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Um Método Integrado de Avaliação de Risco de Incêndio em Edifícios Residenciais

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Abstrato

Os incêndios em edifícios são caracterizados por uma elevada incerteza, pelo que a sua avaliação do risco de incêndio é uma tarefa muito desafiante. Muitos índices e parâmetros relacionados a incêndios em edifícios são ambíguos e incertos; como resultado, é necessário um método flexível e robusto para processar dados quantitativos ou qualitativos e atualizar as informações existentes quando novos dados estiverem disponíveis. Este artigo apresenta um novo modelo para lidar com a incerteza do risco de incêndio em edifícios residenciais e otimizar sistematicamente sua eficácia de desempenho. O modelo inclui teoria fuzzy, teoria de raciocínio de evidências e métodos de utilidade esperada. O processo de hierarquia de análise fuzzy é aplicado para analisar o sistema de índice de risco de incêndio de edifícios residenciais e determinar os pesos dos índices de risco, enquanto o operador de raciocínio de evidência é usado para sintetizá-los. Três edifícios foram selecionados como estudo de caso para ilustrar o modelo de risco de incêndio proposto. Os resultados mostram que o nível de risco de incêndio de três edifícios

verdadeiramente a situação real da segurança contra incêndios nestes edifícios residenciais. A aplicação deste modelo fornece uma poderosa estrutura matemática para modelagem cooperativa do sistema de avaliação de risco de incêndio e permite que os dados sejam analisados passo a passo de maneira sistemática. Espera-se que o modelo proposto possa fornecer aos gestores e pesquisadores ferramentas flexíveis e transparentes para reduzir efetivamente o risco de incêndio no sistema. Os resultados mostram que o nível de risco de incêndio de três edifícios corresponde a "moderado" ou abaixo do que é consistente com o estudo anterior. Estes resultados também refletem verdadeiramente a situação real da segurança contra incêndios nestes edifícios residenciais. A aplicação deste modelo fornece uma poderosa estrutura matemática para modelagem cooperativa do sistema de avaliação de risco de incêndio e permite que os dados sejam analisados passo a passo de maneira sistemática. Espera-se que o modelo proposto possa fornecer aos gestores e pesquisadores ferramentas flexíveis e transparentes para reduzir efetivamente o risco de incêndio no sistema. A aplicação deste modelo fornece uma poderosa estrutura matemática para modelagem cooperativa do sistema de avaliação de risco de incêndio e permite que os dados sejam analisados passo a passo de maneira sistemática. Espera-se que o modelo proposto possa fornecer aos gestores e pesquisadores ferramentas flexíveis e transparentes para reduzir efetivamente o risco de incêndio no sistema. A aplicação deste modelo fornece uma poderosa estrutura matemática para modelagem cooperativa do sistema de avaliação de risco de incêndio e permite que os dados sejam analisados passo a passo de maneira sistemática. Espera-se que o modelo proposto possa fornecer aos gestores e pesquisadores ferramentas flexíveis e transparentes para reduzir efetivamente o risco de incêndio no sistema.

1. Introdução

Com a aceleração da industrialização, urbanização e mercantilização na China, a indústria da construção civil desenvolveu-se rapidamente. Particularmente, a estrutura e a função dos edifícios estão se tornando mais complexas, e várias novas tecnologias e técnicas estão surgindo constantemente, o que tem levado à situação cada vez mais severa dos incêndios em edifícios. De acordo com as estatísticas fornecidas pelo Ministério da Segurança Pública em 2013, um total de 388.821 incêndios foram registrados na China, em que 52% (202.299) dos incêndios ocorreram em edifícios, resultando em 3.410 civis mortos ou feridos e 3.760 milhões de yuans chineses (CNY) perdas patrimoniais diretas. Atualmente, o incêndio em edifícios é considerado uma enorme ameaça à vida e à produção das pessoas na China, e uma preocupação crescente é como tomar as medidas adequadas para reduzir o risco de incêndio, minimizar os danos e prejuízos causados pelo fogo em edifícios e garantir a segurança contra incêndios dos edifícios. Portanto, é urgente estabelecer um modelo de avaliação de risco de incêndio adequado, e que forneça informações por meio de resultados de análises quantitativas ou qualitativas para tomar decisões sobre a tomada de medidas para reduzir o risco.1, 2].

