

Comparison of FAHP and TOPSIS for Evacuation Capability Assessment of High-rise Buildings

Peng Mei, Yan-Jun Qi, Yu Cui, Song Lu, He-Ping Zhang

Abstract—A lot of computer-based methods have been developed to assess the evacuation capability (EC) of high-rise buildings. Because softwares are time-consuming and not proper for on scene applications, we adopted two methods, fuzzy analytic hierarchy process (FAHP) and technique for order preference by similarity to an ideal solution (TOPSIS), for EC assessment of a high-rise building in Jinan. The EC scores obtained with the two methods and the evacuation time acquired with Pathfinder 2009 for floors 47-60 of the building were compared with each other. The results show that FAHP performs better than TOPSIS for EC assessment of high-rise buildings, especially in the aspect of dealing with the effect of occupant type and distance to exit on EC, tackling complex problem with multi-level structure of criteria, and requiring less amount of computation. However, both FAHP and TOPSIS failed to appropriately handle the situation where the exit width changes while occupants are few.

Keywords—Evacuation capability assessment, FAHP, high-rise buildings, TOPSIS.

I. INTRODUCTION

THE world population surpassed 7 billion in 2011 and this number will reach 9.15 billion in 2050 [1]. More and more people emerge to cities, which are under great population pressure. Mainly driven by this, planners and designers have been trying to achieve higher land utilization ratio, which means providing more floors on limited land area. As a result, lots of high-rise buildings have been or are being built in many cities.

In high-rise buildings, evacuation is an important problem which has been proved by many disastrous incidents. For example, the terrorist attack on the WTC in New York in 2001 resulted in about 2800 deaths, and the fire in a high-rise apartment building in Shanghai in 2010 led to 53 deaths. To assess the Evacuation Capability (EC) of high-rise buildings, lots of computer-based models have been developed [2]. Many programs such as buildingEXODUS [3] and SIMULEX [4] are widely adopted in performance-based design nowadays.

For complex buildings, inputting and running of simulations are time-consuming [5], [6]. The whole process may take days or even weeks. However, it is often the case that designers or

P. Mei is with the State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, 230027, China (e-mail: titanmgb@mail.ustc.edu.cn).

Y.-J. Qi is with Fire Department of Shandong Province, Jinan, 250014, China.

Y. Cui is with the State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, 230027, China.

S. Lu is with the State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, 230027, China.

H.-P. Zhang is with the State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, 230027, China (phone: 86-551-3601665; Fax: 86-551-3601665; e-mail: zhanghp@ustc.edu.cn).

assessors have to perform an assessment on scene and/or within a short time limit, which makes those softwares not suitable for the job. Up to now, there are few literatures about assessing EC under building environment with multi-criteria decision-making (MCDM) approaches. In this paper, fuzzy analytic hierarchy process (FAHP) and technique for order preference by similarity to an ideal solution (TOPSIS) are proposed for EC assessment of high-rise buildings and the results are compared.

II. METHODS AND DATA

A. FAHP

FAHP is an extension of AHP [7] basing on the fuzzy set theory [8]. It is efficient in solving problems with imprecision, uncertainty and vagueness [9]. The triangular fuzzy number (TFN) [10], was used to describe linguistic variables (Table I).

The steps of the FAHP are as follows:

STEP 1: Build the hierarchical structure and make pairwise comparison matrices of criteria using TFN, $M_{ij}=(a_{ij}, b_{ij}, c_{ij})$.

STEP 2: Check the consistency with consistency index (CI) and consistency ratio (CR) suggested by Saaty [11].

TABLE I
TRIANGULAR FUZZY NUMBER

Linguistic variables	Positive TFN	Positive reciprocal TFN
Equally strong	(1, 1, 2)	(1/2, 1, 1)
Moderately strong	(2, 3, 4)	(1/4, 1/3, 1/2)
Strong	(4, 5, 6)	(1/6, 1/5, 1/4)
Very strong	(6, 7, 8)	(1/8, 1/7, 1/6)
Extremely strong	(8, 9, 9)	(1/9, 1/9, 1/8)

Intermediates are omitted

STEP 3: Calculate S_i , the value of the fuzzy synthetic extent:

$$S_i = \sum_{j=1}^m M_{ij} / \sum_{i=1}^n \sum_{j=1}^m M_{ij} \quad (1)$$

STEP 4: The possibility of $S_i=(a_i, b_i, c_i) \geq S_j=(a_j, b_j, c_j)$ is defined as follows:

$$V(S_i \geq S_j) = \begin{cases} 1, & b_j \geq b_i \\ 0, & a_i \geq c_j \\ (a_i - c_j) / [(b_j - c_j) - (b_i - a_i)], & \text{otherwise.} \end{cases} \quad (2)$$

Calculate $\min V(S_j \geq S_i)$, the minimum degree of possibility.

