the evaluation method.

2. State of the Art

At present, researchers worldwide are focused on identifying risk factors, evaluating fire risks, and simulating emergency evacuations in high-rise residential building fires. Zhang Lining used the concept of three types of hazard sources in risk identification to assess the risk of high-rise fires. Ma [6] and Syphard [7] identified risk factors from the perspective of building materials and proposed corresponding preventive measures. Song et al. [8] studied the influence of the total number of elevators and the number of elevators on the

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ISSN: 1791-2377
doi:10.25103/jestr.163.21

optimal stopping floors of elevators based on Pathfinder. They proposed two elevator cooperative evacuation strategies: top priority and segmented top priority. These strategies were also optimized and analyzed. The simulation results showed that the use of elevator cooperative evacuation can effectively improve evacuation efficiency and reduce evacuation time. These studies have laid a foundation for evaluating the risk of high-rise residential building fires.

Studies on fire risk assessment of high-rise residential buildings have focused on two aspects: the establishment of evaluation indicator systems and the measurement of fire risk levels. Many methods can be used to establish evaluation indicator systems. For example, Feng et al. proposed an approach based on the fault tree method to rank the importance of identified influencing factors and determine the main factors [9-11]. Jia et al. [12] suggested a method based on the theory of three types of hazard sources to construct an indicator system for active firefighting, passive fire prevention, and safety management capabilities. In terms of evaluation model research, indicator quantification is a key step in the evaluation process. Various research methods have been used, including the analytic hierarchy process, fuzzy mathematics, gray correlation analysis, and Bayesian networks. For example, Wang et al. [13] used gray clustering and the analytic hierarchy process to propose a comprehensive evaluation system for assessing the fire risk of high-rise residential buildings. These works to some extent addressed the fuzziness of indicator quantification and provided a reliable basis for fair and standardized fire supervision inspections. Wang et al. [14] used the fuzzy comprehensive evaluation method to evaluate fire hazards for reducing the impact of subjective judgment on weight. Wang [15] believed that some indicator values or interrelationships between indicators in the assessment of fire risk in high-rise residential buildings are fuzzy and uncertain. Thus, they used gray correlation analysis to measure the size of the fire risk in the system. Li et al. [16] constructed a Bayesian network model for fire prediction based on the development process and spread a path of fires in high-rise residential buildings. Node variables in the model were determined using past fire accident data and statistical information. The probability of fire accidents under given initial conditions was also predicted.

In summary, although some studies have been conducted domestically and internationally on the risk assessment of high-rise residential building fires, no standardized evaluation criteria and methods are available for assessing the theoretical and methodological aspects of fire risk assessment. Scholars have used different methods to determine the risk level from different perspectives, which leads to significant differences in the results obtained. Therefore, further exploration and analysis are needed by scholars regarding the evaluation methods for high-rise residential buildings. Most scholars have also studied fire risks for high-rise buildings using a broad evaluation index system while ignoring the type of building being investigated. The features of different types of buildings vary greatly, and the indicators that affect fire risks also differ. Scholars have been attempting to improve mathematical methods and even combining new technologies and methods to evaluate fire risks in high-rise buildings. However, subjectivity still exists when calculating the weights of evaluation indicators.

This study aims to promote the theoretical and practical development of fire risk assessment in high-rise residential buildings. Thus, this work combines relevant knowledge in real estate operations and management to establish an evaluation index system for fire risk in high-rise residential communities. Mutation theory is also used to construct a fire risk assessment model based on the mutation series method for high-rise residential buildings. An evaluation index system is validated and analyzed as well as using a specific community case study to ensure the scientific and rational nature of the evaluation index system.

3. Methodology

3.1 Construction of Evaluation Indicator System

Fire accidents in high-rise residential buildings have complexity and uncertainty, and the occurrence of fire will seriously endanger personal and property safety. The indicator system for high-rise residential fire risk constructed in this study mainly considers the firefighting infrastructure and safety management prevention factors of high-rise residential buildings. It integrates the opinions of experts in the field of firefighting emergency and firefighting and rescue personnel. The system also determines the emergency response ability evaluation indicators of high-rise building fire accidents in three dimensions: the status of residential firefighting infrastructure, property management, and community safety management. An assessment indicator system for high-rise residential fire is constructed, including three primary indicators and eleven secondary indicators, as shown in Table 1.

