Chinese Science Bulletin

Improving analytic hierarchy process applied to fire risk analysis of public building

SHI Long†, ZHANG RuiFang, XIE QiYuan & FU LiHua

State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230027, China

The structure importance in Fault Tree Analysis (FTA) reflects how important Basic Events are to Top Event. Attribute at alternative level in Analytic Hierarchy Process (AHP) also reflect its importance to general goal. Based on the coherence of these two methods, an improved AHP is put forward. Using this improved method, how important the attribute is to the fire safety of public building can be analyzed more credibly because of the reduction of subjective judgment. Olympic venues are very important public buildings in China. The fire safety evaluation of them will be a big issue to engineers. Improved AHP is a useful tool to the safety evaluation to these Olympic venues, and it will guide the evaluation in other areas.

public building, fire risk analysis, AHP, FTA, Olympic venues

With the booming development of economy in China, office buildings of different grades have become popular in daily life. Higher requirements of fire safety in public buildings are claimed. Methods of how to evaluate more credibly have become more important. Currently, a lot of evaluation methods have been applied to fire safety in public building, such as Gustav Purt's fire risk evaluation method[1], Fuzzy comprehensive judge method[2], Event tree analysis[3,4], Fault tree analysis[5,6], Analytic Hierarchy Process[7,8].

Because of the limit of occurrence probability of basic events in FTA, the quantitative analysis was rarely used. In AHP, the analysis results were greatly dependent on judgment matrix, which was always influenced by our subjective judgment. In this paper, a combination of qualitative analysis in FTA with quantitative analysis in AHP is taken in order to reduce subjective judgment. It has significant meanings to fire risk analysis in public buildings and also other correlative areas.

The Olympic venues are significant buildings in public buildings. Every four years' Olympic games collected so much attention to it. Lots of fire cases warned safety managers of the fire safety in Olympic venues[9,10]. On May 11, 1985 the main stand of Bradford City Football Club caught fire. Fifty six people were burnt to death and about 250 injured. More and more engineers concentrated their attentions to fire safety of the Olympic venues, such as the National Stadium, National Aquatics Center, Peking University Gymnasium, etc. High personnel load, large spaces, complicated structures are the three important characters of these Olympic venues. How to evaluate fire risk of the Olympic venues more credibly is meaningful to engineers.

1 Basic principles

1.1 Fault tree analysis

Fault tree diagrams represent the logical relationship between sub-system and component failures and how they combine to cause system failures. It follows the logic analysis principle which deduces the reasons of fault events from results, and these factors are connected by logic gates. The way using fault tree to analyze the

Received April 10, 2008; accepted December 11, 2008
doi: 10.1007/s11434-009-0056-z

†Corresponding author (email: shilong@mail.ustc.edu.cn)

Support by the National Natural Science Foundation of China (Grant No. 50536030), National Project of Scientific and Technical Supporting Programs funded by Ministry of Science & Technology of China (Grant No. 2006BAK06B02) and China Postdoctoral Science Foundation (Grant No. 20070410220)

Citation: Shi L, Zhang R F, Xie Q Y, et al. Improving analytic hierarchy process applied to fire risk analysis of public building. Chinese Sci Bull, 2009, 54(8): 1442-1450, doi: 10.1007/s11434-009-0056-z

failures is called fault tree analysis[11–14].

If all basic events happened, it will lead to top event appearance. The combination of several basic events will also have the same effect and is called minimal cut set, meaning all the unique combination of component failures that would cause system failure. Every single cut set means a way to result top event appearance. Consequently, the larger number of cut sets represents the higher possibility of top event appearance. On the contrary, a union of opposite basic events will stop the top event appearance and is named minimal path set, meaning all the unique union of components assuring system safety. Each minimal path set means that there is a method to stop top event appearance, therefore, the larger number of minimal path sets means safer systems.

Many methods can be used to obtain minimal cut sets, Boolean Algebra Arithmetic and Fussell-Vesely methods are two of them[15]. Because of the duality of minimal cut set and minimal path set, the usual way to gain minimal path sets should first change fault tree to success tree by replacing the gates in an opposite way, for example replacing the AND gates to OR gates and OR gates to AND gates. So the minimal cut sets in success tree are the minimal path cuts in the original fault tree. To make it clear, each basic event in success tree should add an apostrophe which denotes the opposite event in fault tree.

Fault tree is made up of many basic events with different importance to the top event. The importance grade of basic events to top event can be gained when the occurrence probability of each basic event is the same. This kind of importance is called structure importance[14], and is given by:

$$I_{\varphi}(i)=\frac{1}{k}\sum_{j=1}^{m}\frac{1}{R_j}, \tag{1}$$

where k is the number of minimal cut or path sets in fault tree; m is the number of minimal cut or path sets containing the basic event i; R_j is the number of basic event minimal cut j or path set j which contains basic event i.