Existem principalmente quatro tipos convencionais de métodos de análise de risco de incêndio: lista de verificação, descrição, índice e método de probabilidade [3]. No entanto, a maioria dessas abordagens tem desvantagens prescritivas que dificultam a análise quantitativa do risco de incêndio devido à incapacidade de lidar com as incertezas associadas aos fatores de risco de incêndio do sistema. Com a melhoria do projeto de proteção contra incêndio baseado em desempenho, surgiram alguns modelos de análise de risco de incêndio e software correspondente, como FiRECAM™ (Fire Risk Evaluation and Cost Assessment Model) [4 , 5], FIERAsystem (Fire Evaluation and Risk Assessment system) [6], sistema de classificação de risco de incêndio para edifícios existentes usando a abordagem de conjuntos difusos [11]. Liu et ai. construiu um sistema de análise de risco de incêndio para edifícios comerciais usando o método de peso de entropia da estrutura [12]. Xin e Huang propuseram métodos de agrupamento de cenários no processo do modelo de análise de risco de incêndio para edifícios residenciais [2]. Resumidamente, esses métodos revelam dois desafios principais em um ambiente incerto associado aos fatores de risco de incêndio do sistema. O primeiro desafio enfrentado por esses métodos é a falta de capacidade de processar uma variedade de dados adequados para mecanismos de raciocínio de risco de incêndio, e o segundo é a falta de capacidade de analisar a interdependência dos fatores de risco. Neste artigo, é apresentado um modelo de análise de risco de incêndio integrado à teoria fuzzy e à teoria do raciocínio probatório (ER) para edifícios residenciais. Comparado com a abordagem tradicional de raciocínio fuzzy, o ER tem a vantagem de evitar a perda de informações úteis; portanto, pode ser aplicado para modelar sistemas complexos. A estrutura deste modelo está organizada da seguinte forma. A seção 2 ilustra a metodologia da pesquisa. Seção3 apresenta um estudo de caso para verificar a viabilidade da metodologia. As seções 4 e 5 discutem os resultados empíricos e as conclusões.

2. Metodologia

Técnicas de avaliação quantitativa de risco (QRA) são geralmente usadas para avaliar incertezas em incêndios em edifícios. No entanto, devido à falta de estatísticas de acidentes de incêndio, uma solução eficaz é integrar julgamentos de especialistas no processo de QRA. QRA consiste em quatro procedimentos principais: identificação do perigo, cálculo da probabilidade de ocorrência, avaliação da gravidade da consequência e quantificação do risco [13 , 14]. Para processar a estrutura complexa do sistema e promover um método de implementação flexível, diferentes técnicas de tomada de decisão podem ser utilizadas, como processo de hierarquia analítica fuzzy, teoria dos conjuntos fuzzy e método de raciocínio de evidências. Devido ao fato de que a lógica fuzzy pode fornecer uma maneira flexível de representar as informações vagas resultantes da falta de dados ou conhecimento. Portanto, a teoria dos conjuntos fuzzy tem uma ampla aplicação em diferentes campos, como engenharia de confiabilidade, segurança de sistemas e avaliação de riscos [15].

A estrutura proposta, mostrada na Figura 1 , permite a análise passo a passo do risco de incêndio do túnel de utilidade de forma transparente, conforme descrito a seguir:

(1) Identificar fatores de risco de incêndio e estabelecer a estrutura hierárquica do sistema de índices
(2) Using fuzzy analytic hierarchy process (FAHP) to calculate the weights of indexes
(3) Applying the belief degree structure based on the fuzzy set theory to measure the fire risk
(4) Aggregating the result of the fire risk using the evidence reasoning (ER) algorithm
(5) Using the expected utility method to obtain a clear result of the fire risk
(6) Sensitivity analysis

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Figure 1

The procedure for fire risk assessment in residential buildings.

2.1. Identifying Fire Risk Factors and Establishing the Hierarchical Structure of the Index System

In order to make better decisions on fire control protection and emergency evacuation measures, a structured and systematic approach is needed. It is better to describe the fire risk problem in a hierarchical structure so that decision makers could have a thorough understanding of the system, especially when it is a complex system with multilevel structural indexes.

According to NFPA550 Guidelines, to achieve fire safety, reducing the fire risk mainly starts from two aspects: one is to prevent the occurrence of fire, and the other is to control the impact of fire [16]. In this paper, fire risk factors of these two aspects are, respectively, defined as disaster-causing factors and loss-controlling factors. Disaster-causing factors may cause the fire risk to be transformed into disaster before fire occurs, while loss control factors signified various fire protection and management measures to control the development process of fire and mainly involved four aspects: passive measures, active measures, fire management, and fire brigade fighting.

Based on the characteristics of residential building fire and the literature review [6, 17–20], the factors influencing the risk of building fires are analyzed from the two aspects of disaster-causing factors and loss-controlling factors. A general hierarchical structure (presented in Figure 2) is finally established after theoretical preparation, the initial construction of the index system, the optimization of the index system, and the determination of the index system.

