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Entropy Weight-Logarithmic Fuzzy Multiobjective Programming Method for Evaluating Emergency Evacuation in Crowded Places: A Case Study of a University Teaching Building

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ABSTRACT The teaching buildings in colleges and universities are crowded and prone to accidents. The emergency evacuation capability of these buildings is evaluated by applying the methods of fault tree, entropy weight-logarithmic fuzzy multiobjective programming (E-LFMP) and fuzzy comprehensive evaluation. An index system was constructed using the basic event structure importance of the accident tree, and the influencing factors were more systematic. In order to improve the objectivity and rationality of the evaluation process and results, this study combines the entropy weight method and multi-objective fuzzy logarithmic programming (LFMP) method to form the entropy weight-logarithmic fuzzy multiobjective programming. Consequently, the weights of different levels of index factors were analyzed and calculated, and more comprehensive content was considered. The fuzzy comprehensive evaluation model is established to evaluate the emergency evacuation ability of a teaching building. The maximum membership degree is 0.4025, and the corresponding grade is "general", indicating that its emergency evacuation ability must be improved. Based on the weight ratio and grade results of indicators in the evaluation model of emergency evacuation capability, safety rectification measures and suggestions were put forward from the aspects of improving information systems, widening evacuation channels and strengthening safety channel maintenance.

INDEX TERMS Entropy weight-logarithmic fuzzy multiobjective programming (E-LFMP), evacuation capability, fault tree, fuzzy comprehensive evaluation, indicator system.

I. INTRODUCTION

The university teaching building is a people-intensive place. In the event of a stampede, the casualty rate is extremely high. On April 12, 2015, a stampede incident at the University of Nairobi in Kenya resulted in one death and 141 injuries. On March 22, 2017, a stampede incident occurred in the Third Experimental Primary School in Fuyang, Henan Province, China, in which 22 students were injured, including one death and five serious injuries. In recent years, campus stampede incidents have occurred frequently [1], and the public safety of university teaching buildings has received

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increasing attention. However, at present, there is no complete index system of emergency evacuation ability for the prevention, disposal and rehabilitation of university teaching buildings and no suitable evaluation system of emergency evacuation ability [2], [3]. Therefore, it is necessary to study the evaluation method of emergency evacuation ability of university teaching buildings.

Studies outside of China on safe evacuation mainly focus on three aspects: the first is the study of evacuation behavior [4]–[6], the second is the study of evacuation time [7], [8], and the third is the influencing factors of safe evacuation [9]–[11]. The main factors affecting emergency evacuation capacity studied in China are different [12], [13] and different methods for evaluating emergency evacuation capacity are used [14]–[16].

Risk assessment methods can be divided into qualitative and quantitative methods, including fault tree analysis (FTA), analytic hierarchy process (AHP), gray system theory and fuzzy comprehensive evaluation [17]–[20]. The qualitative evaluation method can comprehensively and in detail evaluate the problems in the drill and provide practical suggestions for improvement. But it is too dependent on the experience of experts to ensure the effectiveness of the drill evaluation. The quantitative evaluation method focuses on quantitative evaluation results, which are suitable for comparison with drilling effects. When there is no comparison object, the significance of the evaluation process is greater than the meaning of the evaluation results. Therefore, the evaluation index system used in the quantitative assessment can be combined with the qualitative assessment to ensure the comprehensiveness and objectivity of the assessment and is easier to promote [21], [22]. The results of fuzzy risk assessment include not only the probability of occurrence of risk factors and their consequences, but also the reliability and scientificity of risk assessment results [23], [24]. Fuzzy risk assessment also contains some useful uncertainties and fuzzy theory is widely used in various risks [25], [26].

Through analyzing the emergency management status and the research results of emergency capability evaluation, many scholars mainly consider a certain kind of influencing factor. Most evaluations adopt qualitative methods. Qualitative evaluation relies heavily on the personal knowledge and experience of experts. The evaluation results are greatly affected by personal subjective factors. Low-level qualitative evaluation is easy to be in the form. It is difficult to ensure the effectiveness of the evaluation, and it is not convincing. In most cases, the theory of emergency management did not play a role in guiding practice. Emergency decision-making also lacks theoretical quantitative analysis to support. There is no sufficient study for the index system of a special public place in a university building. The regulations and theoretical guidance combined with the actual situation of public buildings is still not adequate, and further research is needed.

At present, the index weighting methods in the multi-objective decision-making process mainly include subjective weighting method, objective weighting method and mixed weighting method. In the process of subjective weighting, decision makers completely deviate from the measured data, and relying solely on the experience and professional knowledge of the decision makers, so it is easy to cause a situation where the subjective preference is too strong. The subjective evaluation method also has the problems of excessive confusion of subjective logic and single evaluation attitude of decision makers. The objective weighting method completely relies on the measured data, without considering the experience and knowledge of the decision-maker, and the measured data may also have certain errors, resulting in the final evaluation results inconsistent with the facts. Moreover, the previous objective weighting method only considered one of the three characteristics of the data: the discreteness, correlation and contrast strength of the measured data, and did not comprehensively consider all three characteristics of the data. Due to the comparative analysis of the advantages and disadvantages of the subjective and objective weighting methods, the traditional subjective weighting method has too strong a subjective preference of policy makers, while the objective weighting method relies too much on the limitation of measured data. Therefore, it is particularly important to integrate the subjective and objective weights. In addition, considering the space limitation, there is no need to separately perform subjective weighting or objective weighting calculation and comparison. This study uses fuzzy mathematical principles to propose a new subjective and objective empowerment methods. The mixed weighting method is formed by combining the subjective and the objective weighting method, and the weights after combination will not only take into account the experience and attitude of the decision-maker, but also effectively use the measured data to avoid the above deficiencies.

This study starts from two lines: subjective weight and objective weight. First of all, the subjective weighting method mainly draws on the principles of fuzzy mathematics and uses triangular fuzzy numbers and multi-objective fuzzy logarithmic programming to achieve the ranking of the relative importance of the index attribute values from macro to micro. The importance ranking matrix between indicators is given from the global level. Then, the objective weighting method is mainly based on the entropy weighting method, which will take into account the discreteness, correlation and contrast strength of the data to a certain extent. Finally, in order to solve the problems of too strong subjective preferences of decision makers and unreasonable utilization of measured data, the weighted average method is used to integrate the newly proposed subjective and objective weights, and the feasibility and practicability of the method are confirmed by examples. Multi-objective fuzzy logarithmic programming (LFMP) is a subjective weighting method. Experts determine the weight of index factors based on their own professional knowledge and past experience. Compared with the analytic hierarchy process, this method is closer to the actual situation, but it will still be affected by the subjective consciousness of experts. However, the entropy weight method is an objective weighting method. The logarithmic planning method can make the determination of index weights more reasonable, and finally make the evaluation results more accurate.

This study takes a university teaching building as an example to study the emergency evacuation of typical densely populated places. And the methods of safety system engineering and risk assessment are used to analyze the factors that easily cause accidents during an emergency in the teaching building. We take a stampede as an incident that is easily caused by emergency evacuation to carry out further analysis. According to the ''man-machine-environment-management'' theory in safety science and the basic event structure importance result obtained by the accident tree analysis, indicators are selected, and expert opinions are considered to optimize indicators and construct a new indicator system. Then the emergency evacuation ability of the teaching building is evaluated and effective measures is proposed. The research results of this study have a certain reference value for improving the emergency evacuation ability of colleges and universities and improving the public security management level of colleges and universities.

II. RESEARCH ON THE RISK ASSESSMENT MODEL OF EMERGENCY EVACUATION CAPABILITY

A. INFLUENCING FACTORS OF EMERGENCY EVACUATION CAPACITY BY FAULT TREE ANALYSIS

According to accident statistics [27], [28], emergency evacuation accidents in a teaching building are mainly caused by trampling. The occurrence of a tramping accident involves two processes: a person falls and trampling occurs. Personal fall is the direct cause of trampling accident. According to trace intersecting theory [29], [30], a person fall event can be analyzed from two aspects: the unsafe behavior of the person and the unsafe state of the object. The occurrence of trampling is an indirect cause of accidents. Structural defects of teaching buildings or the lack of management during an emergency evacuation are the necessary conditions for the accident. Thus trampling events can be analyzed from the aspects of structural facility defects and deficiencies of safety management and of education. Falls and tramples are the main causes of trampling accidents. And these two factors are considered the intermediate events of emergency evacuation trampling accidents in a teaching building [1], [31]. Hence, basic events, as the top event in emergency evacuation accidents in teaching buildings, are further deduced and analyzed.