1.2 Analytic hierarchy process

Analytic Hierarchy Process is a system analysis method developed by Saaty[16,17] in 1970s. AHP model divides the complex system into three levels, namely the objective level (top level), the criteria level (middle level) and the alternative level (bottom level). By organizing and assessing alternatives against a hierarchy of multifaceted objectives, AHP provides a proven, effective means to deal with complex decision making. Furthermore, AHP allows a better, easier, and more efficient identification of selection criteria, as well as their weighting and analysis.

Generally, the objective level contains only one top goal and there are several factors at the middle level, and each factor is made up of some attributes at the alternative level. Based on the connection of each factor and attribute, AHP model will be built from the top to bottom just like tree structure. The attributes contained in the same factor at the objective level have effect to it, in the mean time, and each factor also affects the top goal.

To gain a judgment matrix, attributes belonging to the same factor at the criteria level are compared pair-wise in a quantitative way to express the relative preference. To construct the judgment matrix, there are a lot of scales[18] and 1—9 scales are the commonly used. The comparison scales of judgment and their meanings are shown in Table 1.

Table 1 The comparison scales of judgment and their meanings[19]

Scale	Verbal judgment of preferences
1	Equally preferred
3	Moderately preferred
5	Strongly preferred
7	Very strongly preferred
9	Extremely preferred
2, 4, 6, 8	Mean-value of two near situations above

After constructing the judgment matrix, weights of factors can be shown in the eigenvector of the matrix, which is related to the largest eigenvalue. Details are presented in Ref. [19] and [20].

2 Build AHP model by fault tree

2.1 Fault tree

The casualty in public building fire is mainly due to two reasons, one is the control failure of fire and the other is the evacuation failure. The fault tree with the top event in public building fire resulting in casualty is shown in Figure 1.

Reasons for casualty in public building begin with two middle events, i.e. fire spreading and evacuation failures, and twenty basic events are deduced according to these two middle events. The symbols and their meanings in this fault tree are shown in Table 2.

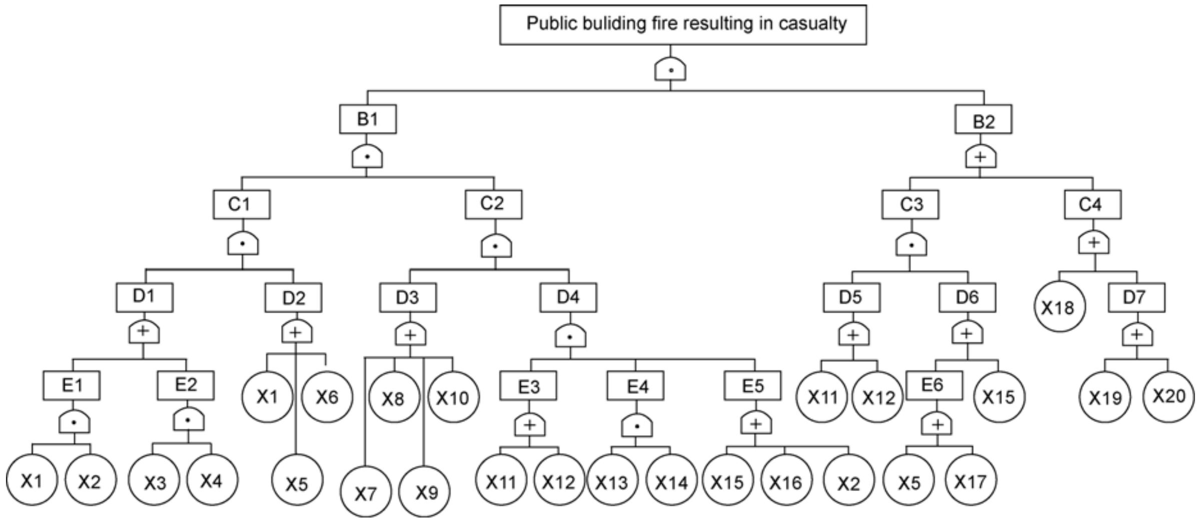

Figure 1 The fault tree of public building fire resulting in casualty.