Table 1. High-rise residential buildings risk evaluation index system

Primary indicator	Secondary indicator	Tertiary indicator
High-rise residential fire risk assessment system M	Residential fire-fighting infrastructure status M_1	Automatic sprinkler system M_{11} Fire extinguisher system M_{12} Automatic alarm system M_{13} Evacuation exit M_{14}
	Property management M_2	Level of education M_{21} Firefighting training M_{22} Fire hazard investigation and rectification M_{23}
	Community safety management M_3	Fire management system M_{31} Regular fire safety inspections M_{32} Fire safety publicity M_{33} Fire emergency response plan M_{34}

3.2 Data Verification and Processing

This study mainly collects experts' opinions on various indicators through a questionnaire survey. Validity checks need to be conducted on the questionnaire to prevent individual experts from having biased ideas, unreasonable questionnaire design, or data deviation. The validity check of the questionnaire mainly tests the degree to which the questionnaire content objectively reflects the measured content, including reliability and validity checks.

(1) Reliability Check

Reliability refers to the consistency or stability of the diverse sample data obtained from the questionnaire survey, which reflects whether the questionnaire design is reasonable. Cronbach's alpha coefficient method is used in this study to conduct the reliability check. The overall reliability of the questionnaire of above 0.7 and the reliability of the subscale of above 0.6 indicate that the questionnaire content has high consistency. Therefore, it is an acceptable standard. The calculation formula for Cronbach's alpha coefficient is:

$$\alpha=\left(\frac{k}{k-1}\right)*\left(1-\frac{\sum s_i^2}{S_T^{\,2}}\right) \tag{1}$$

where K is the number of questions in the questionnaire, S_i^2 is the variance of scores for questions across all samples, and is the variance of total scores across all samples.

(2) Validity Check

The KMO test and Bartlett's test of sphericity need to be conducted to test the suitability of the questionnaire data for factor analysis. The KMO test can calculate the correlation coefficient between variables. The principle of factor analysis is to extract a few common factors from variables that are correlated. Thus, if the KMO test meets acceptable statistical criteria, then the questionnaire data are suitable for factor analysis. Otherwise, they are unsuitable. The formula for calculating the KMO value is shown in Formula (2).

$$KMO=\frac{\sum\sum_{i\neq j} r_{ij}^2}{\sum\sum_{i\neq j} r_{ij}^2+\sum\sum_{i\neq j}\alpha_{ij}^2} \tag{2}$$

where r_{ij} represents the correlation coefficient between variables and α_{ij} represents the partial correlation coefficient between variables.

Bartlett's test of sphericity mainly uses the conformity between the obtained correlation matrix and the unit matrix to determine whether variables are correlated. If the correlation matrix is the unit matrix, then the variables are independent and not correlated, which is unsuitable for factor analysis; otherwise, they are suitable. Formulas (3) and (4) show Bartlett's test of sphericity.

$$K^2=\frac{(n-r)\ln MSe-\sum_{i=1}^{r}(n_i-1)\ln s_i^2}{c} \tag{3}$$

$$c=1+\frac{1}{3(r-1)}\left[\sum_{i=1}^{r}\frac{1}{n_i-1}-\frac{1}{n-r}\right] \tag{4}$$

where r represents the number of columns in the scale, n represents the sample size, s_i^2 represents the standard deviation of each sample, and i represents the number of rows in the scale.

Content validity testing refers to the degree to which a scale's design represents actual values. It can be tested using results obtained from factor rotation in factor analysis. The common factors in factor analysis are objectively existing factors that cannot be directly observed. Each variable can be expressed as a linear function of the common factors plus the unique factors, which is:

$$X_i=a_{i1}F_1+a_{i2}F_2+\cdots+a_{im}F_m+\varepsilon_i,\ (i=1,2,\cdots,p) \tag{5}$$

where $F_1,F_2,\ldots,F_m$ represents the common factor and ε_i represents the unique factor of X_i. This model can be represented using matrices as follows:

$$X=AF+\varepsilon \tag{6}$$

where

$$X=\begin{bmatrix}X_1\\X_2\\\vdots\\X_p\end{bmatrix},\ A=\begin{bmatrix}a_{11}&a_{12}&\cdots&a_{1m}\\a_{21}&a_{22}&\cdots&a_{2m}\\\cdots&\cdots&\cdots&\cdots\\a_{p1}&a_{p2}&\cdots&a_{pm}\end{bmatrix},\ F=\begin{bmatrix}F_1\\F_2\\\vdots\\F_m\end{bmatrix},\ \varepsilon=\begin{bmatrix}\varepsilon_1\\\varepsilon_2\\\vdots\\\varepsilon_p\end{bmatrix} \tag{7}$$

The following conditions need to be satisfied:

1) $m\leq p$;

2) $Cov(F,\varepsilon)=0$, which means that the common and unique factors are uncorrelated;

3) $D_F=D(F)=\begin{bmatrix}1&&&0\\&1&&\\&&\ddots&\\0&&&1\end{bmatrix}=I_m$, which implies that each common factor is uncorrelated and has a variance of 1;

4) $D_\varepsilon=D(\varepsilon)=\begin{bmatrix}\sigma_1^2&&&0\\&\sigma_2^2&&\\&&\ddots&\\0&&&\sigma_P^2\end{bmatrix}$, which denotes that each unique factor is uncorrelated and may have different variances.

The matrix A in the model is called the factor loading matrix, and a_{ij} is called the factor loading, which represents the loading of the variable i on the j factor. If X_i is viewed as a point in an m-dimensional space, then a_{ij}. represents its projection onto the axis F_j.

3.3 Quantitative Risk Management

3.3.1 Dimensionless Data Processing

According to the established evaluation index system, each control variable has a different impact on the state variable. However, the index system includes not only quantitative indicators but also qualitative indicators, and the data ranges and measurement units are inconsistent. This study adopts the concept of relative membership degree to normalize the positive indicators y_{ij}^p and negative indicators y_{ij}^n for unifying the dimensions of the index layer parameters. The positive indicator with a larger value has a greater positive effect on the fire risk, and vice versa. The specific calculation formula is:

$$\text{Positive indicators: } y^p=\begin{cases}0 & (x<x_{\min})\\ \dfrac{x-x_{\min}}{x_{\max}-x_{\min}} & (x_{\min}\leq x\leq x_{\max})\\ 1 & (x>x_{\max})\end{cases} \tag{8}$$

Negative indicators: $$y^n = \begin{cases} 0 & x > x_{\max} \\ \dfrac{x_{\max} - x}{x_{\max} - x_{\min}} & (x_{\min} \le x \le x_{\max}) \\ 1 & x < x_{\min} \end{cases} \tag{9}$$

where y is the standardized value, x is the initial value of a certain indicator in a certain year and time interval, $x_{\min}$ is the minimum value of a certain indicator in the period, and $x_{\max}$ is the maximum value of a certain indicator in the period.

3.3.2 Calculation Rules for Complementary Relationships

The values of the underlying indicators that have been dimensionless processed are calculated according to the normalization formula of the mutation model to obtain the mutation membership degree value. Then, different formulas are used for the recursive calculation of the upper-level indicators according to the complementary relationships of the same-level indicators. The calculation rules for different complementary relationships are discussed as follows:

(1) Complementarity Rule

If an obvious correlation exists between indicators at the same level, or if each indicator can complement each other about the upper-level indicator, then the indicators at this level have complementarity. After normalization of the mutation membership degree values, the calculation formula is shown in Formula (10).

$$x = \frac{x_1 + x_2 + \cdots x_n}{n} \tag{10}$$

(2) Non-complementarity Rule

If no correlation exists between indicators at the same level and the effects and influences on the upper-level indicators are completely separate, then the indicators at this level have non-complementarity. After normalization of the mutation membership degree values, the calculation formula is shown in Formula (11).

$$x = \min\left\{x_1, x_2, \cdots, x_n\right\} \tag{11}$$

3.3.3 Determining the Relative Importance of Evaluation Indicators based on the Entropy Weight Method

The entropy weight method is used in this study to calculate the weights of each indicator, as follows [17]:

The proportion of the indicator value in the year i under the jth indicator is calculated as follows:

$$f_{ij} = \frac{y_{ij}}{\sum_{i=1}^{n} y_{ij}} (i = 1, 2, \cdots, n) \tag{12}$$

The entropy value of the jth indicator is calculated as follows:

$$e_j = -k \sum\nolimits_{j=1}^{n} f_{ij} \ln(f_{ij}), \; k = \frac{1}{\ln(n)} \tag{13}$$

The weight of the jth indicator is calculated as follows:

$$w_i = \frac{1 - e_j}{n - \sum_{j=1}^{m} e_j}, \; \sum_{j=1}^{m} w_j = 1(0 \le w_j \le 1) \tag{14}$$

3.4 Assessment Model for High-rise Residential Fire Risk

Catastrophe theory studies situations of discontinuity and sudden qualitative changes caused by external or internal factors. Many experts and scholars have also demonstrated the compatibility of fire and catastrophe theory. They believe that the occurrence of fire accidents can be understood as a qualitative change in various parameters within the system. Moreover, the system changes from a safe state to a fire state, which a catastrophic phenomenon is. The spread of fire also conforms to the laws of catastrophe theory.

The catastrophe progression method is developed based on catastrophe theory; it combines fuzzy mathematics principles and the normalization formula for comprehensive quantitative operations, and then, it obtains the total membership function [18]. Compared with other methods, the catastrophe progression method balances the relative importance of each evaluation indicator, combines qualitative and quantitative methods, and avoids the problem of subjectivity; it is also more scientific and reasonable and especially suitable for multi-objective comprehensive evaluation.

3.4.1 Classification of Catastrophe Models

The catastrophe model is a hierarchical structure model composed of state variables x and control variables u, v, w, and t. In this model, the state variable x represents the behavioral state of the system itself and can be regarded as the upper-level indicator in the risk assessment indicator system. Meanwhile, the control variables u, v, w, and t represent the determining factors of the system's catastrophic change, that is, the corresponding lower-level indicators. When the number of indicators differs, the constructed catastrophe model and potential function also differ [19]. The structure and corresponding normalization formulas of the four common elementary catastrophe models are shown in Table 2.

Table 2. Common catastrophe model equations and normalization formulas

Mutation model	Dimensionality	Potential function	Normalization formula
Fold change mutation	1	$f(x) = x^3 + ux$	$x_u = u^{1/2}$
Pointed mutation	2	$f(x) = x^4 + ux^2 + vx$	$x_u = u^{1/2}, x_v = v^{1/3}$
Tail mutation	3	$f(x) = \frac{1}{5}x^5 + \frac{1}{3}ux^3 + \frac{1}{2}vx^2 + wx$	$x_u = u^{1/2}, x_v = v^{1/3}, x_w = w^{1/4}$
Butterfly mutation	4	$f(x) = \frac{1}{6}x^6 + \frac{1}{4}ux^4 + \frac{1}{3}vx^3 + \frac{1}{2}wx^2 + tx$	$x_u = u^{1/2}, x_v = v^{1/3}, x_w = w^{1/4}, x_t = t^{1/5}$

3.4.2 Determination of Fire Risk Level

The conventional risk classification standard is based on the principle of average distribution. This standard is generally divided into four levels: low, moderate, high, and extreme. The corresponding level of each level needs to be determined based on the total mutation membership function value. The distribution of system evaluation values for each level is shown in Table 3.

Table 3. High-rise residential fire risk level division

Evaluation level	Extreme	High	Moderate	Low
Evaluation criteria	$0 \le x < 0.40$	$0.40 \le x < 0.60$	$0.60 \le x < 0.80$	$0.80 \le x < 1.00$
Evaluation level classification	Level I	Level II	Level III	Level IV

However, the abovementioned classification standard is unsuitable for the conclusions obtained by the mutation evaluation method. The values of the comprehensive mutation function obtained are biased toward 1 and the difference between the evaluation values is small due to the mathematical characteristics of the normalization formula in the mutation evaluation method. The obtained values of mutation comprehensive evaluation need to be transformed to overcome the aforementioned shortcomings. The selection of the membership degree values of the underlying indicators is to select four values in [0.1, 0.4] and insert 16 values in [0.4, 1]. Then, the normalization formula is used for the recursive operation to obtain the mutation membership function value *y*. Finally, the corresponding relationship between *x* and *y* is established, as shown in Table 4.