1) PERSON FALLS: THE DIRECT CAUSE OF THE ACCIDENT

The unsafe behaviors of human beings and the unsafe state of things together comprise the intermediate events in personal falls.

Unsafe behaviors of people. In emergency evacuation of the teaching building, a weak sense of personal safety, limited emergency response ability or low psychological quality cause representative unsafe behaviors such as reverse movements, bending shoes, fighting, pushing and panic.

The unsafe state of the object. The unsafe condition of the object is an inevitable condition for the falling of a person. The main direct factors causing the person falling are channel blockage, unreasonable staircase design, sliding ground and insufficient lighting.

2) TRAMPLING: AN INDIRECT CAUSE OF THE ACCIDENT

When a person falls, if the structure of the teaching building is reasonable and the emergency evacuation is appropriate, these factors can curb the occurrence of trampling accidents. Therefore, structural defects and deficiencies in management and education are the main indirect causes of the accident.

Defects in structural facilities. Technical reasons caused by the design and construction of the teaching building are the main indirect causes of accidents. They are mainly divided into three aspects: the number of safety exits is too small; the distribution of classrooms is unreasonable and the evacuation passages are unreasonable. The irrationalities of the evacuation passages can be divided into two basic events: a narrow evacuation channel and the unreasonable location of the evacuation channel.

Insufficient management and education. In the case of emergency evacuation, accidents can easily occur when the emergency command is faulty or the emergency equipment is missing. The lack of management and education is mainly reflected in the insufficient capacity of emergency agencies, inadequate contingency plans, lack of safety awareness and ability, unclear evacuation instructions and inadequate emergency drills.

Based on the above deductive analysis, the fault tree causing the trampling accident during an emergency evacuation of a teaching building is shown in Fig. 1.

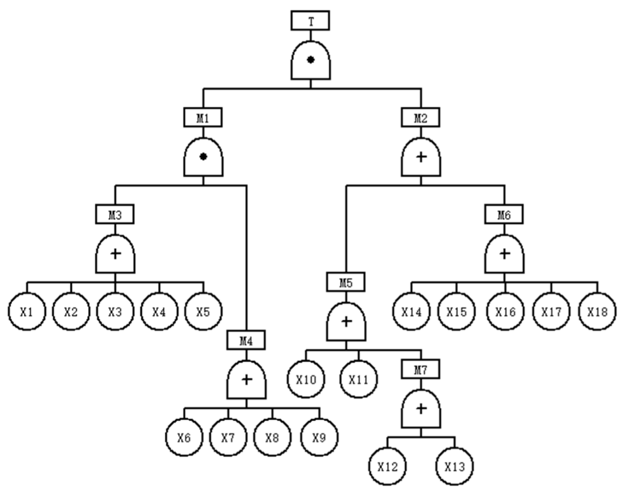

FIGURE 1. Fault tree of trampling accident.

The different symbols represent different events. The specific meanings are shown in Table 1.

$$T = M1 \cdot M2$$
$$= (M3 \cdot M4) \cdot (M5 + M6)$$

TABLE 1. Meaning of basic events.

Symbol	Event name	Symbol	Event name
T	Evacuation trampling accident	X6	Channel blockage
M1	People fall	X7	Unreasonable staircase design
M2	Stampede	X8	The ground is not slip-resistant
M3	Unsafe behavior of human	X9	Insufficient lighting
M4	Unsafe state of matter	X10	Few safety exits
M5	Structural defect	X11	Unreasonable distribution of classrooms
M6	Insufficient management and education	X12	Narrow evacuation channels
M7	Unreasonable evacuation channel design	X13	Unreasonable locations of the evacuation channels
X1	Reverse motion	X14	Insufficient level of emergency agencies
X2	Bend down and tie shoelaces	X15	Emergency plan is not in place
X3	Play and fight	X16	Insufficient safety awareness and ability
X4	Push	X17	Unclear evacuation indication
X5	Panic	X18	Emergency drill is not in place

$$
\begin{aligned}
&= [(X1 + X2 + X3 + X4 + X5) \cdot (X6+X7+X8+X9)] \\
&\quad \times [(X10 + X11 + M7) \\
&\quad + (X14 + X15 + X16 + X17 + X18)] \\
&= [(X1 + X2 + X3 + X4 + X5) \cdot (X6+X7+X8+X9)] \\
&\quad \times [(X10 + X11 + X12 + X13) \\
&\quad + (X14 + X15 + X16 + X17 + X18)]
\end{aligned}
$$

It can be seen that there are 18 basic incidents causing stampede accidents. These basic events intuitively reflect the emergency evacuation capacity of college teaching buildings. It also constitute a direct basis for evaluating the emergency evacuation capability index system of the teaching building. The Boolean algebra method is used to calculate the structural importance of the emergency evacuation trampling accident tree of the teaching building. An objective basis is provided for determining the weight of the evaluation index system.

There are three minimum path sets calculated: {X1, X2, X3, X4, X5}, {X6, X7, X8, X9}, {X10, X11, X12, X13, X14, X15, X16, X17, X18}. According to the minimum path sets, the structural importance is calculated as follows:

I[X6] = I[X7] = I[X8] = I[X9] > I[X1] = I[X2] = I[X3] = I[X4] = I[X5] > I[X10] = I[X11] = I[X12] = I[X13] = I[X14] = I[X15] = I[X16] = I[X17] = I[X18]

The main causes of the stampede accident are the following (in order of importance): the basic events of the unsafe state of the composition, the unsafe behaviors of the person, the indirect cause of the accident due to structural defects of the teaching building, and the lack of management education.

B. ESTABLISHMENT OF EVACUATION CAPABILITY INDEX SYSTEM BASED ON FAULT TREE ANALYSIS

The evaluation index system is the basis for evaluating the emergency response capability in public places. The design of the indicator system should abide by the principles of scientificity, importance, systematicness and operability [32], [33]. The basis of index system construction is: Combined with the relevant research results, this study analyses the emergency evacuation capacity of teaching buildings from the perspective of ''man-machine-environment-management'' in safety science. Also, it screens the indicators according to the results of fault tree analysis and expert opinions. The index system of emergency evacuation capacity is established from the aspect of ''man-building-management''. The evaluation indicator system mainly includes four evaluation indicator levels. The target level is the emergency evacuation capability for emergencies in college buildings. The first-level indicator layer includes three evaluation factors: personal escape ability, building evacuation ability and emergency management ability. The second-level indicator layer includes sixteen evaluation factors. The third-level indicator layer is an unfolding analysis of the conditions of the secondary indicator, evacuation channel, including four evaluation factors. The details are showed in Fig. 2.

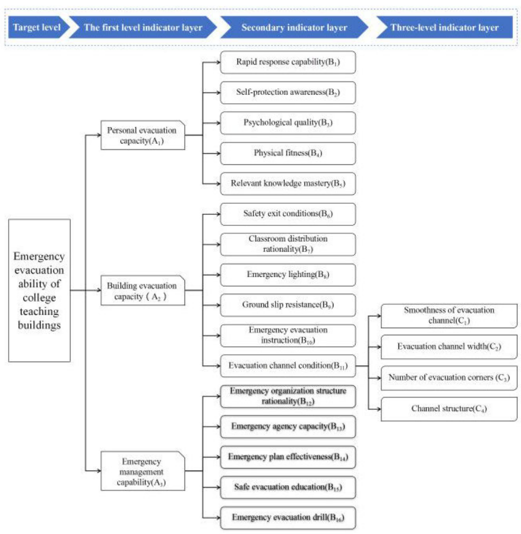

FIGURE 2. Emergency evacuation capability evaluation index system.