Table 2 Symbols and their meanings in fault tree

Symbols and meanings	Symbols and meanings	Symbols and meanings
B1 Fire spread	E2 Unsuccessful fire-fighting of fire bridge	X8 Poor fire resistance rating
B2 Evacuation failure	E3 Poor fire-fighting capacity of building itself	X9 Smoke control system failure
C1 Fire happen	E4 No in time fire suppression	X10 Reasonless fire compartment
C2 Control fire failure	E5 Lack self-rescue capacity	X11 Lack fire-fighting capacity of fire bridge
C3 Self-rescue and rescue failure	F1 Inadvertent usage of open fire	X12 Long distant of fire station
C4 Cannot escape	F2 Electrical failure fire	X13 Fire hydrant system failure
D1 Exist hazards	X1 Lack daily safety inspection	X14 Sprinkler system failure
D2 Lack management	X2 Poor occupants' fire-prevention quality	X15 Fire alarm system failure
D3 Poor fire-resistant ability of building	X3 Lack safety facilities of distribution equipment	X16 Lack fire-fighting equipment
D4 Poor fire-fighting capacity	X4 Poor fire-resistant of electrical equipment	X17 Lack emergency plan and drill
D5 Rescue failure of fire bridge	X5 Lack safety knowledge propaganda	X18 High personnel load
D6 Self-rescue failure	X6 Poor management level	X19 Strait evacuation exits
D7 Poor evacuation capacity	X7 Fuel load in building	X20 No evacuation indicators or unclear
E1 Fire sources		

2.2 AHP model

Because of the different description between FTP and AHP, basic events in fault tree should be changed to attributes in AHP model by modifying the description to a neutral one. Then these attributes are classified into different factors at the criteria level, such as safety management, fire protection facilities, building structure and fire protection factors. The top goal is fire safety of public building. The AHP model constructed by fault tree is shown in Table 3.

2.3 Judgment matrix

In AHP model, judgment matrix (**A** or a_{ij}) can be constructed by pair-wise comparisons between factors at the same level. The judgment matrix is the analysis basic of AHP and the weight of factors to top goal can be obtained from it.

As the value of structure importance is fraction, it is too vague to express relative preference in pair-wise comparison. So the judgment factor is come out in formula 2. LCM is least common multiple of each denominator value, which comes from structure importance in formula 1.

$$\chi(i) = I_{\varphi}(i) \cdot \mathrm{g\,LCM}\,. \tag{2}$$

Judgment factor reflects the importance of basic events to top goal and can be used to construct judgment matrix by pair-wise comparison. As each factor at the criteria level contains several attributes at the alternative level, the judgment factor of each factor can be calculated by summing them up and is denoted as $\sum_{i=1}^{m} \chi(i)$.

Table 3 Analytic hierarchy process model

Objective level	Criteria level	Alternative level	
Fire safety of public building	Safety management (B1)	Daily fire safety inspection (X1)	Safety knowledge propaganda (X5)
		Safety facilities of distribution equipment (X3)	Management level (X6)
		Fire-resistant of electrical equipment (X4)	Emergency plan and drill (X17)
	Fire protection facilities (B2)	Smoke control system (X9)	Fire alarm system (X15)
		Fire hydrant system (X13)	Fire-fighting equipments (X16)
		Sprinkler system (X14)	
	Building structure (B3)	Fuel load in building (X7)	Evacuation exits (X19)
		Fire resistance rating(X8)	Evacuation indicators (X20)
		Fire compartment (X10)	
	Fire protection factors (B4)	Occupants' fire-prevention quality (X2)	Distant of fire station (X12)
		Fire-fighting capacity of fire bridge (X11)	Personnel load (X18)

Generally, a_{ij} in the judgment matrix always expressed as an integer and can be rounded as an integer, and is expressed by:

$$\begin{cases} a_{ij}=\dfrac{\sum_{i=1}^{m}\chi(i)}{\sum_{j=1}^{n}\chi(j)}, & \sum_{i=1}^{m}\chi(i)\geqslant\sum_{j=1}^{n}\chi(j), \\ a_{ji}=\dfrac{\sum_{j=1}^{n}\chi(j)}{\sum_{i=1}^{m}\chi(i)}, & \sum_{i=1}^{m}\chi(i)<\sum_{j=1}^{n}\chi(j), \end{cases} \tag{3}$$

where m, n denote the number of attributes belonging to each factor at the criteria level; i, j are row and line number in the judgment matrix respectively.

Each factor at the criteria level contains several attributes at the alternative level. At the alternative level, the judgment matrix by pair-wise comparisons is denoted as:

$$\begin{cases} a_{ij}=\dfrac{\chi(i)}{\chi(j)}, & \chi(i)\geqslant\chi(j), \\ a_{ji}=\dfrac{\chi(j)}{\chi(i)}, & \chi(i)<\chi(j), \end{cases} \tag{4}$$

where i, j are row and line number in the judgment matrix respectively.

3 The improved AHP

3.1 The combined weight

Utilizing the judgment matrix constructed by structure importance in FTA, the weight of each factor can be gained and is denoted as W'. The weight of each factor can also be gained through experts' judgment and is expressed as W'' in AHP. As the structure importance and the weight have the same effect on top event or goal, these two can be combined with each other to make the judgment more credible, and the combined weight can be expressed by:

$$W=\frac{\alpha W'+\beta W''}{\alpha+\beta}, \tag{5}$$

where α, β are the weight coefficients, which are the summation of scale factor (φ) and consistency ratio factor (ε).