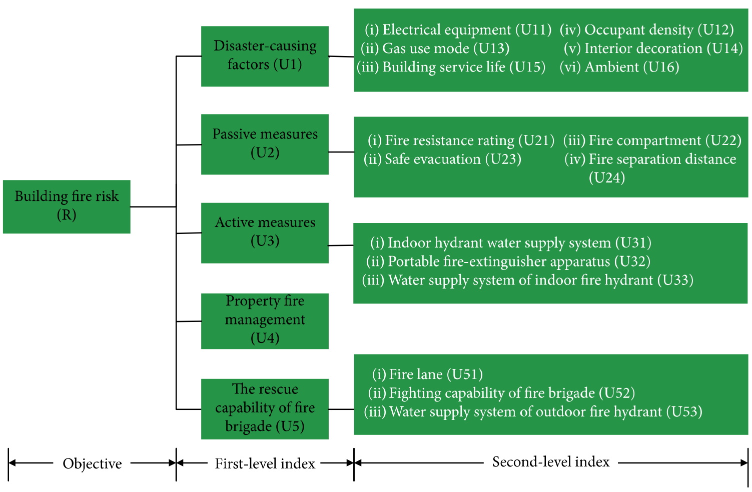

Figure 2

The hierarchical structure for the residential building fire risk model.

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numbers to construct judgment matrices and combined with the extent analysis method to calculate the weights of each index in the hierarchical structure. Finally, the traditional AHP is transformed into the FAHP in the fuzzy environment, which can provide more practical results [22].

2.2.1. Triangular Fuzzy Number

Suppose the triangular fuzzy number is M, and its membership function $\mu_M : R \longrightarrow [0,1]$ is equal to

$$\mu_M(x) = \begin{cases} \dfrac{x-l}{m-l}, & l \le x \le m, \\ \dfrac{x-u}{m-u}, & m \le x \le u, \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

$$\mu_M(x) = \begin{cases} \dfrac{x-l}{m-l}, & l \le x \le m, \\ \dfrac{x-u}{m-u}, & m \le x \le u, \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

Herein, $l \le m \le u$, l and u represent the lower and upper boundary value of triangular fuzzy number M, respectively, and m represents the median value of triangular fuzzy number M. Generally, triangular fuzzy number M can be abbreviated as (l, x, m). Let $M_1 = (l_1, x_1, m_1)$ and $M_2 = (l_2, x_2, m_2)$ be triangular fuzzy numbers; then, the possibility degree of $M_1 \ge M_2$ is defined as follows:

$$V(M_1 \ge M_2) = \begin{cases} 1, & m_1 \ge m_2, \\ \dfrac{l_2 - u_1}{(m_1 - u_1) - (m_2 - l_2)}, & m_1 < m_2, l_2 \le u_1, \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

$$V(M_1 \ge M_2) = \begin{cases} 1, & m_1 \ge m_2, \\ \dfrac{l_2 - u_1}{(m_1 - u_1) - (m_2 - l_2)}, & m_1 < m_2, l_2 \le u_1, \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

2.2.2. Fuzzy Synthetic Extent

Consider $X = \{x_1, x_2, \ldots, x_n\}$ as a set of analytic objects and $U = \{u_1, u_2, \ldots, u_n\}$ as a target set; we can get the extent value of the i-th object satisfying the j-th goal, in which the sign is $M_{E_i}^j$. Then, the value of synthetic extent of the i-th object is defined as [21, 23]

$$S_i = \sum_{j=1}^{m} M_{E_i}^j \left(\sum_{i=1}^{n} \sum_{j=1}^{m} M_{E_i}^j \right)^{-1}. \quad (3)$$

2.2.3. The Procedure of the FAHP

In the evaluation of the fire risk, the determination of the weight of each fire risk factor is particularly

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(2) The judgment matrix is constructed by triangular fuzzy numbers (according to Table 1) through a pairwise comparison of the index system by experts [24, 25].
(3) According to equation (3), the value S_i of synthetic extent S_i of each factor is obtained.
(4) The possibility degree $d'(A_i)$ is calculated such that factor A_i is more important than others:

$$d'\left(A_i\right) = \underbrace{\min}_{j=1,2,\ldots,n,j\neq i} V\left(S_i \geq S_j\right), i = 1, 2, \ldots, n. \quad (4)$$

$$d'\left(A_i\right) = \underbrace{\min}_{j=1,2,\ldots,n,j\neq i} V\left(S_i \geq S_j\right), \quad i = 1, 2, \ldots, n. \quad (4)$$

Table 1

Relative importance described by the triangular fuzzy numbers.

Then, the weight vector is obtained:

$$W' = \left(d'\left(A_1\right), d'\left(A_2\right), \ldots, d'\left(A_n\right)\right)^T. \quad (5)$$

Finally, the normalized weight vector is obtained.

2.3. Application of the Belief Structure for the Fire Risk Calculation

After identifying fire risk factors and establishing the hierarchical structure of the index system, another important task of risk management is to assess the risk, which is an effective way to prevent or reduce the effect of the fire [2]. In this paper, the fire risk of residential buildings is defined as the result of comprehensive measurement associated to the occurrence likelihood and the consequence severity of the fire. The formula is as follows:

$$P = L \otimes S, \quad (6)$$

where P is the magnitude of the fire risk presented by various potential fire hazards, L refers to the occurrence likelihood of potential fire hazards or fire risk factors, S implies the consequence severity of potential fire hazards or fire risk factors, and $\otimes$ represents the interconnection relationship between L and S.