1) PERSONNEL EVACUATION ABILITY (A_1)

When an emergency occurs in a teaching building, the task of emergency evacuation is to safely evacuate students and working groups from the teaching building. Therefore, the evacuation ability of the personnel is the most direct factor affecting the evaluation of the emergency evacuation ability of the teaching building. There are also differences in the evacuation and escape abilities. According to the deductive reasoning of the accident tree analysis method, it can be seen that the basic events of unsafe behavior that belong to people mainly include reverse movement, bending over laces, slapstick, coaxing, and panic. The lack of safety awareness and ability caused by the lack of safety education in safety management will also affect the evacuation ability of personnel. According to these unsafe behaviors and safety management factors, the index factors reflecting the evacuation ability of personnel can be summarized into five points, namely: Quick response ability, self-protection consciousness, psychological quality ability, physical fitness ability and related knowledge mastery.

a: QUICK RESPONSE ABILITY (B_1)
The speed of personnel's reaction directly affects the time required for all personnel in the teaching building to be evacuated. The difference in quick response ability is caused by the age segmentation and safety awareness of the evacuated people.

b: SELF-PROTECTION CONSCIOUSNESS (B_2)
During the evacuation process, if lack of self-protection consciousness, such as bending over to tie shoelaces or slapstick during evacuation, not only will hurt yourself, but also because of the large crowd density during evacuation, it is easy to cause cluster accidents such as trampling.

c: PSYCHOLOGICAL QUALITY ABILITY (B_3)
In the event of an emergency, if the psychological quality of the personnel is poor, it is easy to cause panic, make wrong decisions or even lose the ability to act unsafely. The psychological quality of the personnel, acctually, is related to self-experience and learning knowledge, which can be improved through safety education and training.

d: PHYSICAL FITNESS (B_4)
Physical fitness is very important during emergency evacuation. If the evacuated population lacks exercise or there are old, weak and sick people during the evacuation, due to the large flow of people during the evacuation, the density of the crowd is large, and physical reasons are likely to affect evacuation. However, most of the people in the teaching building of colleges and universities are young people, and generally they will not affect the evacuation during emergency evacuation due to their physical constitution.

e: RELEVANT KNOWLEDGE MASTERY (B_5)
In the event of emergencies in the teaching building, if personnel fail to detect danger in time and take relevant measures, it is easy to cause the expansion of the event and the occurrence of secondary accidents. Thus the mastery of the relevant knowledge of the personnel can be effective. The occurrence of these incidents and the mastery of personnel's relevant knowledge are mainly affected by safety education and the promotion of relevant knowledge.

2) BUILDING EVACUATION CAPACITY (A_2)
From the perspective of emergency evacuation, the teaching building should have corresponding evacuation conditions, such as the number of safety exits and the width of safety exits. Combining the results obtained by the accident tree analysis method, it can be seen that the unsafe state of the objects and the defects of the building structure and facilities are the main factors that affect the emergency evacuation capacity of the building. According to the eight basic events of these two intermediate events, the building's The evacuation capacity is divided into six secondary indicators: safe exit conditions, rationality of classroom distribution, emergency lighting facilities, ground slip resistance, emergency evacuation instructions, and evacuation channel conditions.

a: SAFE EXIT CONDITIONS (B_6)
The number of personnel in public places such as university teaching buildings is large and the density is high. In order to ensure that personnel can evacuate the building safely and as soon as possible, the number and width of safe exits must meet the requirements. There are specific specifications for the design of safe exports [34].

b: THE RATIONALITY OF CLASSROOM DISTRIBUTION (B_7)
The integration of the functions of college teaching buildings and the complexity of building construction make the distribution of classrooms obviously uneven. The teaching building in this study is a typical ''U'' type building, and there are more classrooms at the corner of the floor. Therefore, it is more difficult for people to evacuate when a sudden cluster event occurs.

c: EMERGENCY LIGHTING FACILITIES (B_8)
In the case of emergency evacuation, reasonable emergency lighting facilities can effectively reduce the evacuation time of the crowd and reduce the panic psychology of the crowd. If the emergency lighting facilities are not set up reasonably, it is likely to cause the evacuation personnel to make a wrong decision and choose the wrong escape route.

d: GROUND ANTI-SLIP PROPERTY (B_9)
The design of college teaching buildings is developing in the direction of aesthetics. Many stairs and passages are decorated with marble materials. The ground is very smooth. It is very easy for people to slip during emergency evacuation. Anti-skid lines should be set reasonably to reduce the occurrence of trampling accidents during evacuation.

e: EMERGENCY EVACUATION INSTRUCTIONS (B_{10})
In the case where the crowd is not familiar with the structure of the building, the emergency evacuation instructions can well instruct the crowd to find the evacuation exit, effectively reducing the blind movements of people in a panic escape and reverse movement during evacuation.

f: EVACUATION CHANNEL CONDITIONS (B_{11})
After escaping from the classroom and entering the corridor, the crowd needs to enter the stairway to the safety exit

through the evacuation channel. Therefore, the conditions of the evacuation channel have a great impact on the emergency evacuation capacity of the teaching building. The specific performances are: smoothness, the width of the evacuation channel, the number of evacuation corners and the structure of the channel. Clearance of evacuation passage (C_1): The evacuation passage must be unblocked. If the evacuation passage is blocked by garbage during evacuation, or the fire door leading to the stairs is closed, it is easy to cause panic and trampling accidents during crowd evacuation. The width of the evacuation channel (C_2): "Code for Fire Protection Design of Buildings" and related standards clearly stipulate the width of the evacuation channel, and the total width of the evacuation channel should not be less than 0.65m / 100 people when meeting the requirement of first and second grade fire resistance levels. Number of evacuation corners (C_3): During crowd evacuation, excessive number of stair corners can easily cause dizziness and visual fatigue, which can affect the evacuation personnel's psychology and affect the evacuation escape of the crowd. The structure of the channel (C_4): The structure of the channel is complex, which is very easy to cause difficulty and confusion in the selection of personnel during emergency evacuation. The structure of the evacuation channel should be as concise as possible to avoid diversification of the direction and width.

3) EMERGENCY MANAGEMENT CAPABILITY (A_3)

Reasonable emergency management preparation, preparation of emergency plans and emergency drills can greatly improve the processing speed and response efficiency of emergency response in the event of an emergency. In addition, the organization structure system of emergency evacuation command and the publicity and education of relevant emergency knowledge before the accident can provide a certain foundation for improving the emergency evacuation capability of the teaching building. The emergency management capabilities of the teaching building are mainly reflected in five secondary indicators, including the rationality of the emergency organization structure, the capabilities of the emergency organization, the effectiveness of the emergency plan, the safety evacuation education and the emergency evacuation exercises.

a: RATIONALITY OF EMERGENCY ORGANIZATION STRUCTURE (B_{12})

The following factors will effectively shorten the response time to increase the speed of emergency evacuation: a reasonable emergency organization structure, clarifying the obligations and tasks of the responsible subjects, and ensuring that the objects of emergency evacuation understand the development of the emergency and the evacuation route at the first time.

b: EMERGENCY AGENCY CAPABILITIES (B_{13})

Emergency agency capabilities include the emergency evacuation capabilities of emergency commanders and rescuers, and the effectiveness of basic rescue facilities such as broadcast systems and video surveillance systems.

c: EFFECTIVENESS OF THE EMERGENCY PLAN (B_{14})

The emergency plan not only needs to be meticulous and targeted, but also needs to be updated in a timely manner, with flexibility to prevent the occurrence of unrelated derivative events.

d: SAFETY EVACUATION EDUCATION (B_{15})

Emergency evacuation after an emergency is important, but related education and publicity before an emergency are also very important. If evacuated people can receive systematic safety education before an accident, they can greatly improve their safety evacuation ability.

e: EMERGENCY EVACUATION DRILL (B_{16})

Because the structure of college teaching buildings is complex and some emergency evacuation passages are hidden, many people do not know the specific evacuation passages and evacuation routes. However, the crowd in college teaching buildings is generally fixed, so regular organization emergency evacuation exercises can significantly improve the emergency evacuation ability of teaching buildings.

C. ENTROPY LFMP METHOD TO DETERMINE INDEX WEIGHTS

One is usually accustomed to constructing a judgment matrix using the analytic hierarchy process for decision analysis. But this method does not take into account the ambiguity of human judgment in decision-making and has obvious subjectivity. In actual life, experts are used to giving fuzzy numbers and fuzzy intervals. Therefore, this study uses triangular fuzzy numbers to compare two index factors [35]–[37] and then carries out weight analysis based on the multiobjective fuzzy logarithmic programming (LFMP) theory of triangular fuzzy numbers.

Multiobjective fuzzy logarithm programming (LFMP) is a subjective weighting method. Although this method is closer to the actual situation than the analytic hierarchy process, it is still subject to the subjective consciousness of experts. To eliminate the influence of subjective consciousness as much as possible, this study intends to introduce the entropy weight method. It is an objective weighting method without the arbitrariness of the subjective weighting method. It can be used in combination with the multiobjective fuzzy logarithmic programming method to determine index weights more reasonably and evaluation results more accurately.

1) TRIANGULAR FUZZY NUMBERS AND MULTIOBJECTIVE FUZZY LOGARITHM PROGRAMMING THEORY

Triangular fuzzy numbers are mainly represented by three parameters l, m, u, and are denoted as (l,m,u), l and u represent the lower and upper bounds of triangular fuzzy Numbers, respectively, and they represent the degree of fuzziness. The larger the interval, the stronger the degree of fuzziness, and m represents the optimal value [38], [39]. A function of a triangular fuzzy number has the following form:

$$\mu(x)=\begin{cases}0, & x<l\\ \dfrac{x-l}{m-l}, & l\le x\le m\\ \dfrac{u-x}{u-m}, & m\le x\le u\\ 0, & x>u\end{cases} \tag{1}$$

where $x\in R$, and $0<l\le m\le u$.