Scale factor reflects the errors when different numerical scales are chosen. Similarly, the consistency ratio factor also relate to the errors in the calculation of judgment matrix. So the weight coefficient can be gained by combining these two factors together. Details will be expatiated in sections below.

3.2 The weight coefficient

3.2.1 Numerical scale for judgment matrix. Saaty compared 1—9 scales with other 26 kinds of numerical scales[20]. In the experiment, four chairs were placed in line and had the distances of 8.230, 13.716, 19.202, 25.603 meters from the light source respectively. The judger stood by the light source and judged the relative brightness of each chair. In this way, the judgment matrix was constructed. By calculating the eigenvector related to the largest eigenvalue, relative brightness (a_i) of each chair can be gained. In the mean time, actual relative brightness (b_i) can be obtained by the Light Intensity Law. Details are represented in ref. [20]. These two data arrays $a1$, a_2, ⋯, a_n and b_1, b_2, ⋯, b_n are compared by Root Mean Square (RMS)[20], which is expressed by:

$$\mathrm{RMS}=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(a_i-b_i)^2}\,. \tag{6}$$

RMS values reflect the credibility of judgment matrix and can be used to gain the scale factor (φ), and can be expressed by:

$$\varphi = 1 - \frac{RMS - R_{\min}}{R_{\max} - R_{\min}}, \tag{7}$$

where RMS is the root mean square of these two data arrays; $R_{\max}$ is the maximal value of RMS, which happens when 1—90 scales are chosen; R_{min} is the minimal value of RMS, which happens when 1—9 scales are chosen.

Different chosen numerical scales result in different RMS values. Scale factors can be obtained by formula 7, and are listed in Table 4.

3.2.2 Consistency check of judgment matrix. When the pair-wise comparisons are taken to construct judgment matrix, whose order is larger than two, there will be judgment errors as calculation process develops. Therefore, the consistency check is useful when the order of judgment matrix is larger than two. Consistency Index (CI)[19] is used for consistency check and goes as follow:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1}. \tag{8}$$

Consistency Ratio (CR) also reflects incredibility of a judgment matrix, and CR factor is expressed as:

$$\varepsilon = 1 - \frac{\mathrm{CR} - \mathrm{CR}_{\min}}{\mathrm{CR}_{\max} - \mathrm{CR}_{\min}} = 1 - 10\mathrm{CR}, \tag{9}$$

where $\mathrm{CR}_{\max}$ is the maximal value of CR and the value is 0.1; $\mathrm{CR}_{\min}$ denotes the minimal value of CR and the value is zero.

CR[19] mentioned in formula 9 is denoted as consistency ratio of an AHP model in total hierarchy permutation and goes as follow:

$$\mathrm{CR} = \frac{\sum_{j=1}^{m} a_j \mathrm{CI}_j}{\sum_{j=1}^{m} a_j \mathrm{RI}_j}, \tag{10}$$

where a_j is the weight of each factor at the criteria level; CI_j is the CI value of attributes at the criteria level; RI_j is the Random consistency index and shown in Table 5.

4 Application example

4.1 Construction of judgment matrix

Construction by fault tree. It is difficult to gain structure importance by calculating the minimal cut sets because of the huge number of minimal cut sets in this fault tree. In an easier way, the structure importance can be obtained by calculating the minimal path sets, which is gained by changing the fault tree to a success tree. There are twelve minimal path sets in this fault tree:

$P_1 = \{X'_1, X'_3\}$ $P_2 = \{X'_1, X'_4\}$

$P_3 = \{X'_2, X'_3\}$ $P_4 = \{X'_2, X'_4\}$

$P_5 = \{X'_7\}$ $P_6 = \{X'_1, X'_5, X'_6\}$

$P_7 = \{X'_8, X'_9, X'_{10}\}$ $P_8 = \{X'_{11}, X'_{12}\}$

$P_9 = \{X'_{13}\}$ $P_{10} = \{X'_{14}\}$

$P_{11} = \{X'_2, X'_5, X'_{16}\}$

$P_{12} = \{X'_5, X'_{15}, X'_{17}, X'_{18}, X'_{19}, X'_{20}\}$

Through formula 1, the structure importance of each basic event is listed in Table 6.

