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Construction Safety Risk Assessment for Existing Building Renovation Project Based on Entropy-Unascertained Measure Theory

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Abstract: With the development of society, there are more and more existing building renovation projects. According to the common construction safety problems, and based on the characteristics of the construction process of renovation project, this paper established a construction safety risk assessment model of renovation project based on entropy-unascertained measure theory. Firstly, the assessment index system was determined by risk identification and analysis. Secondly, the unascertained measure theory was applied to the construction safety risk assessment of renovation project, and the weight of each index was determined by the entropy weight method. Finally, taking the actual renovation projects as examples to calculate its safety risk grade, it is found that the assessment results of the model are basically consistent with the actual situation of the site by comparison. The research shows that the model can provide a new idea to quantitatively assess the construction safety risk of renovation project and provide a reliable basis for the management and control of the construction safety of existing building renovation project.

Keywords: existing building; renovation project; construction safety; risk assessment; unascertained measure theory; entropy weight method

1. Introduction

With the development and progress of society, the construction industry has developed rapidly, and the treatment of old buildings has also undergone great changes. Like old residential buildings, old dormitory buildings, etc., were built for a long time, with inadequate supporting facilities, their functions can no longer meet the needs of modern people's lives and work [1]. Like old factory buildings, old silos, etc., were idle or abandoned due to industrial transformation, resulting in a large amount of waste of building space resources [2]. The cost of demolition and reconstruction is large, the construction period is long and the environmental pollution is large. Therefore, the transformation and reuse of existing buildings has become a new way for the utilization of old buildings. For example, the Orsay Railway Station in the center of Paris was successfully transformed into the Orsay Museum, which achieved the functional change and exerted great value [3], and the "Silo Wharf" granary in Baltimore was regenerated into a complex of residential and commercial services, and has become a model of urban regeneration and a new landmark for Baltimore [4,5]. Western countries began to pay attention to the research on the protection and renovation of old buildings earlier, and developed rapidly, which provided powerful theoretical guidance for the later research of building renovation [6,7].

In order to better inherit the historical context of the city and promote green development. The state attaches great importance to the protection and regeneration of existing buildings. The

Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD) issued a document "Notice of the Ministry of Housing and Urban-Rural Development of the People's Republic of China on further improving the reservation, utilization and renovation of existing buildings in cities (JC [2018] No. 96)" [8], proposing that all localities should fully recognize the value of existing buildings, adhere to the principle of full utilization and functional renewal, and attach great importance to and strengthen the preservation, utilization, renewal and transformation of existing buildings. On the whole, the renovation of existing building has become the best way to deal with old buildings reasonably.

At present, the research on the renewal and utilization of existing buildings is gradually deepening. It mainly includes pre planning, planning and architectural design [9], operation and maintenance, energy and thermal comfort [10]. In addition, there are many other researches, such as accelerating the process of recycling old buildings through ecological sustainable development, adapting to the changing urban demand through ecological transformation [11], and proposing the energy-saving renovation strategy suitable for old buildings [12]. However, from the current research results, the past studies mostly focus on the design or operation stage of buildings.

Compared with new buildings, the construction process of existing buildings has many unique characteristics. Firstly, the existing buildings have been built and used for a long time, and the structural components may be damaged to some extent, so there may already be some uncertain hazards. Secondly, there are many limitations during construction, such as site limitations, space limitations, instrument limitations and technical limitations. These will have a bad impact on construction safety. In addition, the construction period of the renovation project is relatively short, the safety management work is often neglected, and the safety investment is extremely small, the practitioners do not understand the characteristics and rules of the transformation operation, and there are blind operation and barbaric construction phenomena, which resulted in great potential safety hazards in the construction of existing construction renovation project [13]. So it is extremely important to conduct in-depth research on the safety risk assessment of the construction process of existing building renovation project.

2. Literature Review

In the 1930s, risk management and comprehensive evaluation gradually emerged in the United States. In the 1960s, the American insurance management association (ASIM) introduced risk management into teaching for the first time, which indicated that risk management has become a new discipline [14]. After World War II, the chemical industry, aerospace industry, petroleum industry and nuclear industry began to develop at a high speed [15]. Since the 1960s and 1970s, the United States has applied safety research results to construction enterprises and construction projects, making the average accident rate of the construction industry decline significantly. In 1975, Nuclear Regulatory Commission (NRC) developed and established the famous probabilistic risk assessment method, which became a milestone in the history of engineering risk analysis. Misra et al. proposed a fuzzy fault tree analysis method, which was applied in safety risk assessment [16]; Dunyak et al. established a reliable fuzzy model by introducing the expansion theory, which can effectively deal with the fuzziness of the risk of each bottom event in the fault tree [17]; Roberts proposed the integrated quantitative risk management theory and established the decision support theory after risk analysis, arranging and screening [18]; Fung et al. created a risk assessment model, which can help identify and predict the risk levels [19]; Leu et al. built a safety risk assessment model based on improved Bayesian network (BN) of fault tree (FT) [20]; Gamble et al. established the fuzzy and grey correlation analysis model and evaluated duration risk, cost risk, quality risk and safety risk separately [21]; Aminbakhsh et al. presented a safety risk assessment framework, which can give priority to the security risk of the project before making a reasonable budget [22]; Tian proposed a grey hierarchy evaluation model, which can assign the importance priority sequence of safety management measures [23]; Zhao et al. proposed a a hybrid risk evaluation model based on the cloud model and fuzzy comprehensive evaluation method [24]; Esmaeili et al. presented an attribute-based risk identification and analysis method [25,26]; Ning et al. established a safety risk assessment model to carry out site layout and safety management [27]; Huang et al. proposed an improved AHP-Grey model of construction safety evaluation, this model can better reflect the actual safety situation of construction [28]; Gebrehiwet et al. proposed an integrated model of the technique for order preference by similarity to an ideal solution (TOPSIS) and fuzzy comprehensive evaluation (FCE) [29]; Leśniak et al. presented a method for creating risk management strategies using a standard algorithm that includes risk identification, risk analysis, and risk assessment [30]; Dong et al. proposed the Pb-Zn mine safety risk evaluation model based on the fuzzy-grey correlation analysis method [31].