The function of the triangular fuzzy number can be represented by Fig. 3.

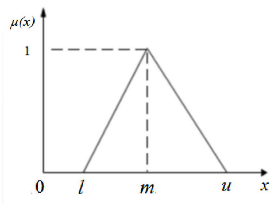

FIGURE 3. Function of the triangular fuzzy number.

For two triangular fuzzy numbers $\tilde{A}=(l_1,m_1,u_1)$, $\tilde{B}=(l_2,m_2,u_2)$, we have the following algorithms.

Sum of two numbers:

$$\tilde{A}\oplus\tilde{B}=(l_1+l_2,m_1+m_2,u_1+u_2) \tag{2}$$

Product of two numbers:

$$\tilde{A}\otimes\tilde{B}=(l_1\times l_2,m_1\times m_2,u_1\times u_2) \tag{3}$$

Quotient of two numbers:

$$\tilde{A}\div\tilde{B}=(\frac{l_1}{l_2},\frac{\mathrm{m}_1}{m_2},\frac{u_1}{u_2}) \tag{4}$$

The reciprocal of triangular fuzzy number:

$$\frac{1}{\tilde{A}}=(\frac{1}{l_1},\frac{1}{m_1},\frac{1}{u_1}) \tag{5}$$

The introduction of triangular fuzzy number theory can make the expert's decision more reasonable. The judgment matrix represented by the triangular fuzzy number is shown in formula (6). Where $\tilde{a}_{ij}$ represents the relative importance of the i-th evaluation index to the j-th evaluation object, $i=1,2,\ldots,\mathrm{m}$; $j=1,2,\ldots,\mathrm{n}$.

$$\begin{aligned}\tilde{A}&=(\tilde{a}_{ij})_{m\times n}\\ &=\begin{bmatrix}(1,1,1) & (l_{12},m_{12},u_{12}) & \cdots & (l_{1n},m_{1n},u_{1n})\\ (l_{21},m_{21},u_{21}) & (1,1,1) & \cdots & (l_{2n},m_{2n},u_{2n})\\ \vdots & \vdots & \ddots & \vdots\\ (l_{m1},m_{m1},u_{m1}) & (l_{m2},m_{m2},u_{m2}) & \cdots & (1,1,1)\end{bmatrix}\\ l_{ij}&=\frac{1}{u_{ji}},\quad \mathrm{m}_{ij}=\frac{1}{m_{ji}},\ u_{ij}=\frac{1}{l_{ji}},\\ &0\le l_{ij}\le m_{ij}\le u_{ij},l_{ii}=m_{ii}=u_{ii}=1\end{aligned} \tag{6}$$

According to Kahraman's research, the relative importance of factor X_i and factor X_j ranges from (l_{ij}, m_{ij}, u_{ij}), and m_{ij} represents the most likely relative importance. In the pairwise comparison fuzzy judgment matrix for index evaluation, the value of triangular fuzzy number is shown in Table 2 below.

TABLE 2. Triangular fuzzy number scale.

Grade	Meaning	Triangular fuzzy expression	Inverse expression
1	Element j is equally as important as element i	(1, 1, 1)	(1, 1, 1)
2	Slightly less important	(1, 2, 3)	(1/3, 1/2, 1)
3	Slightly important	(2, 3, 4)	(1/4, 1/3, 1/2)
4	Between slightly important and more important	(3,4,5)	(1/5, 1/4, 1/3)
5	More important	(4, 5, 6)	(1/6,1/5,1/4)
6	Between more important and very important	(5, 6, 7)	(1/7, 1/6, 1,5)
7	Very important	(6, 7, 8)	(1/8, 1/7, 1/6)
8	Between very important and extremely important	(7, 8, 9)	(1/9, 1/8, 1/7)
9	Extremely important	(8, 9, 10)	(1/10, 1/9, 1/8)

Using triangular fuzzy numbers to represent fuzzy judgment matrices, Mikhailov proposed a nonlinear optimization method [40], [41]. This study improves it according to the actual situation and transforms it into a multiobjective solution, as follows.

With w_i/w_j as the independent variable, the formula (1) can be transformed into:

$$u_{ij}\left(\frac{w_i}{w_j}\right)=\begin{cases}\dfrac{(w_i/w_j)-l_{ij}}{m_{ij}-l_{ij}}, & \dfrac{w_i}{w_j}\le m_{ij}\\ \dfrac{u_{ij}-(w_i/w_j)}{u_{ij}-m_{ij}}, & \dfrac{w_i}{w_j}\ge m_{ij}\end{cases} \tag{7}$$

where $u_{ij}(w_i/w_j)$ represents the importance of w_i/w_j for the fuzzy matrix $\tilde{A}=(\tilde{a}_{ij})_{m\times n}$, so the logarithmic form of the fuzzy matrix is as shown in equation (8).

$$u_{ij}\left(\ln\left(\frac{w_i}{w_j}\right)\right)=\begin{cases}\dfrac{\ln(w_i/w_j)-\ln l_{ij}}{\ln m_{ij}-\ln l_{ij}}, & \ln\left(\dfrac{w_i}{w_j}\right)\le m_{ij}\\ \dfrac{\ln u_{ij}-\ln(w_i/w_j)}{\ln u_{ij}-\ln m_{ij}}, & \ln\left(\dfrac{w_i}{w_j}\right)\ge m_{ij}\end{cases} \tag{8}$$

where $u_{ij}(\ln(w_i/w_j))$ denotes the membership degree of $\ln(w_i/w_j)$ to the fuzzy matrix $\tilde{a}_{ij}=(\ln l_{ij},\ln m_{ij},\ln u_{ij})$. Let λ be the minimum degree of membership:

$$\begin{aligned}\lambda=\min\{&\mathrm{u_{ij}}(\ln(w_i/w_j))\quad |i=1,\cdots,\mathrm{m}-1;\\ &j=i+1,\cdots,\mathrm{n}\}\end{aligned} \tag{9}$$

According to the membership degree formula, the extremum solution of the formula (8) can be transformed into a nonlinear programming problem, as shown in formula (10).

$$\begin{aligned}&\max\ \lambda\\ &s.t.\begin{cases}u_{ij}(\ln(w_i/w_j))\ge\lambda, & i=1,\cdots,\mathrm{m}-1;\\ & j=i+1,\cdots,\mathrm{n}\\ w_j\ge 0, & i=1,\cdots,\mathrm{n}\end{cases}\end{aligned} \tag{10}$$

Equation (10) is a nonlinear inequality constrained programming problem with maximum value. And it can be transformed into a nonlinear inequality constrained programming problem with minimum value.

$$\min\ 1-\lambda$$
$$\text{s.t.}\begin{cases}\ln w_i - \ln w_j - \lambda \ln(m_{ij}/l_{ij}) \geq \ln l_{ij}, \\ \qquad i=1,\cdots,\mathrm{m}-1;\ j=i+1,\cdots,\mathrm{n} \\ -\ln w_i + \ln w_j - \lambda \ln(u_{ij}/m_{ij}) \geq -\ln u_{ij}, \\ \qquad i=1,\cdots,\mathrm{m}-1;\ j=i+1,\cdots,\mathrm{n} \\ w_j \geq 0, \quad i=1,\cdots,\mathrm{m}\end{cases} \tag{11}$$

In general, multiple sets of solutions can be obtained from the above formula. But the only optimal solution cannot be obtained. To make the obtained value close to the actual situation, the objective function is added. And the nonlinear fuzzy logarithm programming model is converted into multiobjective fuzzy logarithm programming. The new target inequality group is as follows:

$$\min\ J=(1-\lambda)^2$$
$$F=\sum_{i=1}^{n-1}(x_i^2+\sum_{j=i+1}^{n}(x_j^2))$$
$$s.t.\begin{cases}x_i - x_j + \lambda \ln(u_{ij}/m_{ij}) + n_{ij} \leq \ln u_{ij}, \\ \qquad i=1,\cdots,\mathrm{m}-1;\ j=i+1,\cdots,\mathrm{n} \\ -x_i + x_j + \lambda \ln(m_{ij}/l_{ij}) + \delta_{ij} \leq -\ln l_{ij}, \\ \qquad i=1,\cdots,\mathrm{m}-1;\ j=i+1,\cdots,\mathrm{n} \\ \lambda,\ x_i \geq 0, \quad i=1,\cdots,\mathrm{m}\end{cases} \tag{12}$$

where $x_i = \ln w_i$, $i = 1, 2,\ldots,$m.