Based on the structure importance of each basic event, the least common multiple of each denominator can be obtained and the value is 72. Through formula 2, judgment factor can be gained and details are listed in Table 6. As shown in Table 3, safety management at the criteria level contains six attributes, i.e. X'_1, X'_3, X'_4, X'_5, X'_6, X'_{17}. So the judgment factor of safety management denoted as $\sum_{i=1}^{m} \chi(1)$ is the summation of the judgment factors of each attribute, which belongs to safety management. In this way, the judgment factor value of safety management, fire protection facilities, building structure and fire protection factors are 26, 19, 12 and 15,

Table 4 Scale factors with different numerical scales

Scales	3	5	7	9	11	13	15	17	18	26
φ	0.4610	0.7597	0.9286	1.000	0.8506	0.7468	0.6948	0.6234	0.5844	0.4091
Scales	30	34	36	44	52	60	68	75	85	90
φ	0.3831	0.3182	0.2922	0.2078	0.1688	0.1429	0.0909	0.0779	0.0325	0

Scale factors of the missing scales in the middle can be gained by interpolation method.

Table 5 The value of random consistency index (RI)[21]

Size of matrix	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 6 Structure importance and judgment factors of each basic event

Basic events	X'_1	X'_2	X'_3	X'_4	X'_5	X'_6	X'_7	X'_8	X'_9	X'_{10}
Structure importance	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{12}$	$\frac{1}{12}$	$\frac{1}{24}$	$\frac{1}{36}$	$\frac{1}{12}$	$\frac{1}{36}$	$\frac{1}{36}$	$\frac{1}{36}$
Judgment factor $\chi(i)$	8	8	6	6	3	2	6	2	2	2
Basic events	X'_{11}	X'_{12}	X'_{13}	X'_{14}	X'_{15}	X'_{16}	X'_{17}	X'_{18}	X'_{19}	X'_{20}
Structure importance	$\frac{1}{24}$	$\frac{1}{24}$	$\frac{1}{12}$	$\frac{1}{12}$	$\frac{1}{24}$	$\frac{1}{36}$	$\frac{1}{72}$	$\frac{1}{72}$	$\frac{1}{72}$	$\frac{1}{72}$
Judgment factor $\chi(i)$	3	3	6	6	3	2	1	1	1	1

respectively. Using formula 3, a_{14} in the judgment matrix is calculated in this way: $a_{14} = \sum_{i=1}^{m} \chi(1) / \sum_{i=1}^{m} \chi(4) = 1.7 \approx 2$. The judgment matrix at the criteria level is shown in Table 7.

The local weight of attributes can be gained in the same way as factors at the criteria level goes. By total hierarchy permutation in AHP model, the global weights of each attribute can be obtained and are shown in Table 9.

Construction by traditional AHP. In traditional AHP, the judgment matrix is obtained by choosing numerical scale and the usual choice is 1—9 scales shown in Table 1. The pair-wise comparisons are taken among four factors at the criteria level, namely safety management, fire protection facilities, building structure and fire protection factors, by experts' judgment and the judgment matrix gained is shown in Table 8.

In the same way, the judgment matrix can also be carried out at the alternative level between the attributes belonged to the same factor, and the local weights of each attributes can be obtained. The global weights of each attribute can be gained through total hierarchy permutation in AHP model and are shown in Table 9.

4.2 Weight coefficient α and β

Based on the AHP model constructed by fault tree, the maximal value of numerical scale value as known above is 26, which is the judgment factor of safety management at the criteria level. Table 4 show the scale factor (φ) is 0.4091 when the judgment factor is 26. Through formula 9 and 10, CR factor can be gained and the value is 0.9590. So weight coefficient of AHP model constructed by fault tree goes as follow:

$$\alpha = \text{scale factor } (\varphi) + \text{CR factor } (\varepsilon) = 1.3681$$

Similarly, in traditional AHP model, the maximal value of numerical scale is 9, which is usually used by decision-maker. As shown in Table 4, the scale factor (φ) is 1.0. The calculation of CR factors is just like the way above and the value is 0.5650, so the weight coefficient of traditional AHP model is:

$$\beta = \text{scale factor } (\varphi) + \text{CR factor } (\varepsilon) = 1.5650$$

4.3 Results and analysis

Using formula 5, the combined weight of each attribute in the improved AHP model can be carried out by W′ and W″, which are gained from the AHP model constructed by fault tree and traditional AHP model respectively. And the combined weight of each attribute is listed in Table 9. The rank-order of each attribute is

Table 7 Judgment matrix of each factor at the objective level constructed by fault tree

	B1	B2	B3	B4	Weight
Safety management (B1)	1	1	2	2	0.3381
Fire protection facilities (B2)	1	1	2	1	0.2881
Building structure (B3)	1/2	1/2	1	1	0.1690
Fire protection factors (B4)	1/2	1	1	1	0.2048

Table 8 Judgment matrix of each factor at the criteria level constructed by traditional AHP