From the above, we can see that many risk assessment methods used in safety risk assessment, and some results have been achieved. The common safety risk assessment methods are expert scoring method, Delphi method, analytic hierarchy process, fuzzy comprehensive evaluation method, fault tree analysis method, grey comprehensive evaluation method, support vector machine method, TOPSIS method, artificial neural network method, and matter element extension method [32]. However, there are few studies on the safety risk assessment in the construction process of existing building renovation project. The main reason is that the renovation project is different from the new construction project. In short, the new construction project is from "blank" to "building entity", and the renovation project is from "building entity" to "partial demolition" to "building entity". There are many factors affecting the safety risk in the construction process of renovation project, and there are many complexities and uncertainties. For example, the rationality of reconstruction project design, the rationality of construction sequence of demolition, reinforcement and transformation, the construction conditions such as the narrow construction site, and the limited use of large machinery, the impact of construction conditions such as narrow construction sites and limited use of large machinery. These all have some degree of complexities and uncertainties. However, these assessment methods mentioned above cannot be used to deal with uncertainties. Therefore, seeking scientific and reasonable mathematical methods to analyze and deal with various uncertainty problem in the process of safety risk assessment is the focus and difficulty of scientific assessment.

3. Model Development

The purpose of this section is to establish a construction safety risk assessment model for renovation project. This section mainly includes three aspects: 1. Establishing the construction safety risk assessment index system through risk identification and analysis and determining the index grading standards through theoretical research and expert experience. 2. Introducing the basic ideas and algorithms of the unascertained measure theory. 3. Building the construction safety risk assessment model based on the first two parts and introducing the implementation steps of the model.

3.1. Establishment of the Risk Assessment Index System

Establishing a scientific and reasonable assessment index system is the key to safety risk assessment, which affects the reliability and accuracy of the assessment results.

3.1.1. Risk Identification and Analysis

The risk assessment usually begins from the risk identification and analysis of the project. In order to build a reasonable assessment index system for construction safety risk of renovation project, through consulting literature, visiting relevant experts and practitioners of owners, design units, construction units, supervision units, engineering quality inspection units, schools, and other units, the relevant risk factors were identified and analyzed. According to the actual situation of the renovation project and the common safety risks [33], the factors affecting the construction safety risks are divided into five categories: human risk factors, technical risk factors, material and equipment risk factors, management risk factors, environmental risk factors.

Human risk factors: people are the direct participants in the construction process. The physical and psychological conditions, professional skills and safety awareness of the operators play a decisive role in construction safety risks. Therefore, the dominant role of human beings and the improvement of human activity ability can ensure the renovation project construction safety of existing building.

Technical risk factors: the construction technology of renovation project is very different from the general construction technology, including wall opening, floor slab opening, external elevators, component reinforcement, partial demolition, etc. These will have great security risks and must be strictly controlled.

Material and equipment risk factors: the impact of materials and equipments on construction safety are mainly reflected in: whether the materials are qualified, whether the temporary support and safety protection are reasonable, whether the equipment installation and operation control are safe, whether the materials transportation and stacking in the operation area are reasonable, whether the mechanical equipment is periodically inspected, etc.

Management risk factors: there are many factors involved in safety management, including the establishment and improvement of safety production responsibility system, supervision of the use of safety protection measures, identification of on-site hazard sources, safety technology disclosure, the use of safety protection supplies, regular safety inspections, safety hazard investigation and emergency measures, etc. Therefore, scientific safety management is an important link to ensure the construction safety of existing building renovation project.

Environmental risk factors: the construction site environment will also have a certain degree of impact on the construction safety of renovation project, including climate conditions, civilized construction, safety and protection, construction waste cleaning and environmental impact.

3.1.2. Establishment of the Index System

The scientific assessment index system is the basis for a reasonable assessment. According to the five major safety risk factors identified in Section 3.1.1, this paper constructs the construction safety risk assessment index system for existing building renovation project, as shown in Table 1.

Table 1. Construction safety risk assessment index system for existing building renovation project.

Primary Index	Secondary Index
Human risk factors (I_1)	Professional skill of workers (I_{11}) Safety awareness of workers (I_{12}) Health status of workers (I_{13}) Safety protection situation of workers (I_{14})
Technical risk factors (I_2)	Reliability of existing structural members (I_{21}) Reasonable degree of construction scheme (I_{22}) Technical level of partial demolition (I_{23}) Technical level of reinforcement and reconstruction (I_{24}) Interference degree of various types of work (I_{25}) Safety monitoring technology of time-varying structure (I_{26})
Material and equipment risk factors (I_3)	Material equipment qualification (I_{31}) Material stacking situation (I_{32}) Mechanical equipment disassembly and operation (I_{33}) Temporary support and safety protection (I_{34})
Management risk factors (I_4)	Application of safety precautions (I_{41}) Implementation of the safe production responsibility system (I_{42}) Safety periodic inspection (I_{43}) Safety management and control (I_{44})
Environmental risk factors (I_5)	Climatic conditions (I_{51}) Civilized construction (I_{52}) Site protection conditions (I_{53}) Surrounding environmental impacts (I_{54})

3.1.3. Index Grading Standards

This paper determines the index grading standards through theoretical research and expert experience, and converts qualitative indexes into semi-quantitative indexes. Based on the literature review, project investigation and consulting expert opinions, the construction safety risk assessment is divided into four grades, i.e., Grade I, Grade II, Grade III, and Grade IV, which means respectively that the safety risk is low, the safety risk is general, the safety risk is high, the safety risk is very high. The specific index grading standards are shown in Table 2.