2.3.1. Fuzzy Linguistic Variables for the Fire Risk

After defining the fire risk, it is necessary to transform the factors into the same form of fuzzy evaluation grade. Due to the uncertainty, analysts tend to use linguistic variable terms rather than precise numerical values to evaluate the fire risk. Therefore, this paper uses a ranking form of fuzzy linguistic variables to represent the fire risk profile of each factor.

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degree to construct a belief structure with the same set of assessment grades [26]. These sets' form of each factor could be expressed as follows:

$$R_L = [R_{L1}, R_{L2}, R_{L3}, R_{L4}, R_{L5}] = \{\text{highly unlikely}, \text{unlikely slight}, \text{likely}, \text{reasonably likely}, \text{highly likely}\},$$
$$R_S = [R_{S1}, R_{S2}, R_{S3}, R_{S4}, R_{S5}] = \{\text{negligible}, \text{slight}, \text{moderate}, \text{serious}, \text{catastrophic}\},$$
$$R = [R_1, R_2, R_3, R_4, R_5] = \{\text{very low}, \text{low}, \text{medium}, \text{high}, \text{very high}\}. \quad (7)$$

$$R_L = [R_{L1}, R_{L2}, R_{L3}, R_{L4}, R_{L5}] = \{\text{highly unlikely}, \text{unlikely slight}, \text{likely}, \text{reasonably likely}, \text{highly likely}\},$$
$$R_S = [R_{S1}, R_{S2}, R_{S3}, R_{S4}, R_{S5}] = \{\text{negligible}, \text{slight}, \text{moderate}, \text{serious}, \text{catastrophic}\},$$
$$R = [R_1, R_2, R_3, R_4, R_5] = \{\text{very low}, \text{low}, \text{medium}, \text{high}, \text{very high}\}.$$

Among them, R_L, R_S, and R represent the evaluation grade variables of the occurrence likelihood of fire, consequence severity of fire, and fire risk, respectively.

2.3.2. Fire Risk Level Based on a Belief Structure

Because of the complexity and uncertainty of the system, the type of membership function is not the dominant factor in the risk assessment analysis of the system [27]. Therefore, as listed in Table 2 and Figure 2, this paper applies the triangular membership function which is the most commonly used one to describe the subjective linguistic variables [15] and adopts the five-phase method, adjusted and modified from Ngai and Wat [28] to represent the occurrence likelihood of fire (L) and the consequence severity of building fire (S), respectively. Suppose that the occurrence likelihood of building fire (L) and the consequence severity of building fire (S) for each factor are independent of each other; they are denoted

Table 2

Linguistic variables described by the triangular membership number.

Fuzzy risk P with a belief structure can be obtained through the following steps:

(1) According to formula (8), calculate FTN_{LS} of each factor
(2) Map the calculated FTN_{LS} to the FTN_P membership curve, and obtain the intersection points of each fuzzy language level variable (note: if there is more than one intersection point on a certain fuzzy language level variable, take the intersection point with the largest longitudinal coordinate value), as shown in Figures 3 and 4
(3) Obtain a set of intersection values (β_P), which denote five nonstandardized linguistic variable levels of risk P in the form of fuzzy sets
(4) Normalize β_P, and obtain the basic belief degree β of each factor related to its fire risk

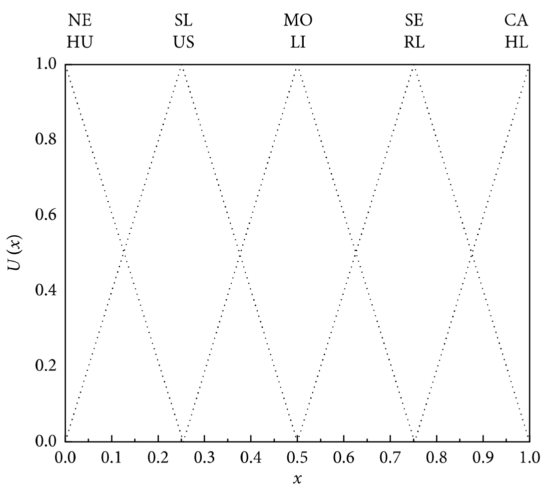
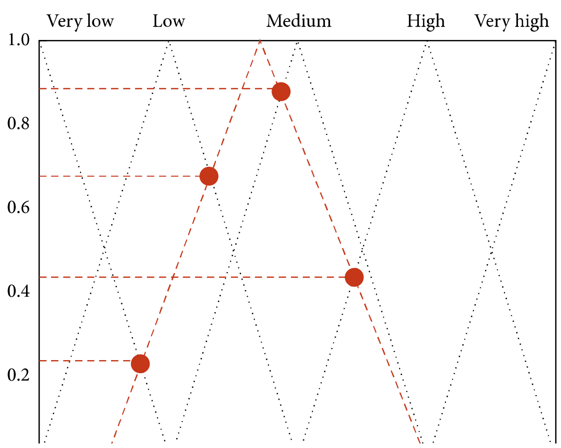


Figure 3

Triangular fuzzy membership function.