	B1	B2	B3	B4	Weight
Safety management(B1)	1	1	2	3	0.3562
Fire protection facilities(B2)	1	1	2	2	0.3250
Building structure(B3)	1/2	1/2	1	2	0.1937
Fire protection factors(B4)	1/3	1/2	1/2	1	0.1251

Table 9 The combined weight of each attribute

Attribute level	Attribute name	W′	Rank-ordering	W″	Rank-ordering	W	Rank-ordering
X1	Daily safety inspection	0.0965	2	0.1237	1	0.1110	1
X3	Safety facilities of distribution equipment	0.0817	6	0.0218	15	0.0497	9
X4	Fire-resistant of electrical equipment	0.0817	6	0.0270	14	0.0525	8
X5	Safety knowledge propaganda	0.0404	9	0.0871	3	0.0653	5
X6	Management level	0.0249	16	0.0422	10	0.0341	15
X17	Emergency plan and drill	0.0130	20	0.0544	8	0.0351	14
X9	Smoke control system	0.0285	12	0.0216	16	0.0248	17
X13	Fire hydrant system	0.0902	3	0.0371	11	0.0619	6
X14	Sprinkler system	0.0902	3	0.1152	2	0.1035	2
X15	Fire alarm system	0.0508	8	0.0873	4	0.0703	4
X16	Fire-fighting equipment	0.0285	12	0.0639	6	0.0474	10
X7	Fuel load in building	0.0845	5	0.0753	5	0.0796	3
X8	Fire resistance rating	0.0282	14	0.0131	19	0.0201	19
X10	Fire compartment	0.0282	14	0.0521	9	0.0410	11
X19	Evacuation exits	0.0141	17	0.0322	13	0.0238	18
X20	Evacuation indicators	0.0141	17	0.0210	17	0.0178	20
X2	Occupants' fire-prevention quality	0.1135	1	0.0120	20	0.0593	7
X11	Fire-fight capacity of fire bridge	0.0390	10	0.0202	18	0.0290	16
X12	Distant of fire station	0.0390	10	0.0347	12	0.0367	13
X18	Personnel load	0.0134	19	0.0583	7	0.0374	12

gained by accumulative sequence.

As shown in Table 9, the rank-ordering of three attributes ascended greatly in the improved AHP, such as Occupants' fire-prevention quality (X2), Safety facilities of distribution equipments (X3) and Fire-resistant of electrical equipment (X4). It is found that the rank-ordering of Occupants' fire-prevention quality (X2) rose from 20 to 7 in the improved AHP. A fire statistics showed that 42987 fires happened in 2004 in China because of people's fault (about 30.2 percent) and electrical problems (about 20.7 percent)[22]. People's fault was one type of activities in occupants' fire-prevention quality and was the main reason causing the fire. In traditional AHP, the rank-ordering of X2 is 20 and there exists the underestimation of occupants' fire-prevention. So the result of improved AHP avoids this kind of underestimation and reduces misjudgment. The rank-ordering of Safety facilities of distribution equipments (X3) and Fire-resistant of electrical equipments (X4) rise by 6 in the improved AHP. Electrical problem is the second important reason causing fire, and the rank-ordering in the improved AHP answer for this statistics data correctly.

There are also some attributes descending their rank-ordering in the improved AHP. Take evacuation exits (X19) for example, the rank-ordering descended from 13 to 18. That is to say, evacuation exit is less important to the personal safety comparing with some other attributes in public building. 74 persons died in the fire of Illinois State Hospital in 1948. Although there were plenty of evacuation exits, so many people died when fire spread rapidly because flammable materials were used in this hospital largely[23]. From this case, it is known that Fuel load in building (X7) is more important to evacuation exits (X19). The rank-ordering of X7 and X19 in the improved AHP was proved by this case exactly. Personnel load (X18) has effect on personal safety in public building. So many people died because of high personnel load. However, personnel load is not so important to personal safety when the evacuation keeps in good order. No casualty happened in the fire in Sendai supermarket in Japan and 2000 persons evacuated safely because of great evacuation order[23]. This case has a favorable illustration to the improved AHP.

Besides, several attributes have the same rank-ordering of weight, such as daily safety inspection (X1), Fire resistance rating (X8), Sprinkler system (X14), Fire alarm system (X15). Sprinkler system had great influence on fire safety of buildings. A fire statistics in USA showed that residential sprinklers decreased the home fire death rate per 100 fires by 74%[24]. Also fire alarm system had great significance to fire safety. On November 29, 1995, the electrical cables in Shanghai Stadium released smoke because of overload. The given cues by fire alarm system avoided a big fire.

Differences exist in these two evaluation method. Because of the without thinking of the occurrence probability of basic events in FTA and existent of subjective judgment in the construction of judgment matrix, in some extent, there will exist error in the result. Therefore, the analysis result of the improved AHP in this paper, which is the combination of these two evaluation methods, will show more creditability in evaluation.