Table 4. Correspondence relationship

x_i	1.00	0.98	0.96	0.94	0.92	0.90	0.86	0.83	0.80	0.75
y_i	1.0000	0.9998	0.9989	0.9962	0.9933	0.9905	0.9866	0.9835	0.9794	0.9745
x_i	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.30	0.20	0.10
y_i	0.9697	0.9645	0.9601	0.9562	0.9502	0.9447	0.9392	0.9251	0.9069	0.8846

x_i and y_i are fitted, and the linear relationship between x_i and y_i is shown in the figure below, that is, the evaluation value x_i calculated by the mutation evaluation model can be converted into an absolute grading index.

Therefore, a risk classification table for high-rise residential building fires based on mutation function values can be obtained through transformation, as shown in Table 5.

Table 5. Standards for risk assessment levels of high-rise residential building fires

Risk Level	Conversion Interval	Bottom Index Value
Low Risk	≥0.9794	≥0.8
Moderate Risk	[0.9601,0.9794)	[0.6,0.8)
High Risk	[0.9392,0.9601)	[0.4,0.6)
Extreme Risk	＜0.9392	＜0.4

4. Results and Discussion

As an example, this study evaluates the fire risk of a high-rise residential building located in Zhengzhou, China, using a well-established model. The goal is to assess the current fire risk and compare the results with the building's existing fire safety evaluation to determine the model's feasibility and rationality.

4.1 Overview of the High-rise Building

The residential high-rise located in Zhengzhou was constructed in 2017 and boasts 27 floors, each with a height of 2.8 meters, resulting in a total building height of 78.5 meters. Every floor is outfitted with an automatic sprinkler and fire alarm system, as well as fire extinguishers and hydrants. Additionally, each unit is equipped with two elevators and a safety evacuation channel.

(1) Personnel Characteristics

Located in the new city area of Zhengzhou, the building has the added convenience of being situated next to the subway, making transportation easy and accessible. Its residents are predominantly young white-collar workers who work in the surrounding area and possess a high degree of mobility. About 43% of the total population has lived there for over a year, giving them a moderate level of familiarity with the building. The majority of its inhabitants, 85.2% to be exact, is aged between 22-30 years old and is characterized by their high level of physical fitness and education.

Based on the survey, the fire safety competency level of the management personnel is quite high. Approximately 50% of the personnel are graduates from reputable universities, with over 60% having more than 3 years of work experience in safety. The management team undergoes annual training and assessment to ensure that their skills are up to date.

(2) Building Fire Protection Facilities

1) Active Firefighting Equipment

The building has automatic sprinkler systems installed in areas like the underground garage and corridor. These systems have functional nozzles and pipes filled with water, ready to respond immediately in case of a fire. Indoor fire hydrants have unobstructed pipes connected to the external water supply, while outdoor hydrants have low water pressure. The high-rise residential building follows regulations for a natural smoke exhaust system. However, there are a few fire extinguishers that have expired or are damaged inside the building.

2) Passive Fire Protection Equipment

The electrical cables at power consumption points are buried underground after being directly laid from the substation through designated pipes. Concrete is used to seal cables passing through the road. The electrical wires have a degree of aging. Every building floor is equipped with a self-closing fire door with fire-resistance rating of 0.5 h. Multi-floor fire doors are always open for easy passage, but some on certain floors are damaged and unable to close securely. To ensure safety, fire-retardant paint is used in evacuation corridors, although some areas may have objects piled up.

3) Safety Evacuation Equipment

The evacuation staircase on the same floor is located at a maximum distance of 20 meters from any room. The residential staircase provides direct access to the outside on the ground floor and to the rooftop on the top floor. The evacuation route follows a straight path with no turns.

However, the evacuation passages on all six floors are currently blocked with objects, which create a severe obstacle. The safety signs on each floor are positioned appropriately and have sufficient brightness. Furthermore, emergency lighting with a brightness of 6.0LX is installed in the corridors, evacuation staircases, first-floor lobby, and refuge areas. The emergency power supply system is in good condition and ready for use in case of any emergency.