Table 2. The index grading standards.

Index	Grade I (C_1)	Grade II (C_2)	Grade III (C_3)	Grade IV (C_4)
	(90,100]	(75,90]	(60,75]	(0,60]
I_{11}	Extremely skilled in related process technology	Skilled in related process technology	General skilled in related process technology	Unskilled in related process technology
I_{12}	Very high safety alertness and very strong safety awareness	High safety alertness and strong safety awareness	General safety alertness, general safety awareness	Poor safety alertness and weak safety awareness
I_{13}	Small workload and low labor intensity	Normal workload and normal labor intensity	Heavy workload and high labor intensity	Very heavy workload, very high labor intensity, and long-term overload work
I_{14}	All workers wear safety equipment	Basically all workers wear safety equipment	Some workers wear safety equipment	Very few workers wear safety equipment
I_{21}	Very safe and very reliable	Basically safe and basically reliable	Generally safe and generally reliable	Unsafe and unreliable
I_{22}	Very reasonable	Basically reasonable	Slightly reasonable	Unreasonable
I_{23}	Very high level	High level	General level	Low level
I_{24}	Very high level	High level	General level	Low level
I_{25}	No interference	Slight interference	Medium interference	Great interference
I_{26}	Safety monitoring of all structural components	Safety monitoring of most structural components safety monitoring	Safety monitoring of local structural components	Safety monitoring of very few structural components or no safety monitoring
I_{31}	Fully qualified	Large amount of qualified	Small amount of qualified	Very few qualified
I_{32}	The stacking position is reasonable	The stacking position is basically reasonable	The stacking position is unreasonable, but the impact on the surrounding is small	The stacking position is very unreasonable and the layout is very confusing
I_{33}	The operation condition is good, and there is basically no fault.	The operation condition is good, and there are occasional minor faults.	The operation condition is general and there are few faults.	The operation condition is poor and there are many faults.
I_{34}	Incomplete and unreasonable	Basically complete and basically reasonable	Generally complete and generally reasonable	Incomplete and unreasonable
I_{41}	Safety protection measures are strictly in accordance with regulations	Safety protection measures are basically in normal use	Safety protection measures are generally in normal use	Safety precautions are used poorly or not used
I_{42}	The implementation status is very good	The implementation status is good	The implementation status is general	The implementation status is poor
I_{43}	The safety inspection system is perfect, and safety management personnel regularly inspect the site.	The safety inspection system is basically perfect, and the safety management personnel inspect the site many times.	The safety inspection system is incomplete, and safety management personnel occasionally inspect the site.	There is no clear safety inspection system, and safety management personnel rarely inspect the site.
I_{44}	Have a perfect emergency early warning system, a complete emergency plan, and can effectively deal with accidents on site.	Have a basic emergency agency, a basic emergency plan, and can timely deal with accidents on site.	The emergency agency is not well set up, the emergency plan is not clear, and the ability to deal with on-site accidents is general.	No clear emergency agency, no emergency plan, and the ability to deal with on-site accidents is poor.
I_{51}	No bad weather	Occasionally bad weather	A lot of bad weather	Frequent bad weather
I_{52}	Meet the requirements of civilized construction	Basically meet the requirements of civilized construction	Generally meet the requirements of civilized construction	Do not meet the requirements of civilized construction
I_{53}	On-site protection is in place	On-site protection is basically in place	On-site protection is generally in place	On-site protection is not in place or missing
I_{54}	The surrounding area is empty and has little impact.	The surrounding area is relatively empty, and have less impact.	There are many buildings around the site, and have certain impact.	There are many buildings around the site, and have great impact.

3.2. Entropy-Unascertained Measure Theory

The theory of unascertained information and its mathematical processing was first put forward by Wang Guangyuan in 1990, It is a new theory of uncertain information [34]. Unascertained information indicates that the evidence that people have mastered is not enough to grasp the real quantity relationship or the real state of things, which causes subjective and cognitive uncertainty in the minds of decision makers or evaluators. It can be said that all systems with behavioral factors are unascertained. However, how to quantitatively describe the unascertained state or the unascertained size of the thing, Liu et al. established the unascertained mathematical theory, and proposed an evaluation model of unascertained measure theory to describe a thing in an unascertained state or with some unascertained nature by a real number between 0 and 1 [35]. Afterwards, the unascertained measure theory has been rapidly developed and applied, and has been widely used in many fields such as reliability assessment [36], safety risk assessment [37–39], social development assessment [40], bidding quotation [41], project delivery [42], and has achieved good results.

Considering many uncertainties in existing building renovation project, the unascertained measure theory can analyze and deal with these uncertainties. Therefore, this paper uses the unascertained measure theory to establish the construction safety risk assessment model of renovation project, and applies the model to the actual engineering examples. It is hoped that this model can provide a new idea for the safety risk assessment of existing building renovation project.

3.2.1. Definition of Unascertained Measure

Suppose that the assessment object (that is, the research object that needs to be assessed) $X = \{X_1, X_2, \cdots, X_n\}$ and the assessment index set (that is, the set of established assessment indexes) $I = \{I_1, I_2, \cdots, I_m\}$. If x_{ij} denotes the measured value of the i-th assessment object X_i with respect to the j-th assessment index I_j, then X_i can be expressed as an m-dimensional vector named $\{x_{i1}, x_{i2}, \cdots, x_{im}\}$. Suppose that the assessment grade space (that is, the set of all assessment grades) $U = \left\{C_1, C_2, \cdots, C_p\right\}$, $C_k(k = 1, 2, \cdots, p)$ is the k assessment grade. Furthermore, suppose that the k grade is higher than the $k+1$ grade in the safety risk, that is $C_k > C_{k+1}$. If $C_1 > C_2 > \cdots > C_p$ or $C_1 < C_2 < \cdots < C_p$ is satisfied, $\left\{C_1, C_2, \cdots, C_p\right\}$ is called an ordered segmentation class of assessment space U.