Known from Table 9, attributes such as daily safety inspection (X1), sprinkler system (X14), fire load (X7) and fire alarm system (X15) have important influence on fire safety of public buildings and safety managers should pay attention to these attributes.

5 Safety assessment of Olympic venues

5.1 Fuzzy AHP

The fuzzy AHP[25,26] is used in this paper to evaluate the Olympic venues. Safety levels in Olympic venues are listed in Table 10. Based on these safety levels, the mark in evaluation vector of Olympic venues for excellence, good, medium, bad, very bad are 95, 85, 75, 65, 55 respectively.

Combining the weight from the improved AHP and the judgment to Olympic venues, an evaluation mark will be gained. The mark will be a good reflection of fire safety in Olympic venues. From Table 9, the weight of factors at the criteria level can be gained:

$$w = [0.3477\ \ 0.3079\ \ 0.1823\ \ 0.1624].$$

At the alternative level, the weight of attributes can be calculated by normalization. The weights of attributes at the attribute level to top goal are gained by the improved AHP:

$$w_{B1} = [0.3192\ 0.1429\ 0.1510\ 0.1878\ 0.0981\ 0.1009]$$

$$w_{B2} = [0.0805\ 0.2010\ 0.3361\ 0.2283\ 0.1539]$$

$$w_{B3} = [0.4366\ 0.1103\ 0.2249\ 0.1306\ 0.0976]$$

$$w_{B4} = [0.3651\ 0.1786\ 0.2260\ 0.2303].$$

5.2 Assessment and results

The assessment of Olympic venue was really a huge project and evaluation by a single person might bring prejudgment. Five experts formed the expert assessment group. Attributes at the alternatively level were judged according to investigations. The safety level of each attributes at the alternatively level had to be confirmed by every expert. Take one Olympic venue for example, with the collection of judgment from every expert, the judgment matrixes are came out:

$$R_1 = \begin{bmatrix} 0.8 & 0.2 & 0 & 0 & 0 \\ 0.6 & 0.4 & 0 & 0 & 0 \\ 0.4 & 0.4 & 0.2 & 0 & 0 \\ 0.2 & 0.4 & 0.2 & 0 & 0 \\ 0.8 & 0.2 & 0 & 0 & 0 \\ 0.6 & 0.2 & 0.2 & 0 & 0 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} 0.4 & 0.4 & 0.2 & 0 & 0 \\ 0.4 & 0.4 & 0.2 & 0 & 0 \\ 0.2 & 0.6 & 0.2 & 0 & 0 \\ 0.4 & 0.2 & 0.2 & 0.2 & 0 \\ 0.6 & 0.2 & 0.2 & 0 & 0 \end{bmatrix}$$

$$R_3 = \begin{bmatrix} 0.8 & 0.2 & 0 & 0 & 0 \\ 0.4 & 0.6 & 0 & 0 & 0 \\ 0.6 & 0.2 & 0.2 & 0 & 0 \\ 0.4 & 0.2 & 0.4 & 0 & 0 \\ 0.4 & 0.4 & 0.2 & 0 & 0 \end{bmatrix}$$

$$R_4 = \begin{bmatrix} 0.2 & 0.6 & 0.2 & 0 & 0 \\ 0.6 & 0.2 & 0.2 & 0 & 0 \\ 0.8 & 0.2 & 0 & 0 & 0 \\ 0.4 & 0.4 & 0.2 & 0 & 0 \end{bmatrix}$$

Details about the fuzzy AHP were represented in ref. [27]. Using the weight obtained from the improved AHP and the judgment matrixes, the final mark of Olympic venue could be calculated:

$$\boldsymbol{F} = [95\ 85\ 75\ 65\ 55] \cdot [0.4995\ 0.3351\ 0.1386\ 0.0141\ 0]^{\mathrm{T}} = 87.25.$$

From Table 10, it is know that the safety level of this Olympic venue is good.

6 Conclusion

FTA and AHP were widely used in risk evaluation in various areas. Based on the coherence and merits of FTA

Table 10 Safety levels in Olympic venues

Mark	⩾ 90	90−80	80−70	70−60	<60
Safety level	Excellence	Good	Medium	Bad	Very bad

and AHP, combining structure importance of each basic event in fault tree with the weight in traditional AHP, the combined weights of attributes have been carried out. The improved AHP reduces the judgment error and makes the analysis more creditable when the qualitative analysis in FTA and quantitative analysis in AHP are combined.