(3) Fire Safety Management

The management of the building's fire safety is the responsibility of property management. They have a 24-hour fire control center and a well-established system for assigning responsibility in case of accidents. All firefighting equipment is inspected and maintained every 3 months, and there has been only one small-scale emergency drill. Daily fire inspections are recorded, but there have been cases of false registration. The building undergoes safety inspections every 3 months, and special firefighting facilities are maintained and repaired annually.

4.2 Quantitative Calculation of High-rise Fire Risk

4.2.1 Reliability and Validity Testing

(1) Reliability Testing

The collected questionnaire was subjected to reliability testing using the SPSS software, and the *Cronbach's* α coefficient of the questionnaire was 0.819, which indicates good internal consistency. The reliability analysis is shown in Table 6.

Table 6. Reliability analysis of the questionnaire

Indicators	*Cronbach's* α	Number of Items
Test value	0.819	11

(2) Validity Testing

Before the explanatory power of each indicator in the established indicator system for risk was examined through exploratory factor analysis, the correlation between the indicators and their suitability for factor analysis was confirmed using *Bartlett*'s sphericity test and the KMO test. Therefore, this study also chose the KMO and *Bartlett*'s sphericity test to test the questionnaire's validity. The results are shown in Table 7.

Table 7. KMO and Bartlett's sphericity test

KMO Test Statistic		0.741
Bartlett's Sphericity Test	Approx. Chi-Square	104.3
	df	63
	Sig	0.000

According to the results of the KMO and Bartlett's sphericity test in Table 6, a correlation exists between the indicators, which meet the conditions for factor analysis. The questionnaire data were processed by exploratory factor analysis using the SPSS software, and the results are shown in Table 8. Three common factors were extracted based on the standard of retaining factors with eigenvalues greater than 1 through orthogonal rotation, and the cumulative variance explanation reached 68.63%.

Table 8. Results of exploratory factor analysis of questionnaire data

Element	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	Variance%	Cumulative%	Total	Variance%	Cumulative%
1	7.836	25.836	25.836	7.836	25.836	25.836
2	5.527	19.271	45.075	5.527	19.239	45.075
3	3.215	15.988	60.465	3.215	15.390	60.465
4	0.819	7.535	68.63			
5	0.762	6.672	75.302			
6	0.662	6.101	81.403			
7	0.553	5.13	86.533			
8	0.417	4.827	91.36			
9	0.330	3.692	95.052			
10	0.236	2.795	97.847			
11	0.108	2.153	100			

4.2.2 Dimensionless Processing of Underlying Indicator Data

Referring to relevant industry standards such as the "Code for Fire Protection Design of Buildings" and the "Fire Protection Law of the People's Republic of China" and based on the unique requirements and indicator standards of high-rise building fires, five relevant experts in this field were invited to determine the critical and actual sample values of different evaluation factors based on the on-site investigation of the residential community. The basic data obtained for each indicator are shown in Table 9.

Table 9. Basic data for indicators

Serial number	Evaluation index	Indicator properties	Lower limit	Upper limit	Mean
M_{11}	Automatic sprinkler system	+	50	100	92.3
M_{12}	Fire extinguisher system	+	50	100	91.7
M_{13}	Automatic alarm system	+	50	100	96.8
M_{14}	Evacuation exit	+	50	100	95.5
M_{21}	Level of education	+	50	100	93.5
M_{22}	Firefighting training	+	0	60	25.4
M_{23}	Fire hazard investigation and rectification	+	0	30	17.6
M_{41}	Fire management system	+	50	100	94.8
M_{42}	Regular fire safety inspections	+	50	100	96.3
M_{43}	Fire safety publicity	+	30	70	56
M_{44}	Fire emergency response plan	+	50	100	85.2

Based on the basic data obtained in Table 9 and the evaluation indicator types, the dimensionless processing of underlying indicators is performed according to the formula, that is, all control variables are converted into dimensionless indicators with higher scores indicating a better safety level. The conversion results are shown in Table 10.

