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Elevator Safety Risk and Countermeasures based on FTA-TFN

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Abstract: Aiming at problems that elevator security risk research works mainly focus on safety evaluation with less consideration of the risk factors contributing to the accidents mechanism. This paper proposes the method of fault tree analysis (FTA), and introduces the fuzzy numbers in order to improve the reliability of safety risk analysis. Fault Tree Analysis addresses the internal mechanism of the elevator accident caused by risk factors, and crucial aspects of accident control. Moreover, it assesses the probability of accidents more accurately. Then, the triangular fuzzy number (TFN) is taken to address the problem of no statistical probability or imprecise probability of data processing during the process of accident analysis, and improves the reliability of the analysis. Practical application shows that this method can obtain the clear pivotal factors affecting the elevator safety accidents and provide a reliable assessment of an accident probability. At the same time, it facilitates the proposing of risk prevention and controlling measures which enhances the safety management level of the elevator effectively.

Keywords: Elevator, fault tree, security risks, triangular fuzzy numbers

1 Introduction

The relationship between people's lives and the elevator becomes closer and closer, While more and more security issues are gradually exposed. Elevator accident possesses some special characteristics, such as ambiguity, explosive, destructive and bad social effect etc.. Elevator accidents not only cause huge economic losses each year, but also result in the thousands of people's death, which call for higher requirement of the elevator accident risk prevention [1]. Therefore, the analysis of elevator's security risks and countermeasures research can be of great significance.

At present, the domestic studies on elevator safety risk primarily focus on the safety evaluation, in other words the elevator safety is studied with the application of certain evaluation methods through the establishment of a the elevator safety evaluation indicator system. Xu-Yi Gu and Chang-Ming Zhu [2] have proposed a multi-factor risk assessment methods and a criteria of systematic security evaluation to achieve a comprehensive safety evaluation for the elevator system. Zhang Dongping [3] proposes the safety assessment method based on expert system. And the method is applied to the situation grading of the elevator security, improving the systematicness and scientificity of the elevator safety evaluation. Shi Kai [4] has carried on the discussion on the safety of the elevator in China from several aspects, including elevator personnel qualifications, elevator pre-inspection work, the daily maintenance and so forth. Li Xiaoning, and Zheng Xiangpan [5] establish the multilayered comprehensive evaluation for the elevator safety risk assessment model, and analyze the identification between dangerous plot and sources of risks based on risk principles. As can be seen from the current studies of elevator safety evaluation: the scientificity of evaluation system is limited due to the evaluation of influences factors, the great ambiguity, and the complex interaction between factors. The evaluation methods contain people's subjective consciousness, which may lead to the problem that the internal mechanism of elevator accidents cannot be reflected objectively. There are also shortcomings in the reliability of the evaluation results.

Accordingly, this paper adopted the safety engineering theory as a guidance. For the most common door system accident of elevator accident, the paper analyzes the impact of various factors of the accident, and combines the fault tree theory and triangular fuzzy

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numbers to create a fault tree - fuzzy number model. The model is applied to research internal interaction between various factors and the cause of the accident mechanism. A more accurate assessment of probability of door systems accident contributes to a more objective and scientific research on elevator accident. The practical application results show that the proposed method has a certain significance in the preventing and controlling of elevator accident risks.

2 Fault tree - Fuzzy number (FTA-TFN) model

2.1 Fault tree - Fuzzy number (FTA-TFN) model

The fault tree is a causal and logical tree diagram, which looks like an inverted tree, for describing interaction among the various factors that lead to accidents [15, 16]. Fault Tree Analysis (FTA) is not only a logicalvisual accident analysis method, but also easy to be accepted. It is capable of analyzing of all possible combinations of factors contributing to accidents comprehensively.

The fault tree graphic symbols include the event symbols and the logic gate symbols. The event symbols are as shown below (Fig.1):

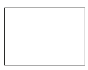
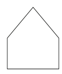
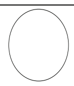
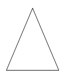
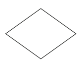
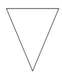
Name of Event	Graphic symbols	Name of Event	Graphic symbols
Resultative Events		Switching Events	
Basic Events		Inductive Events	
Omitted Events		Derivative Events	

Fig. 1: Event Symbols of Fault Tree

Based on the existing researches as well as the help of experts who devote themselves to the inspection of electromechanical equipment in the XX Special Inspection Institute [6–14], the paper builds an the incident list of security accidents for the elevator door system as follows (Table 1).