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As listed in Table 2, if a single factor judged by experts' knowledge and experience takes a fire risk value of that the occurrence likelihood of building fire corresponds to (0.5,0.75,1), the consequence severity of building fire corresponds to (0.25,0.50,0.75). The corresponding value of FTN_{LS} will be (0.125,0.375,0.75). Then, map FTN_{LS} to FTN_{P} to get the set of intersection values (β_P), shown in Figure 4. Finally, the basic belief degree β is obtained after the normalization of β_P, which denotes that five nonstandardized linguistic variables of very low, low, general, high, and very high correspond to 0.25, 0.75, 0.8, 0.4, and 0, respectively.

It is noteworthy that the triangular fuzzy numbers for the occurrence likelihood (L) and the consequence severity (S) of building fire judged by experts cannot be used directly as input data for the synthesis of fire risk results by the evidential reasoning algorithm. They need to convert to five standardized linguistic variable terms before synthesizing the fire risk of each factor [29].

2.4. Synthesizing Assessment Result Using the Evidence Reasoning Algorithm

The theory of evidential reasoning was first proposed by Dempsterin 1967 [30]. Then, in 1976, Shafer further expanded and improved Dempster's work to form a complete and systematic theory [31]. Subsequently, in commemoration of Dempster and Shafer's contribution to the theory of evidence reasoning, the theory was often called Dempster–Shafer theory or D-S theory for abbreviation. D-S theory can be used to deal with uncertain, imprecise, and or inaccurate information. It was originally used as an approximate reasoning tool for information synthesis in expert systems [32]. Later, it was applied to the decision-making judgment of uncertain problems [33]. Due to the uncertainty of the changing system environment and qualitative descriptive information and to consider the influence of the weight in the synthesis of evidence, evidence reasoning algorithm (ER algorithm) was proposed [34].

After knowing the basic belief degree β and the weight ω of each factor, suppose $m_{n,i}$ is a basic probability mass, denoting the degree to which the i-th basic factor e_i supports the general factor y to be evaluated as the n-th grade:

$$m_{n,i} = \omega_i \beta_{n,i}, n = 1, \ldots, N. \tag{9}$$

The unassigned probability mass $m_{H,i}$ is composed of two parts, which represent the unassigned mass function $\overline{m}_{H,i}$ due to the weight and the unassigned mass function $\widetilde{m}_{H,i}$ due to the lack of information and incompleteness:

(10)(11)(12)(13)

$$m_{H,i} = 1 - \sum_{n=1}^{N} m_{n,i} = 1 - \omega_i \sum_{n=1}^{N} \beta_{n,i},$$

$$m_{H,i} = \overline{m}_{H,i} + \widetilde{m}_{H,i},$$

$$\overline{m}_{H,i} = 1 - \omega_i,$$

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$$\widetilde{m}_{H,i} = \omega_i \left(1 - \sum_{n=1}^{N} \beta_{n,i}\right).$$

Suppose $m_{n,I(i+1)}$ represent the combined masses of i basic factors synthesized on the n-th evaluation grade. Suppose $m_{H,I(i+1)}$ represent the unassigned probability mass to the first i basic factors. The formula is as follows:

$$\{H_n\} : m_{n,I(i+1)} = K_{I(i+1)} \left[m_{n,I(i)} m_{n,i+1} + m_{H,I(i)} m_{n,i+1} + m_{n,I(i)} m_{H,i+1}\right], \quad (14)(15)(16)(17)$$

$$\{H\} : \overline{m}_{H,I(i+1)} = K_{I(i+1)} \left[\overline{m}_{H,I(i)} + \overline{m}_{H,i+1}\right],$$

$$\{H\} : \widetilde{m}_{H,I(i+1)} = K_{I(i+1)} \left[\widetilde{m}_{H,I(i)} \widetilde{m}_{H,i+1}\right.$$

$$\left. + \overline{m}_{H,I(i)} \widetilde{m}_{H,i+1} + \widetilde{m}_{H,I(i)} \overline{m}_{H,i+1}\right],$$

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{j=1 \\ j \neq 1}}^{N} m_{t,I(i)} m_{j,i+1}\right]^{-1}, i = 1, \ldots, L-1,$$

(14)

(15)

(16)