Table 10. Dimensionless values of underlying indicators

Index	Dimensionless value	Index	Dimensionless value
M_{11}	0.926	M_{23}	1.000
M_{12}	0.913	M_{41}	0.815
M_{13}	0.837	M_{42}	0.768
M_{14}	0.842	M_{43}	0.937
M_{21}	0.879	M_{44}	0.704
M_{22}	0.861		

4.2.3 Data Entropy Weight Processing

The dimensionless results are subjected to entropy weighting calculation through the process of entropy weighting described earlier. The mutation operations adopted by each level of indicators are marked as well. The specific calculation results are shown in the following Table 11.

Table 11. Calculation results of entropy weighting

Primary indicator	Secondary indicator	Tertiary indicator	Information entropy redundancy	Weight	Itemized ranking
High-rise residential fire risk assessment system *M* (the swallowtail catastrophe)	Residential fire-fighting infrastructure status M1 (the butterfly catastrophe)	Automatic sprinkler system M11	0.2217	0.2150	4
		Fire extinguisher system M12	0.2336	0.2431	3
		Automatic alarm system M13	0.2473	0.2839	1
		Evacuation exit M14	0.0611	0.2726	2
	Property management M2 (the swallowtail catastrophe)	Level of education M21	0.0383	0.1564	3
		Firefighting training M22	0.1825	0.2392	1
		Fire hazard investigation and rectification M23	0.1531	0.2210	2
	Community safety management M3 (the butterfly catastrophe)	Fire management system M31	0.1687	0.1881	3
		Regular fire safety inspections M32	0.2219	0.2839	2
		Fire safety publicity M33	0.1346	0.1581	4
		Fire emergency response plan M34	0.2635	0.3253	1

4.2.4 Evaluation Results Using Mutation Series Method

According to the normalized equation in Table 2, the mutation membership function values of each level and the total mutation function value for the fire risk of the high-rise building are calculated layer by layer, as shown in Table 12. The total mutation function value is 0.979, which is consistent with the conclusion obtained by the actual fire safety inspection department.

Table 12. Membership function values of mutation series method at each level

Corresponding risk level	Fire risk level	Secondary indicator	The value of the catastrophe progression	Tertiary indicator	The value of the catastrophe progression
low fire risk	0.979	M_1	0.987	M_{11}	0.982
				M_{12}	0.993
				M_{13}	0.986
				M_{14}	0.992
		M_2	0.982	M_{21}	0.973
				M_{22}	0.986
				M_{23}	0.985
		M_3	0.973	M_{31}	0.979
				M_{32}	0.983
				M_{33}	0.965
				M_{34}	0.978

5. Conclusions

To address the issue of fire risk assessment in high-rise residential buildings, this study has developed an evaluation index system that takes into account the fire-fighting infrastructure and safety management prevention aspects. This system has been constructed by referring to previous research. A fire risk assessment model for high-rise buildings was created using the mutation series method and adaptability of the mutation model. The study produces the following conclusions:

(1) By comprehensively analyzing the causes of fire risk in high-rise residential buildings and selecting evaluation indexes based on building types, this study aims to offer a more accurate representation of their characteristics. This approach effectively addresses the issues of broad evaluation index systems and unclear building types affecting evaluation results in practical applications.

(2) By utilizing the mutation series method in the assessment model for high-rise residential building fires, the issues of ambiguity and subjectivity in the evaluation process can be effectively resolved while simultaneously improving the reliability of the evaluation results.

(3) After conducting a case analysis and applying an evaluation model, it was determined that the fire risk value of the high-rise residential building in this study is low at 0.979. The results align with the actual fire safety evaluation, proving that this study offers a reliable and efficient technique for assessing and managing fire risk in high-rise residential buildings. Additionally, it introduces a fresh approach to evaluating fire risk in such structures.

To summarize, this research employs the mutation series method to quantitatively analyze the fire risk level of high-rise residential buildings. The model's feasibility and scientific value are demonstrated by means of example calculation and verification, while also providing a novel approach for assessing fire risk in such structures. That being said, the study overlooks the level of consumer safety knowledge possessed by residents in these buildings, indicating a need for further research to address this deficiency and improve overall safety.

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