In the Fault Tree, the causality or logical relationships among events are expressed by the logic gates. Logic gates in the fault tree analysis (FTA) and graphic symbols corresponding to it are indicated as follows (Fig.2).

Fault Tree Analysis (FTA) employs logic gates and relating symbols to represent logical relationship between the basic events and resultative events. The method ultimately determines the relationship between the top event and basic events by reasoning out progressively, so as to establish the fault tree model [19–21]. On this basis, the emphasis of accident prevention and control is confirmed through the analysis of the accident factors according to certain principles of operation (the construction of Fault Tree shown in Fig.4).

Because the actual object usually possesses lots of ambiguity, at the same time, the basic events often lack sufficiently accurate statistical probability, therefore, the introduction of fuzzy numbers is essential during the fault tree analysis,. The triangular fuzzy number (TFN) applied to analyze the fault tree in the paper is more mature, whose function is structured as follows [17, 18]:

$$f(x) = \begin{cases} \frac{x-m+1}{l} & l \le x \le m \\ \frac{m+u-x}{u} & m \le x \le u \\ 0 & \text{others} \end{cases} \quad (1)$$

Abbreviated as $q = (l, m, u), \quad 0 \le l \le m \le u.$

The algorithm of triangular fuzzy number is as follows:

$$\begin{aligned} &\widetilde{q_A} + \widetilde{q_B} = (l_1, m_1, u_1) + (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \\ &\widetilde{q_A} - \widetilde{q_B} = (l_1, m_1, u_1) - (l_2, m_2, u_2) = (l_1 - l_2, m_1 - m_2, u_1 - u_2) \\ &\widetilde{q_A} \cdot \widetilde{q_B} = (l_1, m_1, u_1) \cdot (l_2, m_2, u_2) = (l_1 \cdot l_2, m_1 \cdot m_2, u_1 \cdot u_2) \\ &C \cdot \widetilde{q_A} = (C \cdot l_1, C \cdot m_1, C \cdot u_1) \end{aligned} \quad (2)$$

(1)Fuzzy processing of basic events without statistical probability

The probability of basic event without statistical probability is evaluated by the panel of experts (usually three or more), who apply the 3 method to calculate the range of the average probability value [23, 25]. While the letter “m” is the average value of the probability estimated, and is standard deviation. According to statistical regularities, the confidence interval will be $[m - 3, m + 3]$ and the confidence level is 99.7%.

$$\begin{aligned} &m = E(x) = \frac{1}{n}(q_1 + q_2 + \ldots + q_n) \\ &\sigma = \frac{1}{n}\sqrt{\sum_{j=1}^{n}(x_j - E(x))^2} \end{aligned} \quad (3)$$

Among them, q_n is the probability estimated by experts; n is the number of the experts; x_j represents the probability of the j.

(2)Fuzzy processing of imprecise statistics

Assume that the statistical probability of a basic event is q, then its fuzzy process is as follows: taking $q = m$, the upper and lower bounds of fluctuations in the value given by experts are u and l, then the distribution of fuzzy probability is between $m - l$ and $m + u$.

Table 1: The event list of door system

Code	Name of Basic Events	Code	Name of Resultative Events
X_1	Illegal operation	T	Top Event
X_2	Flaws of installation design	A_1	Extrusion
X_3	Not timely overhaul	A_2	Shearing
X_4	Lack of management of handover	A_3	Falling
X_5	Undocumented work	B_1	People at risk position
X_6	Lack of contingency plan	B_2	Failure of closed protective device
X_7	Lack of training	B_3	The elevator suddenly started
X_8	Normal call	B_4	Falling of car door
X_9	Normal riding	B_5	Falling of layer portal
X_{10}	Weak sense of security	...	...
X_{11}	Lack of safety publicity		
X_{12}	Elevator outage, people trapped		
X_{13}	Elevator car not in flat layer		