According to formula (12), the optimal solution x_i^* can be found, so that the weighted value of the matrix is

$$w_i^* = \frac{\exp(x_i^*)}{\sum_{j=1}^{n}\exp(x_i^*)}, \quad i=1,\ 2,\cdots,\mathrm{m} \tag{13}$$

2) ENTROPY WEIGHT METHOD

The entropy weight method is an objective weighting method. The fuzzy entropy describes the fuzzy degree of a fuzzy set. This study uses the triangular fuzzy number to compare the index factors with fuzzy judgments. When using the entropy weight method, the matrix must be defuzzified by the fuzzy interval operation. And then the entropy weight of the matrix is obtained according to the basic calculation method of the entropy weight method. The detailed calculation of the original data is as follows:

Supposing that in the decision problem with m evaluation objects and n evaluation indicators, a triangular fuzzy number scale (see Table 2) is used to indicate the relative importance of each pair of indicators, and a fuzzy judgment matrix for each indicator in the evaluated target can be obtained:

$$\tilde{A} = \begin{bmatrix}\tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{m1} & \tilde{a}_{m2} & \cdots & \tilde{a}_{mn}\end{bmatrix} \tag{14}$$

where $\tilde{a}_{ij}$ represents the relative importance of the i-th evaluation index to the j-th evaluation object, $i = 1, 2, \ldots,$ m; $j = 1, 2, \ldots,$ n.

The operation theorem of triangular fuzzy numbers is used to determine the nonfuzzy matrix. And then the entropy weight method to calculate the entropy weight of each index.

Replacement using confidence space with confidence level α, the fuzzy matrix is transformed into:

$$\tilde{A}^{\alpha} = \begin{bmatrix}[a_{11}^l, a_{11}^u] & \cdots & [a_{1n}^l, a_{1n}^u] \\ \vdots & \ddots & \vdots \\ [a_{m1}^l, a_{11}^u] & \cdots & [a_{mn}^l, a_{mn}^u]\end{bmatrix} \tag{15}$$

where $\alpha \in [0, 1]$, $a_{ij}^l = (m-l)\alpha + l$, $a_{ij}^u = u - (u-m)\alpha$.

Then α is kept constant, and the index coefficient β is used to indicate the degree of conformity to the importance of the judgment between two indicators. The judgment matrix can finally be expressed as:

$$\tilde{A} = \begin{bmatrix}\tilde{a}_{11}^{\alpha} & \tilde{a}_{12}^{\alpha} & \cdots & \tilde{a}_{1n}^{\alpha} \\ \tilde{a}_{21}^{\alpha} & \tilde{a}_{22}^{\alpha} & \cdots & \tilde{a}_{2n}^{\alpha} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{m1}^{\alpha} & \tilde{a}_{m2}^{\alpha} & \cdots & \tilde{a}_{mn}^{\alpha}\end{bmatrix} \tag{16}$$

In formula (16), $\tilde{a}_{ij}^{\alpha} = \tilde{a}_{ij} = \beta \times a_{ij}^u + (1-\beta) \times \tilde{a}_{ij}^l$, $\forall\beta \in [0, 1]$, the larger the β is, the more confident the result of the judgment.

According to the calculation formula of the entropy weight method, the entropy weights of each index are obtained as follows:

First, normalize the n evaluation indicators:

$$p_{ij} = \frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}} \tag{17}$$

Then, the entropy expression of the i-th index factor is:

$$H_i = -k\sum_{j-1}^{n} p_{ij}\ln(p_{ij}) \tag{18}$$

where $i = 1, 2, \ldots,$ m; $j = 1, 2, \ldots,$ n; $k = 1/\ln n$.

After calculating the entropy of the i-th index factor, the entropy weight of the i-th index factor can be obtained f_i. The expression is:

$$f_i = \frac{1-H_i}{m-\sum_{i=1}^{m} H_i}, \quad 0 \leq f_i \leq 1, \sum_{i=1}^{m} f_i = 1 \tag{19}$$

3) ENTROPY WEIGHT–MULTIOBJECTIVE FUZZY LOGARITHMIC PROGRAMMING

If the results of the entropy weight method and the multiobjective fuzzy logarithm programming are integrated, there are three methods for the mixed calculation of the entropy weight value fi and the multiobjective fuzzy logarithm weight wi.

Mathematical average method. The mathematical averaging process is performed according to the calculated weight results of the two evaluation methods, as shown in formula (20).

$$W_i = (w_i + f_i)/2 \tag{20}$$

Weighted average method. The calculated weight results of the two evaluation methods are weighted and averaged, and then normalized, as shown in formula (21).

$$W_i = \frac{f_i w_i}{\sum_{i=1}^{n} f_i w_i} \tag{21}$$

The normalization method. The calculation weight results of two evaluation methods above are coupled, as shown in equation (22).

$$W_i = \lambda w_i + (1-\lambda) f_i, \quad 0 \le \lambda \le 1 \tag{22}$$

where λ indicates the degree of bias towards evaluation results.

In this study, we use the weighted average method to combine weights determined by the two methods. This method eliminates the subjective randomness of multiobjective fuzzy logarithm programming method and the disadvantage of the entropy weight method. Because it cannot reflect expert opinion. The objective rationality of the determined weight is effectively improved. The above method is used to determine the weight value of index factors at different levels in the evaluation index system of college teaching buildings and to provide weight sets for fuzzy comprehensive evaluation.

D. FUZZY COMPREHENSIVE EVALUATION MODEL

Fuzzy comprehensive evaluation method [41], [42] is a quantitative evaluation method based on fuzzy mathematics theory. The method uses fuzzy theory to make reasonable fuzzy comprehensive evaluation of comprehensive things from different angles and different levels [43], [44], with evaluation including multiple influencing factors and attributes [45]–[48]. Specifically, it can be evaluated by three elements of fuzzy evaluation: factor set, weight set, and comment set [49]–[51].

Factor set: The fuzzy comprehensive evaluation must first determine the set of factors. The factor set is a set of all evaluation index factors in the index system that must evaluate things and is expressed by formula (23).

$$U = \{u_1, u_2, \cdots, u_n\} \tag{23}$$

where $u_i(i = 1, 2, \cdots, \mathrm{n})$ is the evaluation factor in the evaluation index system. Generally, different evaluation targets have different evaluation index systems and index factors. According to the structure of the evaluation index system, it can be divided into the target layer, the first-level indicator layer and the second-level indicator layer.

Weight set: The weight reflects the importance of different index factors to evaluation targets. The weight of each factor is determined by the analytic hierarchy process. The index of this study is determined by entropy weight and by the multiobjective fuzzy logarithm programming method. The weight set is expressed by formula (24).

$$w = \{w_1, w_2, \cdots, w_n\} \tag{24}$$

where $w_i(i = 1, 2, \cdots, \mathrm{n})$ indicates the index weight corresponding to each index factor in the indicator system. The weight of the index factor should satisfy the nonnegative nature. The index weight of each index layer should be normalized. The expression is as shown in (25).

$$\sum_{i=1}^{n} w_i = 1, \quad 0 \le w_i \le 1 \tag{25}$$

Comment set: After determining the weights of the factor set, the indicator level and the index factors, it is necessary to conduct a grade evaluation of each index factor. Normally, the index factor comment is to invite the industry researchers to evaluate each evaluation index according to their own professional knowledge and past experience. The rating is as shown in equation (26).

$$r = \{r_1, r_2, \cdots, r_n\} \tag{26}$$

where $r_i(i = 1, 2, \cdots, n)$ is the comment level corresponding to each index factor. The ratings of this article are divided into five levels: excellent, good, average, poor and very poor. After the rating level of different index factors is obtained, the fuzzy matrix can be used to represent the comment set of the indicator system, as shown in formula (27).