If $\mu_{ijk} = \mu(x_{ij} \in C_k)$ denotes the degree that the measured value x_{ij} belongs to the k-th assessment grade class C_k.

$$0 \le \mu\left(x_{ij} \in C_k\right) \le 1 \ (i = 1, 2, \cdots, n; j = 1, 2, \cdots, m; k = 1, 2, \cdots, p) \tag{1}$$

$$\mu\left(x_{ij} \in U\right) = 1(i = 1, 2, \cdots, n; j = 1, 2, \cdots, m) \tag{2}$$

$$\mu\left|x_{ij} \in \bigcup_{l=1}^{k} C_l\right| = \sum_{l=1}^{k} \mu\left(x_{ij} \in C_l\right)(k = 1, 2, \cdots, p) \tag{3}$$

Equation (1) is called as non-negative boundedness, Equation (2) is called as normalization, and Equation (3) is called as additivity. If μ satisfies Equations (1)~(3), and then μ is called as unascertained measure, abbreviated as measure.

3.2.2. Single-Index Unascertained Measure Matrix

For every assessment object $X_i(i = 1, 2, \cdots, n)$, the matrix of $(\mu_{ijk})_{m\times p}$ is called as the single-index measure assessment matrix of X_i, as shown in the expression of Equation (4).

$$\left(\mu_{ijk}\right)_{m\times p} = \begin{bmatrix} \mu_{i11} & \mu_{i12} & \cdots & \mu_{i1p} \\ \mu_{i21} & \mu_{i22} & \cdots & \mu_{i2p} \\ \vdots & \vdots & \ddots & \vdots \\ \mu_{im1} & \mu_{im2} & \cdots & \mu_{imp} \end{bmatrix} \tag{4}$$

Before establishing the single-index measure matrix, it is necessary to establish a single index measure function. At present, the construction methods of single index measure function mainly include linear type, exponential type, parabolic type and sinusoidal type, etc. No matter what type of simulation function is used, it must satisfy the limiting conditions of Equations (1)~(3). These four types of function graph are shown in Figures 1–4 [37,42].

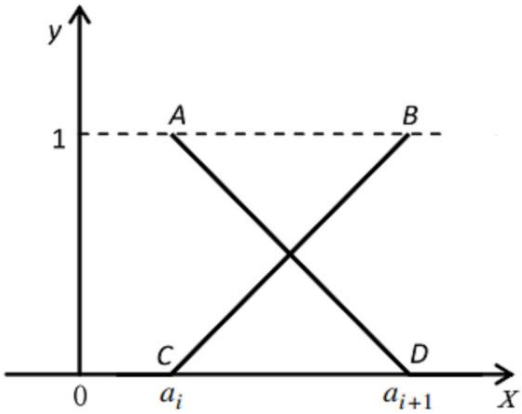

Figure 1. Linear-type function.

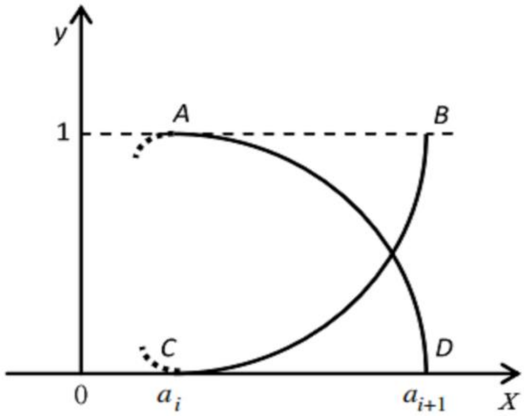

Figure 2. Parabolic-type function.

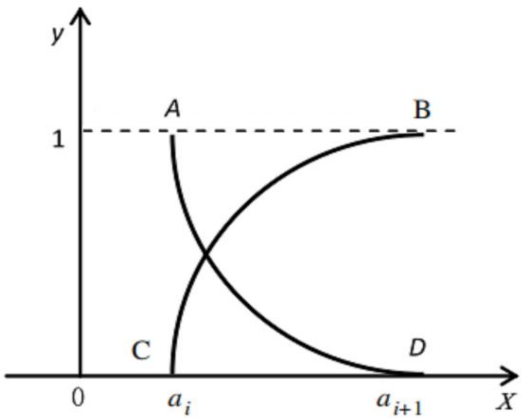

Figure 3. Exponential-type function.

The corresponding expression of unascertained measure functions are as follows:

(1) Function expression of linear type

$$\begin{cases} \mu_i(x) = \begin{cases} \frac{-x}{a_{i+1}-a_i} + \frac{a_{i+1}}{a_{i+1}-a_i} & a_i < x \leq a_{i+1} \\ 0 & x > a_{i+1} \end{cases} \\ \mu_{i+1}(x) = \begin{cases} 0 & x \leq a_i \\ \frac{x}{a_{i+1}-a_i} - \frac{a_i}{a_{i+1}-a_i} & a_i < x \leq a_{i+1} \end{cases} \end{cases} \tag{5}$$

(2) Function expression of parabolic type

$$\begin{cases} \mu_i(x) = \begin{cases} 1 - \left(\frac{x-a_i}{a_{i+1}-a_i}\right)^2 & a_i < x \le a_{i+1} \\ 0 & x > a_{i+1} \end{cases} \\ \mu_{i+1}(x) = \begin{cases} 0 & x \le a_i \\ \left(\frac{x-a_i}{a_{i+1}-a_i}\right)^2 & a_i < x \le a_{i+1} \end{cases} \end{cases} \tag{6}$$