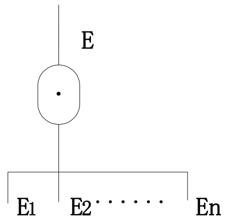
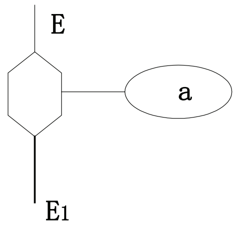
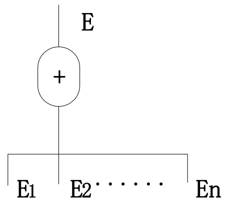
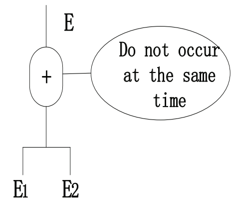
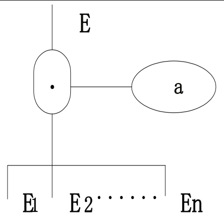
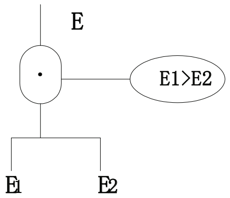
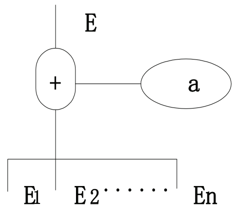
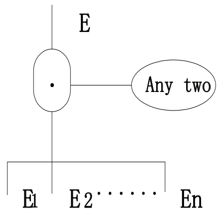
Name of logical gates	Graphic symbols	Name of logical gates	Graphic symbols
And gate		Inhibition gate	
OR gate		Exclusive-or gate	
Condition AND gate		Order of the finite AND gate	
Condition OR gate		Order of the infinite AND gate	

Fig. 2: Graphic symbols of Logical gates

2.2 Fault Tree Analysis indicators

The mathematical description of fault tree based on the structure function is as follows:

$$x_i = \begin{cases} 1 \text{ Unit i happens} \\ 0 \text{ Unit i doesn't happen} \end{cases} \quad (i = 1, 2, \ldots, n)$$
$$y = \begin{cases} 1 \text{ Top event happens} \\ 0 \text{ Top event doesn't happen} \end{cases} \tag{4}$$

Wherein, $y = (x)$ is known as the structure function of the system.

Fault tree employs Boolean algebra rules to compute, and transforms Boolean functions into disjunctive and conjunctive form according to the feature of Boolean algebra [24]:

Disjunctive standard form:

$$f = A_1 + A_2 + \ldots + A_n = \sum_{i=1}^{n} A_i \tag{5}$$

Conjunctive standard form:

$$f = B_1 \cdot B_2 \cdot \ldots \cdot B_n, \quad B_n = \sum_{i=1}^{n} B_i \tag{6}$$

After the Fault Tree Analysis, several important indicators can be obtained as follows [22, 26–29]:

(1)Minimal cut sets

Cut set is a collection of basic events on condition that the top event must occur when these events occur. If a cut set is no longer a cut set when its any event is removed, then the cut set is called minimal cut set. It is the smallest combination of basic events contributing to the occurrence of the top event.

It won' be stopped to use the next layer of events to represent a layer of events from the top of the fault tree following the bottom up approach, until the top event is indicated by all the basic events in Boolean expressions. Then, the minimal cut sets can be obtained after transforming the Boolean expressions into the briefest disjunction.

(2)Minimal path sets

Trail set is a collection of some of the basic events of the fault tree. When these events do not occur, the top event must not occur. If a path set is no longer a path set when its any basic event is removed, then the path set is called minimal path set. It is the smallest combination of basic events that cannot result in the occurrence to the top event. The minimal path set is a necessary and sufficient condition for the non-occurrence of the top event.

The general method applied to seek the minimal path set is the Dual Tree method, that is to say, to convert the fault tree into the dual success tree. The minimal cut sets obtained is the minimal path set sought. The conversion examples of the dual success tree are as follows (Fig.3):

(3)Structure importance

The structure importance of fault tree doesn't take the size of the probability of each event into account, but considers the status of each basic event in the fault tree and the influence degree to the top event based solely on the structure of fault tree.