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m1} & \cdots & r_{mn} \end{bmatrix} \tag{27}$$

From the weight set of the indicator factors determined above, the fuzzy comprehensive evaluation result is:

$$B = W \cdot R = (w_1, w_2, \cdots, w_m) \cdot \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m1} & \cdots & r_{mn} \end{bmatrix} \tag{28}$$

According to the result of formula (28), the risk level of the evaluation target is obtained from the maximum degree of membership. $\cdot$ in the above formula represents a fuzzy operator for fuzzy comprehensive evaluation. Commonly used fuzzy operators are:

$$\begin{aligned} b_j &= \overset{n}{\underset{i=1}{\vee}} \left(w_i \wedge r_{ij}\right) \\ &= \max[\min(w_1, r_{1j}), \cdots, \min(w_n, r_{nj})] \\ & j = 1, 2, \cdots, m \end{aligned} \tag{29}$$

$M(\wedge, \vee)$ $\wedge$ denotes a small operation, $\vee$ denotes a large operation, and the equations are expressed as:

$M(\cdot, \vee)$ denotes the operation of multiplying first and then taking a large one. The equation is expressed as:

$$b_j = \bigvee_{i=1}^{n} \left(w_i \cdot r_{ij}\right) = \max\left[w_1 \cdot r_{1j}, \cdots, w_n, r_{nj}\right] \tag{30}$$

$M(\wedge, \oplus)$ means the operation of taking small one first and then summing up; the equation is expressed as:

$$b_j = \sum_{i=1}^{n} w_i \wedge r_{ij} = \sum_{i=1}^{n} \left[\min\left(a_i, r_{ij}\right)\right],\quad j = 1, 2, \cdots, m \tag{31}$$

$M(\cdot, \oplus)$ denotes the operation of multiplying first and then summing, where the equation is expressed as:

$$b_j = \sum_{i=1}^{n} w_i \cdot r_{ij}, \quad j = 1, 2, \cdots, m \tag{32}$$

Because $M(\cdot, \oplus)$ is calculated according to the weight of each factor, which is more reasonable than other methods, the fuzzy operator method is used in this study for fuzzy comprehensive evaluation.

III. CASE STUDY OF A TEACHING BUILDING IN A UNIVERSITY

A. BASIC OVERVIEW OF A UNIVERSITY TEACHING BUILDING

This study selects the Yifu Teaching Building of a Beijing university, which is located in the northwest corner of the school. It covers an area of about 2931 m^2, including a basement (with the height of −4.2 m), 9 floors (including the first floor to the second floor with the height 4.8 m each, and the third floor to the ninth floor with the height 4.5 m each). The basement and the ninth floor are generally not open to the public. The eighth floor is the computer room. The main floors of the classroom for students are generally on the 1st-7th floors. According to the architectural design of the teaching building, elevators can be taken on Floor 4 and above. In the event of an emergency, when the high-floor students choose evacuation paths, the situation will be complicated due to students' weak safety awareness and uncertain decision making, And according to the classroom curriculum arrangement and activity statistics, the classroom schedule and staff density of the first floor to the third floor of the building are much higher than other floors, so this study selects the 1-3 floors of the teaching building as the main research object. This is a case study. After investigation, it was found that there were mainly the following problems:

1) COMPLEX STRUCTURAL LAYOUT

The shape of the building structure of the Yifu teaching building is U-shaped. According to the personnel survey and analysis, most students are unclear about the distribution of classrooms and emergency exits in the teaching building. Some exits in the teaching building are not open, the emergency exits are hidden, and the evacuation signs are not clear. These problems will affect the personnel to choose the evacuation route and the evacuation speed of the crowd.

2) THE DISTRIBUTION OF PERSONNEL IS DENSE AND UNEVEN

The capacity of the teaching building is large. The buildings on the first to third floors alone can accommodate 2,780 people. With the increase in the number of college enrollment in recent years, there is almost no vacancy in the scheduling of each classroom in the teaching building. Because the structure of the teaching building is U-shaped, the distribution of classrooms on each corner is relatively dense, and the number of students will also be relatively large. Once an emergency occurs, the safety problem of evacuation will be very serious.

3) WEAK SECURITY MANAGEMENT

In addition to the floor manager, the teaching building lacks special security management personnel to conduct hidden safety inspections and daily safety inspections in the teaching building. No special safety evacuation education and emergency evacuation drills are organized. Students are unfamiliar with the emergency evacuation process and evacuation route. Once an emergency occurs, there will be problems such as lack of emergency capacity.

B. DETERMINATION OF THE WEIGHT OF EVALUATION INDICATORS

1) ESTABLISHING A FUZZY COMPARISON MATRIX

In the previous section, basic events of the trampling accident were determined using the fault tree analysis method. According to design principles of the index system, the index system for evaluating emergency evacuation ability of the university teaching building was determined qualitatively. The following is an analysis of the emergency evacuation ability of college and university teaching buildings from the perspective of the occurrence of trampling accidents using the fuzzy comprehensive evaluation method. The index factors of different index layers of the comprehensive teaching building are shown in Tables 3 and 4.

TABLE 3. Index of emergency evacuation capacity of teaching building.

Target layer	First level indicator layer	Secondary indicator layer
Teaching building emergency evacuation ability	Personnel evacuation ability (A_1)	Rapid response capability (B_1)
		Self-protection awareness (B_2)
		Psychological quality (B_3)
		Physical fitness (B_4)
		Relevant knowledge mastery (B_5)
	Building evacuation capacity (A_2)	Safety exit conditions (B_6)
		Classroom distribution rationality (B_7)
		Emergency lighting (B_8)
		Ground slip resistance (B_9)
		Emergency evacuation instruction (B_{10})
		Evacuation channel condition (B_{11})
	Emergency management capability (A_3)	Emergency organization structure rationality (B_{12})
		Emergency agency capacity (B_{13})
		Emergency plan effectiveness (B_{14})
		Safe evacuation education (B_{15})
		Emergency evacuation drill (B_{16})

According to the theory of triangular fuzzy number and multi-objective fuzzy logarithmic programming, the importance of each index factor is quantitatively evaluated. Experts are provided with the scoring reference through structure importance result based on the accident tree analysis method.

TABLE 4. Three-level indicator system for evacuation channel conditions.

Secondary indicator layer	Three-level indicator
Evacuation channel condition (B_{11})	Smoothness of evacuation channels (C_1)
	Evacuation channel width (C_2)
	Number of evacuation corners (C_3)
	Channel structure (C_4)

Then 10 research members are invited to compare each indicator in each subsystem and score according to Table 2. The scoring rule is a comparison between the two factors. And the values are assigned based on the importance of the comparison that affects their evaluation goals. The importance is roughly divided into: equally important, slightly important, more important, very important, and extremely important. The scoring levels corresponding to each level of importance are: 1, 3, 5, 7, 9. The corresponding scoring levels between the two levels of importance are: 2, 4, 6, 8, and the reciprocal of the values respectively indicate the degree of relative insignificance. Evaluation criteria of fuzzy log-first programming theory adopts triangular fuzzy numbers to represent a small interval of importance, concerning for decision makers' hesitation in decision making. For example, when indicator a is compared with indicator b, the decision-maker's decision interval is hesitant between equally important and slightly important levels. And he is more inclined to take the middle value. Then the scoring level is 2 and the corresponding triangular fuzzy is obtained according to Table 2. The value is (1, 2, 3). According to the above scoring assignment criteria, the scoring results are shown in Table 5 to Table 9.

TABLE 5. Comparison matrix of emergency evacuation capacity of teaching buildings.

	A_1	A_2	A_3
A_1	(1,1,1)	(1/3,1/2,1)	(1,2,3)
A_2	(1,2,3)	(1,1,1)	(2,3,4)
A_3	(1/3,1/2,1)	(1/4,1/3,1/2)	(1,1,1)

TABLE 6. Comparison matrix of personnel escape ability.

	B_1	B_2	B_3	B_4	B_5
B_1	(1,1,1)	(1,2,3)	(1,2,3)	(1,1,2)	(1/3,1/2,1)
B_2	(1/3,1/2,1)	(1,1,1)	(1,1,2)	(1/3,1/2,1)	(1/4,1/3,1/2)
B_3	(1/3,1/2,1)	(1/2,1,1)	(1,1,1)	(1/3,1/2,1)	(1/4,1/3,1/2)
B_4	(1/2,1,1)	(1,2,3)	(1,2,3)	(1,1,1)	(1/3,1/2,1)
B_5	(1,2,3)	(2,3,4)	(2,3,4)	(1,2,3)	(1,1,1)

TABLE 7. Comparison matrix of building evacuation capacity.

	B_6	B_7	B_8	B_9	B_{10}	B_{11}
B_6	(1,1,1)	(1,2,3)	(2,3,4)	(1,2,3)	(2,3,4)	(1/3,1/2,1)
B_7	(1/3,1/2,1)	(1,1,1)	(1/3,1/2 ,1)	(1/2,1,1)	(1/3,1/2 ,1)	(1/4,1/3,1/2)
B_8	(1/4,1/3,1/2)	(1,2,3)	(1,1,1)	(1/3,1/2,1)	(1,1,2)	(1/5,1/4,1/3)
B_9	(1/3,1/2,1)	(1,1,2)	(1,2,3)	(1,1,1)	(1,2,3)	(1/4,1/3,1/2)
B_{10}	(1/4,1/3,1/2)	(1,2,3)	(1/2,1,1)	(1/3,1/2,1)	(1,1,1)	(1/5,1/4,1/3)
B_{11}	(1,2,3)	(2,3,4)	(3,4,5)	(2,3,4)	(3,4,5)	(1,1,1)

TABLE 8. Comparison matrix of emergency management capabilities.