(3) Function expression of exponential type

$$\begin{cases} \mu_i(x) = \begin{cases} 1 - \frac{1-e^{x-a_i}}{1-e^{a_{i+1}-a_i}} & a_i < x \le a_{i+1} \\ 0 & x > a_{i+1} \end{cases} \\ \mu_{i+1}(x) = \begin{cases} 0 & x \le a_i \\ \frac{1-e^{x-a_i}}{1-e^{a_{i+1}-a_i}} & a_i < x \le a_{i+1} \end{cases} \end{cases} \tag{7}$$

(4) Function expression of sinusoidal type

$$\begin{cases} \mu_i(x) = \begin{cases} \frac{1}{2} - \frac{1}{2}\sin\frac{\pi}{a_{i+1}-a_i}\left(x - \frac{a_{i+1}-a_i}{2}\right) & a_i < x \le a_{i+1} \\ 0 & x > a_{i+1} \end{cases} \\ \mu_{i+1}(x) = \begin{cases} 0 & x \le a_i \\ \frac{1}{2} + \frac{1}{2}\sin\frac{\pi}{a_{i+1}-a_i}\left(x - \frac{a_{i+1}-a_i}{2}\right) & a_i < x \le a_{i+1} \end{cases} \end{cases} \tag{8}$$

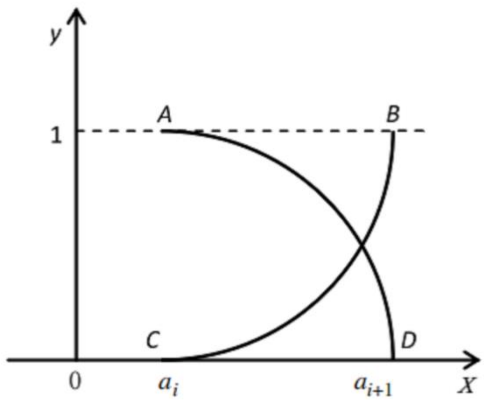

Figure 4. Sinusoidal-type function.

3.2.3. Determination of Index Weight

The entropy weight method is used to determine the weight of each index [43,44], which can make full use of the value of the single-index unascertained measure matrix, avoid the influence of many subjective factors on the results, overcome the subjectivity and limitation of the traditional method to determine the weight, and make the bid evaluation result more scientific and reasonable.

Suppose w_j denotes the relative important degree of measure index compared with other measure indexes. If w_j is satisfied with $0 \le w_j \le 1$ and $\sum_{j=1}^{m} w_j = 1$, then w_j is called as the index weight of I_j, and $w = (w_1, w_2, \cdots, w_n)$ is called as the vector of index weight. The index weight can be determined by the following expressions. According to matrix $(\mu_{ijk})_{m\times p}$, the index weight w_j could be obtained from Equations (9) and (10):

$$H_j = -t\sum_{k=1}^{p} q_{ijk} \ln q_{ijk} \tag{9}$$

$$w_j = \frac{d_j}{\sum\limits_{j=1}^{m} d_j} = \frac{1 - H_j}{m - \sum\limits_{j=1}^{m} H_j} \quad (10)$$

where: $H_j > 0$; $q_{ijk} = \mu_{ijk} / \sum\limits_{k=1}^{p} \mu_{ijk}$; t is the coefficient and $t = 1/\ln p$; μ_{ijk} is the index value, when $\mu_{ijk} = 0$, then $\mu_{ijk} \ln \mu_{ijk} = 0$ $(i = 1, 2, \cdots, n)$.

3.2.4. Multi-Index Comprehensive Measure Assessment Vector

Given that $\mu_{ik} = \mu(X_i \in C_k)$ denotes the degree that the assessment object X_i belongs to the k-th assessment grade class C_k, as shown in the expression of Equation (8). Where $0 \le \mu_{ik} \le 1$, $\sum\limits_{k=1}^{p} \mu_{ik} = 1$ is satisfied. Then the vector $\left\{\mu_{i1}, \mu_{i2}, \cdots, \mu_{ip}\right\}$ is called as the multi-index comprehensive measure assessment vector of X_i.

$$\mu_{ik} = \sum_{j=1}^{m} w_j \cdot \mu_{ijk} (i = 1, 2, \cdots, n; k = 1, 2, \cdots, p) \quad (11)$$

3.2.5. Credible Degree Recognition

In order to get the final assessment result, the credible degree recognition criteria is introduced. Supposed that λ ($\lambda \ge 0.5$, usually take $\lambda = 0.6$ or 0.7) is the credible degree, if $C_1 > C_2 > \cdots > C_p$ is satisfied and p_0 is satisfied with Equation (12). Then the assessment object X_i belongs to the assessment grade C_{p_0}.

$$p_0 = \min \left| p : \sum_{k=1}^{p} \mu_{ik} > \lambda, i = 1, 2, \cdots, n \right| \quad (12)$$

3.3. Implementation Steps of the Model

According to the established assessment index system, this paper constructed the construction safety risk assessment model of existing building reconstruction project based on the unascertained measure theory and entropy weight method, as shown in Figure 5. The specific steps are as follows:

Step 1: Establishing index system and determining grading standards

According to the characteristics of the building renovation project, the construction safety risk assessment index system of the renovation project is constructed. Furthermore, then the index grading standards is determined through theoretical research and expert experience.

Step 2: Collecting project data and determining index value

The safety management staff including the owner, construction unit, supervision unit, quality inspection unit and other relevant units was selected to score the single factor assessment indexes. The final index value of the engineering project can be obtained through data collection.

Step 3: Constructing single-index unascertained measure function

According to the above definition of the single index measure function and the grading standards of the assessment index, the measure function of the construction safety risk assessment index can be constructed.

Step 4: Determining the single-index unascertained measure matrix

According to the constructed single index unascertained measure function and the specific index value of engineering project, the single index measure matrix of engineering project can be obtained.

Step 5: Calculating the index weight

According to the entropy weight method, the weight of each index is calculated from the data in the single index unascertained measure matrix.