When the state of a basic event X_i turns from 0 to 1 (ie 0i li) while the status of the other basic events remain unchanged, the change in the status of the top event may have three cases:

$$\phi(X) = \begin{cases} \text{State changes from 0 to 1} \\ \text{Keep state 0 unchanged} \\ \text{Keep state 1 unchanged} \end{cases} \tag{7}$$

Of these, only the first case describes that the basic event X_i has played an important role in the occurrence of the top event. Thus the structure importance is calculated as follows:

$$I_{\phi(i)} = \frac{1}{2^{n-1}} \sum [\phi(1_i, X) - \phi(0_i, X)] \tag{8}$$

Wherein, n represents the number of basic events. This calculation method is complicated, usually calculating by means of a truth table or software.

(4)Probability of top event

The probability of the top event is calculated by the minimal cut sets and minimal path sets. In general, it is more precise to get solutions through the minimal cut sets.

1) No duplication of basic events within minimal cut sets

When there is no duplication of basic events among the various minimal cut sets, the calculation can follow step-by-step algorithm directly. At first, the probability plot of basic events in various minimum cut sets is obtained, and then the summation of probability of each minimal cut sets is calculated. Formula is as follows:

$$T = \coprod_{j=1}^{m_j} \prod_{x_i \in m_j} q_i = 1 - \prod_{j=1}^{m} (1 - \prod_{i=1, x \in m_j}^{n} q_i) \tag{9}$$

In the formula, M_j represents the j^{th} minimal cut set; j is the sequence number of minimal cut set; m is the total number of minimal cut sets; x_i is the i^{th} event which belongs to the j^{th} minimal cut set.

2)Minimal cut sets with duplicate basic events

When various minimal cut sets include duplication of events, the repeated factor of the probability product in the above formula must be removed. It can be solved through the following equation:

$$T = \sum_{j=1}^{m} \prod_{x_i \in m_j} q_i - \sum_{1 \le j < k \le m} \prod_{x_i \in m_j \bigcup m_k} q_i + \cdots + (-1)^{m-1} \prod_{j=1, x_i \in m_j} q_i \tag{10}$$

In the formula, the letter "j" , "k" are both the codes of minimal cut sets; the expression $x_i \in m_j \bigcup m_k$ represents that the i^{th} basic event belongs to both of two minimal cut sets m_j and m_k. The formula can be seen as the general form of the formula in the first case, and it comes from the expandedness of the first formula.

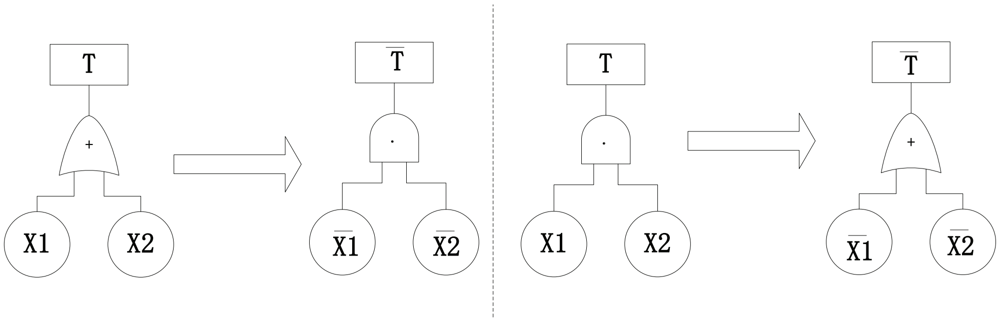


Fig. 3: The conversion examples of the dual success tree

3 Applied Research

Types of elevator safety incidents include the door system accident, hoisting, squatting bottom and other accidents. Among them, the proportion of the door system accident is about 80%, which is the largest. And therefore, the research on the security risks of the elevator door system research is carried out. The door system accident refers to the shearing, extrusion and fall accident, which has the biggest loss and is also the most common accident.

3.1 Construction of the fault tree of elevator door system

The influencing factors of the accident are analyzed on the basis of clarifying the elevator door system accident. Taking the XX elevator as the object of research, and the fault tree of the door system security incidents is constructed as shown below (Fig.4).