	B_{12}	B_{13}	B_{14}	B_{15}	B_{16}
B_{12}	(1,1,1)	(1/3,1/2,1)	(1/3,1/2,1)	(1,2,3)	(1/4,1/3,1/2)
B_{13}	(1,2,3)	(1,1,1)	(1/2,1,1)	(2,3,4)	(1/3,1/2,1)
B_{14}	(1,2,3)	(1,1,2)	(1,1,1)	(2,3,4)	(1/3,1/2,1)
B_{15}	(1/3,1/2,1)	(1/3,1/2,1)	(1/4,1/3,1/2)	(1,1,1)	(1/4,1/3,1/2)
B_{16}	(2,3,4)	(1,2,3)	(1,2,3)	(2,3,4)	(1,1,1)

TABLE 9. Comparison matrix of evacuation channel conditions.

	C_1	C_2	C_3	C_4
C_1	(1,1,1)	(1,2,3)	(3,4,5)	(2,3,4)
C_2	(1/3,1/2,1)	(1,1,1)	(2,3,4)	(1,2,3)
C_3	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1,1,1)	(1/3,1/2,1)
C_4	(1/4,1/3,1/2)	(1/3,1/2,1)	(1,2,3)	(1,1,1)

2) ENTROPY LFMP METHOD TO CALCULATE WEIGHTS

First, the multiobjective fuzzy logarithm programming theory is used. And the weight of the evaluation index system factor is calculated using equation 12. The fuzzy judgment matrix of the target index layer obtained from Table 5 is as follows:

$$\tilde{A} = (\tilde{a}_{ij})_{3\times 3} = \begin{bmatrix} (1,1,1) & (\frac{1}{3},\frac{1}{2},1) & (1,2,3) \\ (1,2,3) & (1,1,1) & (2,3,4) \\ (\frac{1}{3},\frac{1}{2},1) & (\frac{1}{4},\frac{1}{3},\frac{1}{2}) & (1,1,1) \end{bmatrix} \tag{33}$$

Each indicator factor is transformed into a multiobjective fuzzy logarithm programming:

$$\begin{aligned} &\min\ J = (1-\lambda)^2 \\ &F = \sum_{i=1}^{2}\left(x_i^2 + \sum_{j=i+1}^{3}(x_j^2)\right) \\ &s.t. \begin{cases} -x_1 + x_2 + \lambda\ln(3/2) \le -\ln(1/3), \\ x_1 - x_2 + \lambda\ln(2) \le \ln(1), \\ -x_1 + x_3 + \lambda\ln(2) \le -\ln(1), \\ x_1 - x_3 + \lambda\ln(3/2) \le \ln(3), \\ -x_2 + x_3 + \lambda\ln(3/2) \le -\ln(2), \\ x_2 - x_3 + \lambda\ln(4/3) \le \ln(4), \\ x_1, x_2, x_3, \lambda \ge 0 \end{cases} \end{aligned} \tag{34}$$

Using MATLAB software to calculate, the optimal solution of the inequality is obtained.

We then calculate the weight result of the comparison matrix using formula (13):

$$\begin{aligned} w_1^* &= \exp(x_1^*)/\sum_{i=1}^{3}\exp(x_i^*) = 0.2995 \\ w_2^* &= \exp(x_2^*)/\sum_{i=1}^{3}\exp(x_i^*) = 0.5318 \\ w_3^* &= \exp(x_3^*)/\sum_{i=1}^{3}\exp(x_i^*) = 0.1687 \end{aligned} \tag{35}$$

Thus, the weight result of the target layer is: $w_1 = (0.2995, 0.5381, 0.1687)$

By analogy with the above steps, the weight results of other index factors at the index level are calculated.

The weights of the evacuation capability layer:

$$w_{21} = (0.2040,\ 0.1149,\ 0.1149,\ 0.2040,\ 0.3622)$$
$$\lambda = 0.8121$$

The weight of the building evacuation capability layer:

$$w_{22} = (0.2328,\ 0.0907,\ 0.1062,\ 0.1242,\ 0.1062,\ 0.3400)$$
$$\lambda = 0.2268$$

The weight of the emergency management capability layer:

$$w_{23} = (0.1312,\ 0.2273,\ 0.2273,\ 0.0928,\ 0.3214)$$
$$\lambda = 0.5000$$

Evacuation channel condition layer weight:

$$w_3 = (0.5136,\ 0.2924,\ 0.1027,\ 0.1913) \quad \lambda = 1.0000$$

The entropy weight method is then used to solve the triangular fuzzy contrast matrix. The horizontal confidence space $\alpha = 0.05$ and the index coefficient $\beta = 0.5$ are selected. The fuzzy contrast matrix of the first index layer can be transformed into:

$$A_1 = \begin{bmatrix} 2.3275 & 1.2390 & 4.2038 \\ 4.2038 & 2.3275 & 6.5313 \\ 1.2390 & 0.7758 & 2.3275 \end{bmatrix} \tag{36}$$

From the expression of entropy (18), the entropy value can be obtained:

$$H_1 = -\frac{1}{\ln 3}\sum_{j=1}^{4} p_{1j}\ln\left(p_{1j}\right) = 0.8977$$
$$H_2 = -\frac{1}{\ln 3}\sum_{j=1}^{4} p_{2j}\ln\left(p_{2j}\right) = 0.9101$$
$$H_3 = -\frac{1}{\ln 3}\sum_{j=1}^{4} p_{3j}\ln\left(p_{3j}\right) = 0.9273 \tag{37}$$

From the entropy weight formula (19), the corresponding entropy weight can be calculated:

$$f_1 = (0.3862,\ 0.3395,\ 0.2742) \tag{38}$$

Similarly, the entropy weight of other indicator levels can be obtained:

$$f_{21} = (0.2433, 0.1975, 0.1382, 0.2280,\ 0.1930)$$
$$f_{22} = (0.2064, 0.0541, 0.2113, 0.1968, 0.1826, 0.1488)$$
$$f_{23} = (0.2355, 0.1992, 0.2847, 0.1121, 0.1686)$$
$$f_3 = (0.2404, 0.3121, 0.1761, 0.2713) \tag{39}$$

Lastly, the weight determined by the multiobjective fuzzy logarithm programming and the weight determined by the entropy weight method are calculated using the formula (21).

$$W_i = \frac{f_i w_i}{\sum_{i=1}^{n} f_i w_i} = (0.3390,\ 0.5254, 0.1356) \tag{40}$$

This method performs the final calculation on the weights of different levels, and the final weight result is:

$$W_1 = (0.3390,\ 0.5254, 0.1356)$$
$$W_{21} = (0.2426, 0.1109, 0.0776, 0.2273, 0.3416)$$
$$W_{22} = (0.2829, 0.0289, 0.1321, 0.1439, 0.1142, 0.2979)$$
$$W_{23} = (0.1504, 0.2204, 0.3149, 0.0506, 0.2637)$$
$$W_3 = (0.4337, 0.3205, 0.0635, 0.1823) \tag{41}$$

C. FUZZY COMPREHENSIVE EVALUATION

1) ESTABLISHING AN INDICATOR FACTOR LEVEL REVIEW SET

The factors affecting its emergency evacuation ability can be divided into three categories: human, architecture and management. Each index layer has specific index factors. The index factors are divided into qualitative quantitative indicators. The quantitative indicators in this study, referring to the design requirements for emergency evacuation of persons in the code for fire protection design of buildings (GB50016, 2014), are five grades – excellent, good, general, weak and very weak. Results are shown in Table 10.

TABLE 10. Quantitative indicator ranking.

Grade	Very weak	Weak	General	Good	Excellent
Safety exit conditions (number of evacuations)	>500	400-500	300-400	200-300	≤200
Safety education (frequency of annual education)	0	1	2	3	>4
Emergency evacuation exercise (annual exercise frequency)	0	0.2	0.5	1	>2
Evacuation channel width	<1.1	1.1-1.2	1.2-1.3	1.3-1.4	≥1.5
Number of evacuation corners	>6	5	4	3	≤2
Channel structure	S type	U type	T type	L type	Straight type

Due to the different grade conditions of different stairs, passages and exits of the teaching building, the actual comments are ambiguous. For qualitative indicators, scores were taken in the form of questionnaires, which were composed by 6 professors in the field of emergency research and 20 students in the research direction of safe evacuation. In this study, the weight of the expert score is twice the weight of the student's score. The detailed grade score and the corresponding index level are shown in Table 11 and Table 12.