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$$
\begin{aligned}
\{H_n\} : m_{n,I(i+1)} &= K_{I(i+1)} \left[m_{n,I(i)} m_{n,i+1} + m_{H,I(i)} m_{n,i+1} + m_{n,I(i)} m_{H,i+1} \right], \\
\{H\} : \overline{m}_{H,I(i+1)} &= K_{I(i+1)} \left[\overline{m}_{H,I(i)} \overline{m}_{H,i+1} \right], \\
\{H\} : \widetilde{m}_{H,I(i+1)} &= K_{I(i+1)} \left[\widetilde{m}_{H,I(i)} \widetilde{m}_{H,i+1} + \overline{m}_{H,I(i)} \widetilde{m}_{H,i+1} + \widetilde{m}_{H,I(i)} \overline{m}_{H,i+1} \right],
\end{aligned}
$$

where $K_{I(i+1)}$ represents the normalizing factor, which reflects the degree of conflict between the indicators (evidence). Suppose that there is a total of L basic factors for evaluation objectives; then, $m_{n,I(L)}$, $\overline{m}_{H,I(L)}$, and $\widetilde{m}_{H,I(L)}$ are obtained by iteration calculation. After that, the combined belief degree can be obtained by the following normalization process:

$$
K_{I(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{j=1 \\ j \neq 1}}^{N} m_{t,I(i)} m_{j,i+1} \right]^{-1}, \quad i = 1, \ldots, L-1, \tag{18}
$$

$$
\{H_n\} : \beta_n^1 = \frac{m_{n,I(i)}}{1 - \overline{m}_{H,I(L)}}, \quad \{H\} : \beta_H = \frac{\widetilde{m}_{H,I(L)}}{1 - \overline{m}_{H,I(L)}}, \tag{19}
$$

where β_H represents the unassigned belief degree to the general factor y after aggregation. β_n and β_H represent the comprehensive belief degree to the evaluation object.

2.5. Obtaining a Clear Result Using the Expected Utility Method

In fact, the belief degree vector obtained in the former evaluation is the trust distribution of risk under the identification framework, and the result cannot be shown clearly. For example, the identification framework of a building fire risk (i.e., assessment set) is recorded as "very low," "low," "general," "high," where $u(H_n)$ represents the utility of the evaluation grade H_n. In order to further clarify the level of the fire risk corresponding to the utility value, it is necessary to classify the grade of the fire risk. This paper presents the classification as shown in Table 3.

Table 3

Classification of the building fire risk level.

Quantitative evaluation results (utility values) can be obtained by processing the above methods. However, if the basic attribute (factor) information is incomplete or the expert's information about the factor is uncertain, the result obtained by the ER algorithm is also uncertain. [34, 36–38] refer to the concept of utility interval and conquer this problem through minimum utility $u_{\min}(y)$, maximum utility $u_{\max}(y)$, and average utility $u_{\text{avg}}(y)$:

$$u_{\min}(y) = (\beta_1 + \beta_H)\, u(H_1) + \sum_{n=2}^{N} \beta_n u(H_n), \quad (21)$$

$$u_{\max}(y) = \sum_{n=1}^{N-1} \beta_n u(H_n) + (\beta_N + \beta_H)\, u(H_N),$$

(21)

$$u_{\min}(y) = (\beta_1 + \beta_H)\, u(H_1) + \sum_{n=2}^{N} \beta_n u(H_n),$$

$$u_{\max}(y) = \sum_{n=1}^{N-1} \beta_n u(H_n) + (\beta_N + \beta_H)\, u(H_N),$$

$$u_{\text{avg}}(y) = \frac{u_{\max}(y) + u_{\min}(y)}{2}.$$

2.6. Verification of the Model Using Sensitivity Analysis

Due to the influence of external factors, input values obtained from different experts or the same experts in different periods are different. Consequently, the uncertainty is inherent in fire risk assessment. In this paper, a sensitivity analysis method is introduced for studying and predicting the disturbance degree of the model output value (risk magnitude) caused by the change of the input value of each index. Sensitivity analysis is a systematic analysis method, which identifies weak points or areas in the system

(2) If the belief degree at the lowest preference linguistic variable of the lowest-level factors increases by p and q (meanwhile, the belief degree at the highest preference linguistic variable decreases by p and q $(1 > q > p)$) and the utility values of the model output are u_p and u_q, then u_p should be greater than u_p
(3) In the lowest-level factors, the total influence of x factors on the output of the model is always greater than that of $x - y(y \in x)$ factor sets

3. Case Study

Three residential buildings marked from BUILDING-1 to BUILDING-3 were selected as a case study to illustrate the proposed fire risk model. This paper takes BUILDING-1, for example, to describe the calculation process of the model step by step. Based on the hierarchical structure of the fire risk model in Figure 2 and the available information in [40], the fire risk of BUILDING-1can be assessed through the following steps.