3.2 Qualitative analysis of fault tree of the elevator door system

According to the rules of Boolean algebra, the qualitative analysis results of fault tree of the elevator door system are as follows:

(1)Minimal cut sets

$$\begin{aligned}
T &= A_1 + A_2 + A_3 \\
&= (B_1 \cdot B_2) + (B_1 \cdot B_3) + (B_4 \cdot B_5) \\
&= \cdots \\
&= (X_2 \cdot X_{10}) + (X_4 \cdot X_{11} \cdot X_{13}) + (X_2 \cdot X_1) + (X_5 \cdot X_{12}) \\
&+ (X_1 \cdot X_8) + (X_3 \cdot X_1) + (X_3 \cdot X_{10}) + (X_2 \cdot X_9) \\
&+ (X_{10} \cdot X_{12}) + (X_3 \cdot X_9) + (X_{11} \cdot X_{12}) + (X_5 \cdot X_{13}) \\
&+ (X_1 \cdot X_{13}) + (X_2 \cdot X_7 \cdot X_{13}) + (X_4 \cdot X_7 \cdot X_{13}) \\
&+ (X_3 \cdot X_7 \cdot X_{13}) + (X_2 \cdot X_{11}) + (X_6 \cdot X_{12}) \\
&+ (X_7 \cdot X_{10}) + (X_3 \cdot X_{11})
\end{aligned} \tag{11}$$

Thus the obtained minimal cut sets of fault tree of the elevator door system are shown as follows: $\{X_2\ X_{10}\}, \{X_4\ X_{11}\ X_{13}\}, \{X_2\ X_1\}, \{X_5\ X_{12}\}, \{X_1\ X_8\}, \{X_3\ X_1\}, \{X_3\ X_{10}\}, \{X_2\ X_9\}, \{X_{10}\ X_{12}\}, \{X_3\ X_9\}, \{X_{11}\ X_{12}\}, \{X_5\ X_{13}\}, \{X_1\ X_{13}\}, \{X_2\ X_7\ X_{13}\}, \{X_4\ X_7\ X_{13}\}, \{X_3\ X_7\ X_{13}\}, \{X_2\ X_{11}\}, \{X_6\ X_{12}\}, \{X_7\ X_{12}\}, \{X_3\ X_{11}\}$. There are 20 ways in total, that is to say 20-way can result in a door system accident. Then the fault tree can be simplified for above 20 kinds of combinations, grassroots for And gate, high-level for OR gate.

(2)Minimal path sets

Apply the success tree method, derive the dual success tree of the fault tree , and then obtain the minimal cut sets of the success tree by employing Boolean algebra. The minimal cut sets obtained are the minimal path sets of the fault tree. From this, the combinations of basic events which cannot give rise to the top event are obtained. The calculation results are: $\{X_2\ X_1\ X_{12}\ X_3\ X_5\ X_4\}, \{X_2\ X_{11}\ X_1\ X_{12}\ X_3\ X_{10}\ X_5\ X_7\}, \{X_2\ X_{13}\ X_1\ X_{12}\ X_3\}, \{X_{10}\ X_{11}\ X_1\ X_5\ X_9\ X_7\ X_6\}, \{X_2\ X_{13}\ X_8\ X_{12}\ X_3\}, \{X_{10}\ X_{11}\ X_1\ X_{12}\ X_9\ X_5\ X_7\}, \{X_{10}\ X_{13}\ X_1\ X_{12}\ X_9\ X_{11}\}, \{X_2\ X_{11}\ X_1\ X_5\ X_3\ X_{10}\ X_7\ X_6\}, \{X_2\ X_{13}\ X_8\ X_5\ X_3\ X_{10}\ X_{11}\ X_6\ X_7\}$.There are 9 kinds of combination in total.

(3)Structure importance

The structure importance obtained by querying truth table is as shown:$I(1) = 0.1, I(2) = 0.117, I(3) = 0.117, I(4) = 0.033, I(5) = 0.05, I(6) = 0.025, I(7) = 0.075, I(8) = 0.025, I(9) = 0.05, I(10) = 0.075, I(11) = 0.092, I(12) = 0.125, I(13) = 0.117$. Sorted them by size is:

$I(12) > I(13) = I(2) = I(3) > I(1) > I(11) > I(10) = I(7) > I(9) = I(5) > I(4) > I(8) = I(6)$.