The improved AHP helps to analyze how important is each attribute to fire safety of public buildings. And it has great significances to the establishment of fire-protection measures. The daily safety inspection, sprinkler system, fire load and fire alarm system have paramount influence on fire safety of public buildings, and safety managers must pay attention to these attributes. Moreover, the weight of each attribute in public building can be applied by the fuzzy AHP to the evaluation of fire risk of Olympic venues. Also the improved AHP will guide the evaluation in other areas.

1 Fu Q, Zhang H P, Wang H. Study on public building fire risk assessment method. Fire Safe Sci, 2007, 16(3): 137－142
2 Du H B, Zhou X Q, Zhang J Z. Fuzzy synthetic evaluation for fire safety of high-rise buildings. J China Univ Min Technol, 2002, 31(3): 242－245
3 Chu G Q, Chen T, Sun Z H, et.al. Probabilistic risk assessment for evacuees in building fires. Build Environ, 2007(42): 1283－1290
4 Li H M. Analysis of university dormitory electrical fire based on Event Tree Approach. Sci Technol West China, 2008(1): 62－63
5 Liu A H, Shi S L, Wu C. The index system design of the high building fire hazard assessment. Eng Sci, 2006, 8(9): 90－94
6 Zhang G J, Dai X J, Li W. Fault Tree Analysis of fire accident of large-scale hotel. Safe Environ Eng, 2007(4): 83－85
7 Zheng S Z, Gao Y T, Chen B Z. The index system study of building fire hazard evaluation in the city. Fire Sci Technol, 2001, (5): 12－13
8 Hikmat H A, Saba F A N. Developing a green building assessment tool for developing countries – case of Jordan. Build Environ (2008), [doi]
9 Johnson C W. Using evacuation simulations for contingency planning to enhance the security and safety of the 2012 Olympic venues. Safety Sci, 2008(46): 302－322
10 Shi J Y, Ren A Z. Application of computer simulation technology to fire safety analysis of gymnasiums for 2008 Olympic Games. J Nat Disasters, 2005(4): 95－102
11 Vaurio J K. Common cause failure probabilities in standby safety system fault tree analysis with testing—scheme and timing dependencies. Reliab Eng Syst Safe, 2003, (79): 43－57
12 Reay K A, Andrews J D. A fault tree analysis strategy using binary decision diagrams. Reliab Eng Syst Safe, 2002(78): 45－56
13 Chen B Z. Identification, Evaluation and Control of Hazard Installation. Chengdu: Sichuan Publishing House of Science and Technology, 1996: 10－25
14 Wu A Y, Wang C L, Xiao G Q. Application of fault tree analysis in casualty of building fire. China Safe Sci J, 2005, 15(5): 92－95
15 Gu L, Liu X D, Yan H Q. Application of Fault Tree to Risk Assessment of fire and explosion at oil-fuel depot. Envrion Sci Technol, 2007, 30(6): 52－54
16 Saaty T L, Tran L T. On the invalidity of fuzzifying numerical judgments in the Analytic Hierarchy Processs. Math Comput Model. 2007(46): 962－975
17 Saaty T L, Shang J S. Group decision-making: Head-count versus intensity of preference. Socio Econ Plan Sci, 2007(41): 22－37
18 Dong Y C, Xu Y F, Li H Y, et al. A comparative study of the numerical scales and the prioritization methods in AHP. Eur J Oper Res, 2008(186): 229－242
19 Liu T M, Zhang X K, Liu G Z. A Guide of Safety Evaluation Application. Beijing: Chemical Industry Press, 2005: 15－38
20 ZhaoH C, Xu S B, He J S, Analytic Hierarchy Process —One New Method for Decision-making. Beijing: Science Press, 1986: 9－24
21 Kariuki S G, Löwe K. Integrating human factors into process hazard analysis. Reliab Eng Syst Safe, 2007(92): 1764－1773
22 Guo T N. Fire status in 2004 and the fire development tendency as well as counter measures now and in the future. Fire Sci Technol, 2005, 24(3): 263－266
23 Guo R H. The history of fire investigation in America, U.K. and Japan —efforts of fire investigation to evacuation plan in building. Fire Technol Prod Inform, 2002(8): 59－67
24 Rohr K D, Hall J R. U.S. Experience with Sprinklers and other Fire Extinguishing Equipment. Technology Report, Fire Analysis and Research Division, National Fire Protection Association. 2005: 1－5
25 Wang Y M, Luo Y, Hua Z S. On the extent analysis method for Fuzzy AHP and its applications. Eur J Oper Res, 2008(186): 735－747
26 Lin L. The exploration on safety grade assessment of high occupancy public buildings. Master Dissertation. Chongqing: Chongqing University, 2006: 23－64
27 Yu Z P, Lu Y S. Application of fuzzy analytical hierarchy process in enterprise safety assessment. J Safe Sci Technol, 2006, 2(3): 119－121