3.1. Develop a Generic Fire Risk Model for BUILDING-1

At this phase, the identified fire risk factors and a generic fire risk model are presented in Figure 1. The index system of fire risk assessment mainly consists of three levels, including the total target risk, the first-level factor set, and the second-level factor set. According to Wang et al. [41], fuzzy linguistic terms for risk expression are used for effective information processing in the range of 4 to 7. Therefore, this study uses five linguistic terms to denote the assessment of fire risk based on the viewpoint of experts in the field.

3.2. Determine the Weights of Each Factor

Given the hierarchical structure of fire risk in Figure 2, the weight calculations for fire risk factors are conducted. The weight calculations of factors U1, U2, U3, U4, and U5 are taken as an example. Firstly, the judgment matrix is constructed through the pairwise comparison of these five factors by experts (according to Table 1) and presented in Table 4. Then, according to equations (3) and (4), the value of synthetic extent S_i and the possibility degree $d'(A_i)$ of each factor are obtained, respectively. Finally, the normalized weight vector for five factors is obtained. Using a similar way, the weights of all factors can be calculated and listed in Table 5.

Table 4

Triangular fuzzy judgment matrix of indexes U1–U5.

Table 5

Weights of fire risk factors.

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prevention in design of interior decoration of buildings (GB 50222-2017) [43], guidance on building fire risk assessment for property insurance, and CIB W14 Workshop Report [44]. For example, the detailed scoring rules of index U15 (building service life) and index U4 (property fire management) are shown in Table 6. According to these rules, it is easy to obtain the value of FTN_L and FTN_s of each bottom index. Accordingly, by utilising equation (8), the fire risk of each bottom index is presented in Table 7 in the form of FTN_{LS}. Then, FTN_{LS} is mapped to FTN_P for obtaining the intersection point. Finally, the basic belief degree β is obtained after the normalization of β_{P}, and the results are shown in Table 8.

Table 6

Detailed scoring rules of U15 and U4.

Table 7

The fire risk of each factor.

Table 8

Intersection results of fire risk factors.

3.4. Synthesizing Assessment Result Using the Evidence Reasoning Algorithm

On the premise that the weight of each index was obtained, the aggregation calculations for U11, U12, U13, U14, U15, and U16 were implemented according to the D-S operator (equations (9)–(20)); then, the aggregation result of disaster-causing factor U1 is obtained. Similarly, the aggregation results of passive measures U2, active measures U3, property fire management U4, the rescue capability of fire brigade U5 and the objective fire risk R can also be obtained, and the results of the first-level index are presented in Table 9.

Table 9

Aggregation of fire risk factors.

3.5. The Target Fire Risk Assessment Using the Expected Utility Method

From Table 9, the objective fire risk R corresponding to five-level linguistic terms can be expressed as R

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Table 10

Utility value for measuring the building fire risk.

3.6. Sensitivity Analysis

In order to verify the model, the degrees of belief at the lowest preference linguistic variable of the lowest-level factors should increase by 10%, 20%, and 30% (meanwhile, the degrees of belief at the highest preference linguistic variable decrease by 10%, 20%, and 30%). The model output data are tabulated in Table 11, and the graphic display results are listed in Figure 5. It is obvious that all the results are consistent with theorems 1 and 2, respectively. According to theorem 3, if the model is logically reasonable and feasible, the belief degree at the lowest level of the hierarchy structure associated with x factors will always be smaller than the one associated with $x - y\,(y \in x)$ factors. This can be illustrated by comparing the results of different input data, such as if the belief degree at the lowest preference linguistic variable associated with all the lowest-level factors increases by 10% (simultaneously, the one at the highest preference linguistic variable decreases by 10%), the output utility value is 0.1717. However, if the belief degree at the lowest preference linguistic variable associated with U11, U12, U13, U14, U15, U16, U21, U22, U23, U24, U31, U32, and U33 factors increases by 10% (simultaneously, the one at the highest preference linguistic variable decreases by 10%), the output utility value is 0.1826. Considering that 0.1717 is smaller than 0.1826, it can be concluded that the verified model satisfies theorem 3.

Table 11

Increase/decrease model input data.

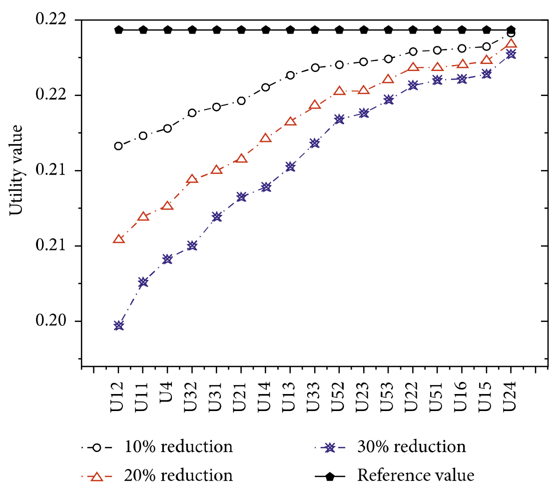

Figure 5

aspects should be paid attention to.