The structure importance of events rank as follow: elevator outage, people trapped > elevator car not in flat layer = flaws of installation design = not timely overhaul > illegal operation > lack of safety publicity > Weak sense of security = lack of training > normal riding = undocumented work > lack of management of handover > normal call = lack of contingency plan.

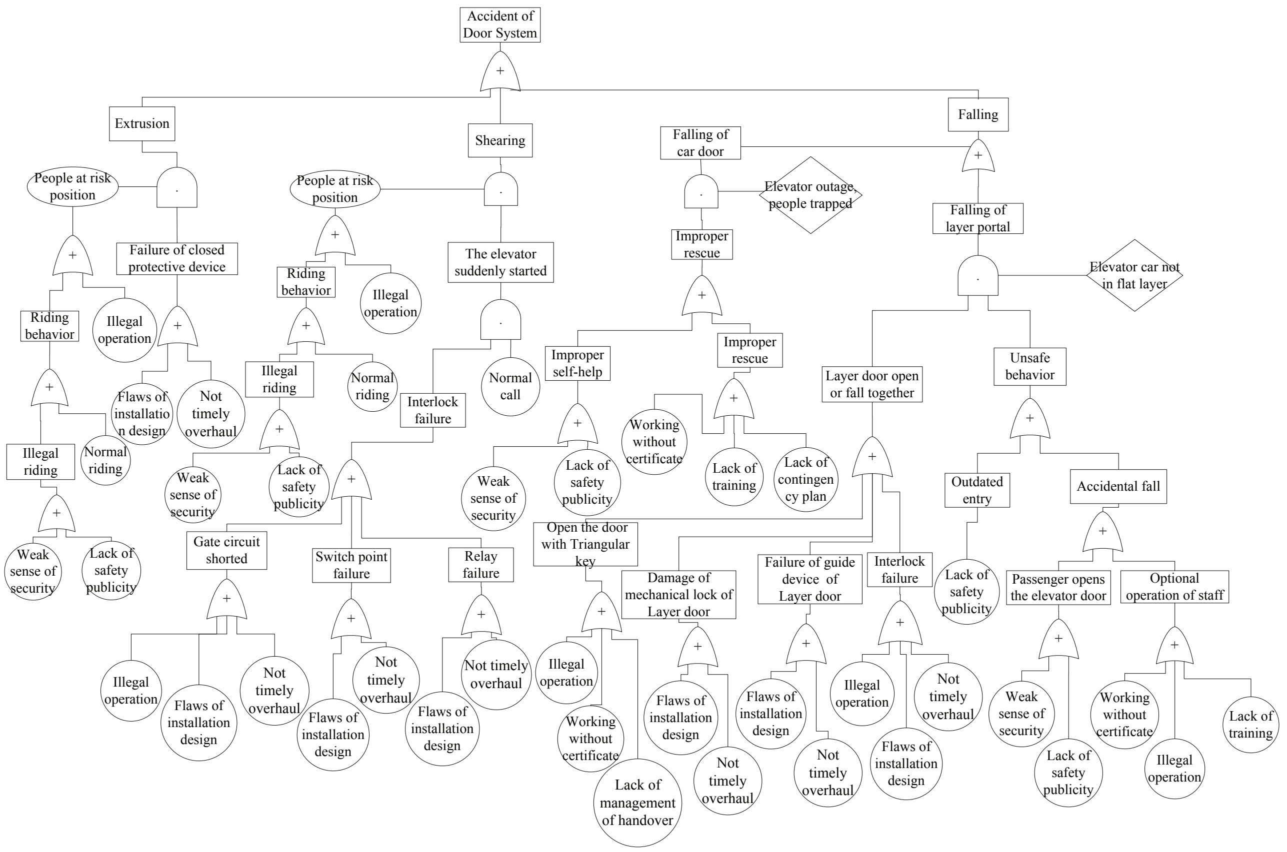


Fig. 4: Fault tree of accident of elevator door system

3.3 The fuzzy probability solving of elevator door system accident

Owning to the fact that the accurate and authoritative statistics are unable to obtain, thus part of the probability of basic events and expert's(electronic equipment expert in the XX Special Inspection Institute) estimate should be taken fuzzy processing. The results are listed in the following table (Table 2).