Step 6: Determining the multi-index comprehensive measure assessment vector

According to the single index unascertained measure matrix and the weight of each index, the multi-index comprehensive measure assessment vector can be obtained.

Step 7: Getting the construction safety risk grade

According to the confidence recognition criterion, the construction safety risk grade of the engineering project is determined.

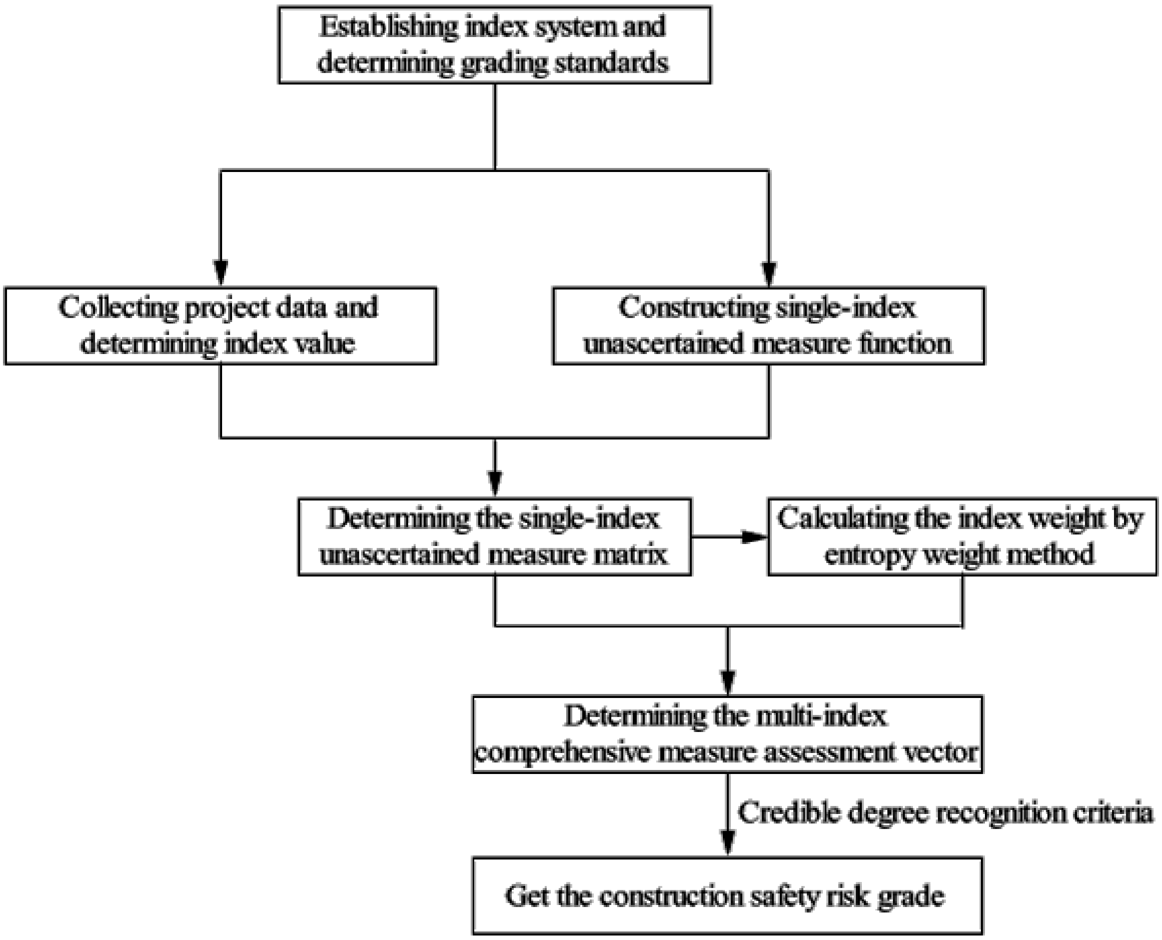

Figure 5. The specific steps of the construction safety risk assessment model.

4. Case Study

In order to avoid the limitation and contingency caused by selecting only one project, this paper selects five projects to verify the validity and feasibility of the model. The five projects are: TY dormitory building renovation project, SYD dormitory building renovation project, SH silo renovation project, BQY factory building renovation project, SGC factory building renovation project. Due to limited space, take TY dormitory building renovation project as an example for detailed analysis.

4.1. Project Introduction

The TY dormitory building renovation project is located in Yanta District, Xi'an City, Shaanxi Province, China. It was originally a student dormitory building with five-storey brick-concrete structure. It was built in 2000, with a length of about 61.5 m, a width of about 16.5 m and a construction area of about 5000 m^2. Now it is transformed into a hotel-style apartment, the scene is shown in Figures 6 and 7.

Figure 6. Building appearance.

Figure 7. Internal situation of the building.

4.2. Assessment Process

4.2.1. Index Value

The safety management staff including the owner, construction unit, supervision unit, quality inspection unit and other relevant units was selected to score the single factor assessment indexes. In order to ensure the objectivity and authenticity of the score, the highest and lowest scores of the indexes are first eliminated, and then the average value of each single factor assessment index is obtained. The final index value is shown in Table 3.