Table 12

Fire risk levels of three buildings.

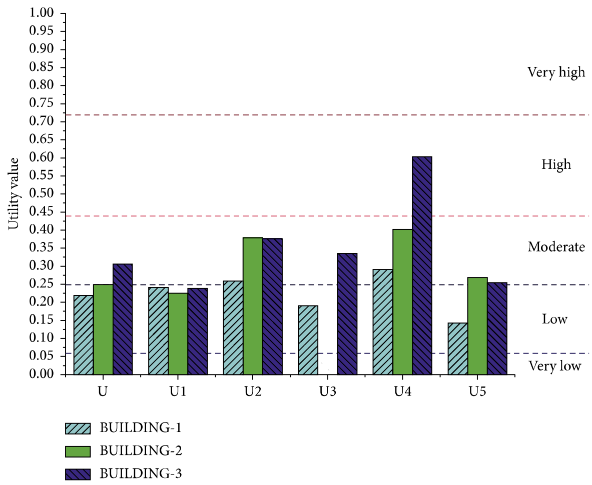

Figure 6

Utility values of the main factors.

In the aspect of disaster-causing factor U1: since the service life of the three residential buildings is less than 10 years and there is no dangerous disaster-causing factor in the internal and external environment of these buildings, the fire risk corresponding to U1 of these buildings is all acceptable.

In the aspect of passive measures U2: U2 of BUILDING-2 and BUILDING-3 was higher than that of BUILDING-1. This was mainly due to obstruction of safe evacuation in the stairwell of BUILDING-2 and BUILDING-3, such as some evacuation passageways are littered with debris and some safety evacuation signs are missing, which mean that the residents may fail to evacuate from these buildings in case of a fire.

In the aspect of active measures U3 and property fire management U4: U3 and U4 of BUILDING-3 were higher than those of BUILDING-1 and BUILDING-2. This was mainly due to the lack of regular maintenance of fire-fighting equipment in BUILDING-3. It can be assured that if there is no regular maintenance and inspection, the reliability of fire-fighting equipment will be reduced. In BUILDING-3, it was found that some fire-fighting equipment were rusty or even abandoned, such as safety monitoring device was out of use, and the fire extinguisher was out of the service date range. In addition, U4 of BUILDING-2 was higher than that of BUILDING-1. This is mainly because that, in BUILDING-2, there is no prejob training of safety management personnel, and daily fire hazard investigation is not carried out.

in the output value of the model. According to Figure 5, it is obvious that the fire risk model is more sensitive to occupant density U12, electrical equipment U11, property fire management U4, portable fire-extinguisher apparatus U32, and indoor hydrant water supply system U31 than other factors. In other words, the uncertainty of these factors has a relatively large influence on the disturbance of the model system. Therefore, the most effective way to reduce the fire risk of residential buildings is to control these five indicators at first. The analysis results are also consistent with the actual fire prevention measures.

In the previous studies [40, 45], grey correlation method and fuzzy clustering method were applied for fire risk assessment in these buildings of China, and the results of these studies are in accordance with the results of our research, which indicated that the presented model is logically feasible and can still maintain its specific function under turbulence or uncertainty conditions.

5. Conclusions

This study proposes a novel model which combines evidence theory, fuzzy theory, and sensitivity analysis technique for assessing the building fire risk using inaccurate input data in order to optimize system operating efficiency by a standardized fuzzy linguistic term. This model is different from the traditional risk assessment model and characterized with flexible data acquisition capability and unified input and output modes. Therefore, it is easy to deal with the uncertainty of the fire risk problem in the complex system.

Furthermore, the model adopts a series of processes, such as weight calculation based on the FAHP, two-dimensional measurement of the fire risk based on triangular fuzzy numbers, construction of the belief structure, factor aggregation via the evidential reasoning algorithm, and assessment results using the expected utility method, to effectively address uncertainties of subjective estimation. In summary, the proposed model has the following advantages for fire risk analysis on the complex system: (1) this model presents a managerial view to analysts in a reasonable, reliable, and transparent way so that they can collaborate with experts' suggestion or on-site investigation to model complex systems under external uncertainties. (2) The model provides an effective tool for researchers to make full use of limited information to assess the fire risk of the whole system and improve its operational flexibility. (3) The model has strong flexibility, has high robustness, and is easy to program. It can be used as a computer tool for fire risk assessment of complex systems under high uncertainty.

This research proposes a quantitative fire risk assessment model which could provide building fire managers and researchers with flexible and transparent tools to effectively reduce the fire risk under the disturbance of fire risk uncertainty of the system. It should be noted that, in our study, the index scoring rules are mainly based on codes and standards, which lead to conservative results. Therefore, the acceptable level of fire risk based on performance-based codes needs to be determined in the future [46].

Data Availability

The data used to support the findings of this study are included within the article.

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