2) PERFORM FUZZY COMPREHENSIVE EVALUATION

The following results are obtained by using equations (15) and (16):

Fuzzy evaluation of secondary indicators. The fuzzy matrix composed of the three-level indicator evaluation

TABLE 11. Subordinate grade of secondary index.

Target layer	Primary evaluation index	Secondary evaluation index	Very weak	Weak	General	Good	Excellent
Teaching building emergency evacuation ability	Personnel escape ability	Rapid response capability	0	0.063	0.250	0.562	0.125
		Self-protection awareness	0.062	0.250	0.500	0.125	0.063
		Psychological quality	0.125	0.375	0.375	0.125	0
		Physical fitness	0.125	0.375	0.375	0.063	0.062
		Relevant knowledge mastery	0.063	0.250	0.500	0.125	0.062
	Building evacuation capacity	Safety exit conditions	0.333	0	0.333	0.167	0.167
		Classroom distribution rationality	0.063	0.500	0.250	0.187	0
		Emergency lighting	0.063	0.187	0.437	0.250	0.063
		Ground slip resistance	0.125	0.437	0.313	0.125	0
		Emergency evacuation instruction	0	0.250	0.375	0.250	0.125
	Emergency management capability	Emergency organization structure rationality	0	0.375	0.375	0.250	0
		Emergency agency capacity	0	0.250	0.500	0.250	0
		Emergency plan effectiveness	0.125	0.375	0.437	0.063	0
		Safe evacuation education	0.25	0.5	0.25	0	0
		Emergency evacuation drill	0	0.5	0.5	0	0

TABLE 12. Three-level indicator subordinate grade of secondary index.

Secondary evaluation index	Three-level indicator evaluation index	Very weak	Weak	General	Good	Excellent
Evacuation channel condition	Smoothness of evacuation channels (C_1)	0	0.125	0.250	0.500	0.125
	Evacuation channel width (C_2)	0	0	0	0.333	0.667
	Number of evacuation corners (C_3)	0.067	0.267	0.067	0.266	0.333
	Channel structure (C_4)	0	0.6	0.2	0.2	0

set is:

$$R_3 = \begin{bmatrix} 0 & 0.125 & 0.25 & 0.5 & 0.125 \\ 0 & 0 & 0 & 0.333 & 0.667 \\ 0.067 & 0.267 & 0.067 & 0.266 & 0.333 \\ 0 & 0.6 & 0.2 & 0.2 & 0 \end{bmatrix} \tag{42}$$

The corresponding weight set is: $W_3 = (0.4337, 0.3205, 0.0635, 0.1823)$, the evaluation result is:

$$\begin{aligned} X_3 &= W_3 \cdot R_3 \\ &= (0.4337,\ 0.3205,\ 0.0635,\ 0.1823) \\ &\quad \cdot \begin{bmatrix} 0 & 0.125 & 0.25 & 0.5 & 0.125 \\ 0 & 0 & 0 & 0.333 & 0.667 \\ 0.067 & 0.267 & 0.067 & 0.266 & 0.333 \\ 0 & 0.6 & 0.2 & 0.2 & 0 \end{bmatrix} \\ &= (0.0043,\ 0.1805,\ 0.1491,\ 0.3769,\ 0.2891) \end{aligned} \tag{43}$$

According to the principle of maximum membership, the maximum membership degree of the evacuation channel condition is 0.3769, and the corresponding level is "good."

Fuzzy evaluation of the first-level indicators. Taking the evacuation ability as an example, the fuzzy matrix comprising the evaluation set is:

$$R_{21} = \begin{bmatrix} 0 & 0.063 & 0.25 & 0.562 & 0.125 \\ 0.062 & 0.25 & 0.5 & 0.125 & 0.063 \\ 0.125 & 0.375 & 0.375 & 0.125 & 0 \\ 0.125 & 0.375 & 0.375 & 0.063 & 0.062 \\ 0.063 & 0.25 & 0.5 & 0.125 & 0.062 \end{bmatrix} \tag{44}$$

The corresponding weight set is: $W_{21} = (0.2426, 0.1109, 0.0776, 0.2273, 0.3416)$, and the evaluation result is:

$$\begin{aligned} X_{21} &= W_{21} \cdot R_{21} \\ &= (0.2426,\ 0.1109,\ 0.0776,\ 0.2273,\ 0.3416) \\ &\quad \cdot \begin{bmatrix} 0 & 0.063 & 0.25 & 0.562 & 0.125 \\ 0.062 & 0.25 & 0.5 & 0.125 & 0.063 \\ 0.125 & 0.375 & 0.375 & 0.125 & 0 \\ 0.125 & 0.375 & 0.375 & 0.063 & 0.062 \\ 0.063 & 0.25 & 0.5 & 0.125 & 0.062 \end{bmatrix} \\ &= (0.0665,\ 0.2502,\ 0.4012,\ 0.2169,\ 0.0726) \end{aligned} \tag{45}$$

The maximum membership degree is 0.4012, and the corresponding rating is "general."

Similarly, the evaluation result of building evacuation ability is: $X_{22} = (0.1236,\ 0.1344,\ 0.3914,\ 0.1945,\ 0.1560)$. The maximum membership is 0.3914, and the corresponding rating is "general."

The evaluation results of emergency management capabilities are: $X_{23} = (0.0520,\ 0.3867,\ 0.4487,\ 0.1125,\ 0)$. The maximum membership degree is 0.4487, and the corresponding level is "general."

Fuzzy comprehensive evaluation of target layer. The fuzzy matrix of the target layer level score obtained from the above calculation results is:

$$R_1 = \begin{bmatrix} 0.0665 & 0.2502 & 0.4012 & 0.2169 & 0.0726 \\ 0.1236 & 0.1344 & 0.3914 & 0.1945 & 0.1560 \\ 0.0520 & 0.3867 & 0.4487 & 0.1125 & 0.0000 \end{bmatrix} \tag{46}$$

Its weight is: $W_1 = (0.3390, 0.5254, 0.1356)$, the evaluation result is:

$$X^* = (0.0945,\ 0.2079,\ 0.4025,\ 0.1920,\ 0.1066) \quad (47)$$

According to the principle of maximum membership degree, the maximum membership degree of emergency evacuation capacity of the teaching building in the school is 0.4025. And the corresponding level is "general." Therefore, the emergency evacuation capacity must be improved, and there is a risk in emergency evacuation in an emergency.

Recommendations include installing emergency evacuation broadcasts in the classroom, installing safety exit signs in corridors and stairwells, establishing a complete information system, widening the evacuation channel, strengthening the safety channel maintenance, and improving the safety literacy of the personnel. According to the distribution of classrooms, the width of the passages and the height of the floors, the classrooms should be used reasonably to improve their emergency evacuation capacity.

IV. CONCLUSIONS

Based on the perspective of stampede accident during emergency evacuation, this study conducted deductive analysis and research, and analyzed the different events that caused the accident. According to the track crossing theory and the accident tree analysis method, the corresponding basic events and the structural importance of different intermediate events were deduced. The index system for evaluating the emergency evacuation ability of university teaching buildings was established from the perspective of man-building-management. The indicators included three levels, including three evaluation factors in the first-level indicator layer, 16 evaluation factors in the second-level indicator layer, and four evaluation factors in the third-level indicator layer for evacuation channel conditions. In addition, it can also provide an effective basis for the establishment of safety risk assessment index system in other crowded public buildings.

The decision-making preference of the traditional subjective weighting method is too strong, while the objective weighting method relies more on measured data. This paper uses fuzzy mathematics to propose a new method of subjective and objective weighting. The hybrid weighting method formed by the combination of subjective weighting method and objective weighting method, namely entropy weight-logarithmic fuzzy multiobjective programming (E-LFMP). The weights after fusion can not only take into account the experience, knowledge and attitudes of decision makers, but also effectively use the measured data. The multi-objective fuzzy logarithmic programming method is used to subjectively determine the weight value of the index factor, and then the entropy weight method is used to objectively determine the weight. Finally, the weighted average method is used to fuse the newly proposed subjective and objective weights, and the method is applied to emergency The new field of evacuation evaluation confirmed the feasibility and practicability of the method through examples, making the results more objective and reasonable.

Taking a university teaching building as a research object for case analysis, the maximum membership degree of the teaching building is 0.4025, and the corresponding level is "general", indicating that its emergency evacuation ability is not ideal. Combined with the weight ratio and grade results of various index factors in the evaluation model of emergency evacuation capacity of university teaching buildings, this study proposes safety rectification suggestions in terms of establishing a complete information system, widening evacuation channels and strengthening the maintenance of safety channels.

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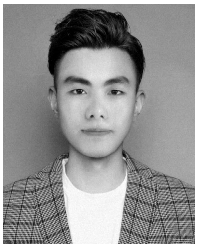

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