4.2.2. Single-Index Unascertained Measure Matrix

The unascertained measure function studied in this paper is linear. The unascertained measure function of each single factor assessment index is constructed as follows:

$$\mu_{ij1} = \begin{cases} 0 & x_{ij} \leq 82.5 \\ \frac{x_{ij}-82.5}{7.5} & 82.5 < x_{ij} \leq 90 \\ 1 & x_{ij} > 90 \end{cases} \quad (13)$$

$$\mu_{ij2} = \begin{cases} 0 & x_{ij} \leq 67.5 \quad or \quad x_{ij} > 90 \\ \frac{x_{ij}-67.5}{15} & 67.5 < x_{ij} \leq 82.5 \\ \frac{90-x_{ij}}{7.5} & 82.5 < x_{ij} \leq 90 \end{cases} \quad (14)$$

$$\mu_{ij3} = \begin{cases} 0 & x_{ij} \leq 60 \quad or \quad x_{ij} > 82.5 \\ \frac{x_{ij}-60}{7.5} & 60 < x_{ij} \leq 67.5 \\ \frac{82.5-x_{ij}}{15} & 67.5 < x_{ij} \leq 82.5 \end{cases} \quad (15)$$

$$\mu_{ij4} = \begin{cases} 1 & x_{ij} \leq 60 \\ \frac{67.5-x_{ij}}{7.5} & 60 < x_{ij} \leq 67.5 \\ 0 & x_{ij} > 67.5 \end{cases} \quad (16)$$

Table 3. Construction safety risk assessment index value of TY dormitory building renovation project.

Index	Scoring by Nine Experts									Final Score
I_{11}	82	80	79	82	82	82	78	83	83	81.43
I_{12}	78	78	79	78	76	79	81	75	82	78.43
I_{13}	89	88	90	89	88	89	88	92	90	89.00
I_{14}	79	77	72	73	78	77	77	73	70	75.29
I_{21}	79	82	83	83	84	82	84	82	80	82.29
I_{22}	79	82	83	83	86	78	85	77	75	81.00
I_{23}	87	87	89	84	89	88	89	81	81	86.43
I_{24}	76	78	71	78	75	77	77	77	68	75.86
I_{25}	74	78	72	72	74	76	78	78	75	75.29
I_{26}	73	71	69	72	74	71	74	71	74	72.29
I_{31}	78	79	82	88	84	88	82	79	79	81.86
I_{32}	72	76	72	75	74	74	71	74	70	73.14
I_{33}	83	85	85	83	85	77	89	88	88	85.29
I_{34}	82	81	80	87	81	85	83	81	80	81.86
I_{41}	73	71	75	76	73	71	77	75	74	73.86
I_{42}	77	81	75	76	75	81	77	82	75	77.43
I_{43}	79	76	74	79	74	73	73	72	70	74.43
I_{44}	77	82	80	81	84	84	81	83	77	81.14
I_{51}	82	90	89	80	87	86	82	84	89	85.57
I_{52}	75	79	76	79	75	75	77	75	74	76.00
I_{53}	71	79	79	76	70	79	75	76	79	76.43
I_{54}	72	79	80	79	81	80	77	73	84	78.43

In this paper, the single factor measure function is represented by a graph, as shown in Figure 8.

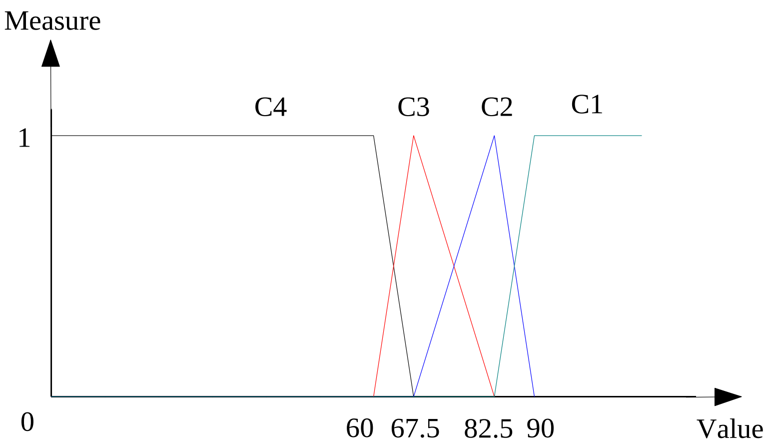

Figure 8. Unascertained measurement function.

According to the index value in Table 3, and based on the unascertained measure function of the single factor assessment index established by Equations (13)~(16), the single index unascertained measure matrix of the TY dormitory renovation project can be obtained.

$$\mu_{22\times4}=\begin{bmatrix} 0 & 0.929 & 0.071 & 0 \\ 0 & 0.729 & 0.271 & 0 \\ 0.867 & 0.133 & 0 & 0 \\ 0 & 0.519 & 0.481 & 0 \\ 0 & 0.986 & 0.014 & 0 \\ 0 & 0.900 & 0.100 & 0 \\ 0.524 & 0.476 & 0 & 0 \\ 0 & 0.557 & 0.443 & 0 \\ 0 & 0.519 & 0.481 & 0 \\ 0 & 0.319 & 0.681 & 0 \\ 0 & 0.957 & 0.043 & 0 \\ 0 & 0.376 & 0.624 & 0 \\ 0.371 & 0.629 & 0 & 0 \\ 0 & 0.957 & 0.043 & 0 \\ 0 & 0.424 & 0.576 & 0 \\ 0 & 0.662 & 0.338 & 0 \\ 0 & 0.462 & 0.538 & 0 \\ 0 & 0.910 & 0.090 & 0 \\ 0.410 & 0.590 & 0 & 0 \\ 0 & 0.567 & 0.433 & 0 \\ 0 & 0.595 & 0.405 & 0 \\ 0 & 0.729 & 0.271 & 0 \end{bmatrix} \tag{17}$$

4.2.3. Index Weight

According to the idea of information entropy method, the weight of each index is calculated from the data in the single index unascertained measure matrix.

$$\begin{aligned} w = (&0.060, 0.042, 0.053, 0.037, 0.070, 0.056, 0.037, 0.037, 0.037, 0.040, 0.064, 0.038, \\ &0.039, 0.064, 0.037, 0.040, 0.037, 0.057, 0.038, 0.037, 0.038, 0.042) \end{aligned} \tag{18}$$

4.2.4. Multi-Index Comprehensive Measure Assessment Vector

According to the single index unascertained measure matrix and the weight of each index, the multi-index comprehensive measure assessment vector of the construction safety risk can be obtained.

$$\mu_{1\times4} = \{0.095,0.671,0.234,0.000\} \tag{19}$$

Similarly, the multi-index comprehensive assessment vectors of SGC plant renovation project, SH silo renovation project, BQY plant renovation project and SYD dormitory building renovation project are obtained, as shown in Table 4.