According to preceding paragraphs, the minimal cut sets of fault tree corresponding with elevator door system possess 20 kinds of combinations. The probability of the top event (elevator door system accident) calculated by the software is as follows:

$T \approx 0.03903$; Fluctuation range: $0.03561 \sim 0.04021$

The standard last year is less than 0.5 per million accidents in elevator door system. In accordance with the standard, the probability of the top event 0.03903 shows that the elevator is a serious security risk. Thus timely and effective measures should be taken to supervise and control basic events in each minimal cut set of Fault Tree Analysis.

3.4 The recommendations of the safety and risk prevention

Based on the foregoing analysis, the elevator exists serious hidden security problems. The prevention programs should be developed comprehensively and systematically from the aspects of personnel, equipment, environment and management. The specific recommendations are as follows:

(1)Focus on monitoring the elevator operation status of the cell. Urge the elevator maintenance companies and residential property to investigate comprehensively the hidden security risks of elevator equipments.

(2)Strictly examine the qualification of the residential elevator operator, maintenance and inspection personnel, and property management personnel who charges the elevator, further strengthen staff training and safety education.

(3)Special inspection departments should alert the residential property that the staff should implement strictly the provisions of the elevator safety management, improve the safety awareness of risk prevention, and give publicity to passenger about the knowledge of elevator safety.

Table 2: Results of Fuzzy Probability

Code One	Name of Basic events	Fuzzy of statistical probability
X_1	Illegal operation	$(0.001, 0.052, 0.002)$
X_2	Flaws of installation design	$(0.0005, 0.003, 0.0005)$
X_3	Not timely overhaul	$(0.008, 0.03, 0.008)$
X_4	Lack of management of handover	$(0.0010.0110.001)$
X_5	Undocumented work	$(0.0060.0230.004)$
X_6	Lack of contingency plan	$(0.0020.0060.002)$
X_7	Lack of training	$(0.010.0830.01)$
X_{11}	Lack of safety publicity	$(0.0070.020.007)$
X_{12}	Elevator outage, people trapped	$(0.00050.0020.0005)$
X_{13}	Elevator car not in flat layer	$(0.00050.0020.0005)$

Code Two	Name of Basic events	Valuation probability of expert	m	σ	(l, m, u)
X_8	Normal call	$(0.40, 0.50, 0.60)$	0.50	0.09	$(0.27, 0.5, 0.27)$
X_9	Normal riding	$(0.20, 0.30, 0.40)$	0.30	0.09	$(0.27, 0.30, 0.27)$
X_{10}	Weak sense of security	$(0.01, 0.01, 0.01)$	0.01	0	$(0, 0.01, 0)$

In accordance with the feedback, the above recommendations are adopted by local special inspection department, and are very effective for safety management of residential elevators in that residential area.

4 Conclusion

From the theory of safety engineering, the paper employs the fault tree and fuzzy mathematical theory to analyze many factors of special equipment (elevator) which can result in the accident, and the interaction mechanism among the factors. Moreover, the paper also assesses the probability of elevator accidents, and proposes prevention recommendations of security risk. The main results of the research are as follows:

(1)Under the guidance of safety engineering theory, the fault tree analysis method is selected (FTA) to analyze the various factors contributing to the elevator door system accidents. According to the results of fault tree analysis, the combinations of basic events leading to elevator door system accidents as well as the structure importance of the basic events in the fault tree are cleared, which provides more precise guidance for the investigation and prevention of elevator safety hazards.

(2)The problems of inaccurate and missing statistics are ordinary in the special equipment accident, and the triangular fuzzy numbers would make the probability of accidents more accurate. The presence of the trading range provides a good complement for the correction of the accident probability, making it more instructive and practical.

The fuzzy fault tree is taken to calculate the probability of special equipment accident, at the same time, amends them to obtain a more objective and realistic projections results through triangular fuzzy numbers. In addition, the study helps to enhance the capacity to prevent the safety risk of the special equipment, which has a certain significance for safety management of special equipment.

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