Table 4. The assessment results.

Project Name	Comprehensive Unascertained Measure				Grade
	C_1	C_2	C_3	C_4	
TY	0.095	0.671	0.234	0.000	II
SYD	0.073	0.214	0.516	0.197	III
SH	0.132	0.587	0.233	0.048	II
BQY	0.623	0.210	0.167	0.000	I
SGC	0.176	0.508	0.213	0.103	II

4.2.5. Credible Degree Recognition

Suppose that $\lambda = 0.7$, and based on the credible degree recognition criterion and Equation (12). When p_0 = 2, from small to large, 0.095 + 0.671 = 0.766 > 0.7, that is, the construction safety risk grade is II; from large to small, 0.234 + 0.671 = 0.905 > 0.7, that is, the construction safety risk grade is II.

Synthesizing the two results, it is determined that the construction safety risk assessment grade of the project is grade II. In this paper, the confidence recognition criteria is used to evaluate two times, from small to large and from large to small. The assessment results are consistent with the actual situation, the error is within the acceptable range, and the assessment results are reliable.

Similarly, the construction safety risk of other renovation projects were calculated and evaluated, and the assessment results are as shown in Table 4.

5. Discussion

From Table 4, we can see the assessment results of each project. Among them, the safety risk grade of the TY dormitory renovation project is grade II, which belongs to a general safety risk and an acceptable state; the safety risk grade of the SYD dormitory renovation project is grade III, which belongs to a high safety risk and an unacceptable state; the safety risk grade of the SH silo renovation project is grade II, which belongs to a general risk and an acceptable state; the safety risk grade of the BQY plant renovation project is grade I, which belongs to a very low safety risk and a negligible state; the safety risk grade of the SGC plant renovation project is grade II, which belongs to a general security risk and an acceptable state. After obtaining the safety risk grade of each project, the project leader, safety management personnel, technical personnel and relevant experts conducted field investigation, discussion and analysis on the actual situation of the project.

Due to the limited space, only the analysis of TY dormitory renovation project is described in detail. In terms of human risk factors, the low quality of front-line construction personnel and weak safety awareness will have a certain impact on construction safety. Regular training of front-line personnel is needed to improve comprehensive quality and safety protection awareness. In terms of technical risk factors, as the renovation project involves wall opening, floor slab opening, external elevators, component reinforcement, partial demolition, etc. Construction units are equipped with various professional and technical personnel, which can meet the construction requirements. In terms of risk factors of materials and equipment, the space inside and outside the project is narrow, and the storage of materials and equipment and their dismantled waste occupied a large space, which caused many inconveniences to other construction. However, the construction unit transported the waste to the site immediately after finding these problems. In terms of management risk factors, all aspects of safety management are in place, rewards and penalties are clear, and safety management documents are well documented and maintained. In terms of environmental risk factors, the project is surrounded by dormitory buildings and residential buildings, and there are no significant hazards.

The same field investigation, discussion and analysis were carried out for the other four projects, which will not be repeated here. By analyzing the basic situation of each project, comparing the assessment results of the model with the on-site situation, it is agreed that the assessment results are scientific and reasonable, and are basically consistent with the on-site situation, which can fully reflect the safety status of the project. It shows that the model is feasible. In addition, the calculation process of the model is simple and easy to operate. In summary, it shows that the model established in this paper can deal with the uncertainty in risk assessment and is very suitable for the construction safety risk assessment of existing building renovation project.

In our opinion, it is a very meaningful thing for construction company to carry out safety assessment of the project. On the one hand, the current safety status of the construction can be obtained; on the other hand, the basic situation of human risk factors, technical risk factors, material and equipment risk factors, management risk factors and environmental risk factors can be understood at the time of data collection. Therefore, based on the risk grade of the assessment results and the current situation of various aspects, a series of safety control measures can be taken to ultimately ensure the construction safety of the project.

6. Conclusions

The renovation of existing building has become the best way to deal with old buildings reasonably. By using specific technical means, old buildings are given new vitality. Not only can it give full play to the old building's own value and show its new use function, but also protect the environment and inherit historical culture. Due to the complexity and uncertainty of existing building renovation project, the construction safety is extremely important.

Firstly, this paper put forward the index system of construction safety risk assessment for renovation project, including five primary indexes: human risk factors, technical risk factors, material and equipment risk factors, management risk factors, environmental risk factors. In the aspect of basic data collection, experts from owners, construction units, supervision units, quality inspection units, schools and other relevant units are invited to conduct on-site surveys and interviews.

Secondly, considering many uncertainties in existing building renovation project, the unascertained measure theory was applied to establish the safety risk assessment model for existing building renovation. The entropy weight method was introduced to determine the weight of each index. The single-index unascertained measure matrix was fully utilized, which avoided the influence of many subjective factors on the assessment results and made the assessment results more scientific and reasonable. The case study shows that the model is feasible and operable in practical engineering applications. Furthermore, then five renovation projects were taken as examples to verify the rationality and feasibility of the model.

In short, the unascertained measure theory can solve the problem of construction safety risk assessment and can provide new ideas and methods for the construction safety management and risk assessment of renovation project in the future. However, there are still some limitations in data collection and model calculation. Although the unascertained measure theory is specially used to deal with uncertainty, there will be certain subjectivity and uncertainty in data collection. In the future, it is better to select some quantitative indicators that can directly obtain the index values from the construction plan or construction site management data. In addition, although the calculation model is not complex, it also needs some mathematical operations. In order to be able to use the model more extensively in the future, further research and optimization should be carried out on the intelligence of the data acquisition and assessment process.

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