STEP 5: The weight factor is given by

$$W' = (d'(A_1), d'(A_2), \dots, d'(A_n))^T \quad (3)$$

where A_i are n criteria, $d'(A_i) = \min V(S_j \geq S_i)$. The normalized weight vector is

$$W = (\omega_{A_1}, \omega_{A_2}, \dots, \omega_{A_n})^T = (d(A_1), d(A_2), \dots, d(A_n))^T \quad (4)$$

STEP 6: Calculate the scores and rank the alternatives.

B. TOPSIS

The TOPSIS [12] is a MCDM method for ranking and selecting several possible alternatives. For a problem, suppose m alternatives are evaluated with respect to the n criteria. The values of all criteria constitute a decision matrix denoted by

$$X=(x_{ij})_{m \times n} = \begin{pmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{pmatrix} \quad (5)$$

The procedure of TOPSIS can be expressed as follows:

STEP 1: Calculate the normalized value r_{ij} for normalized decision matrix:

$$r_{ij} = x_{ij} / \sqrt{\sum_{i=1}^m x_{ij}^2}, \text{ for benefit criterion} \quad (6)$$

$$r_{ij} = 1 - x_{ij} / \sqrt{\sum_{i=1}^m x_{ij}^2}, \text{ for cost criterion} \quad (7)$$

STEP 2: Calculate the weighted normalized decision matrix. The weighted normalized value v_{ij} is calculated as

$$v_{ij} = w_j r_{ij} \quad (8)$$

where w_j is the weight of j -th criterion, which will be determined using FAHP.

STEP 3: Determine the positive ideal solution (PIS) and negative ideal solution (NIS):

$$A^+ = (v_1^+, v_2^+, \dots, v_n^+) \quad (9)$$

$$A^- = (v_1^-, v_2^-, \dots, v_n^-) \quad (10)$$

where $v_j^+ = \max_i v_{ij}$ and $v_j^- = \min_i v_{ij}$.

STEP 4: Calculate the distance of each alternative from PIS and NIS as follows:

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad (11)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \quad (12)$$

STEP 5: Calculate the relative closeness R_i :

$$R_i = S_i^- / (S_i^- + S_i^+) \quad (13)$$

STEP 6: Rank the preference order according to the descending order of R_i , that is, larger R_i means better alternative.

C. Hierarchy, Data and Evacuation Scenarios

The hierarchical structure of EC was built as shown in Fig. 1. Exit width (A_1), occupant type (A_2), occupant number (A_3), and maximum distance to exit (A_4) are included in level 1. The number of children (B_1), male adults (B_2), female adults (B_3), and elders (B_4) are considered as sub-criteria of A_2 .

In consideration of the design of refuge storey and the premise that the refuge storey are places of relative safety, the

floors 47-60 of a 60-floor building in Jinan were chosen as object of study. The floors 47-58 of the building are apartments, floor 59 is a restaurant, and floor 60 is used for sightseeing.

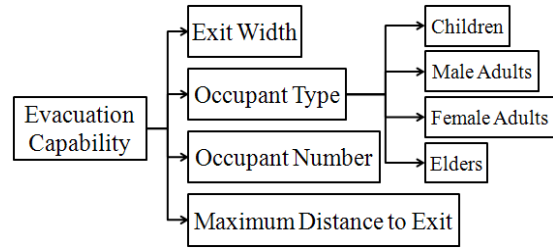


Fig. 1 Hierarchical structure of criteria

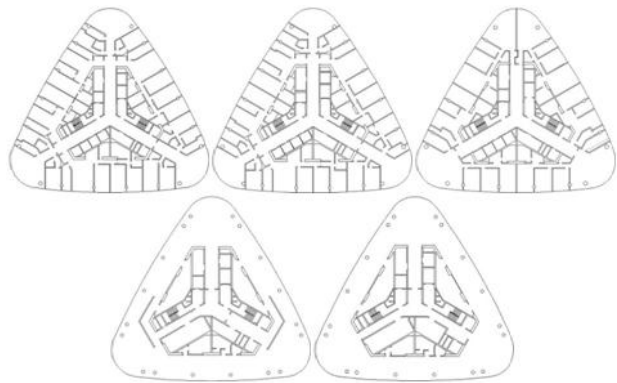


Fig. 2 Floor plans of F47-50, 51-54, 55-58, 59, and 60, sequentially

Data for A_1 and A_4 were acquired according to the floor plans (Fig. 2.) The values of B_1 to B_4 for floor 47-58 were determined due to the apartment layout (Table II). For floors 59-60, these data were provided by proprietors. To synthesize the weights of all criteria, data were normalized, and the raw and normalized data can be found in Table III.

Three scenarios were designed in this paper. Scenario 1 (S1) is an original scenario which uses the data in Table III. In Scenario 2 (S2), a fire near the left stair on floor 51 was considered and the left staircase of floors 51-60 is unavailable for evacuation. For Scenario 3 (S3), the occupant numbers of floors 59-60 are halved. For validation, Pathfinder 2009 (PF) was used to simulate the evacuation time.

TABLE II
APARTMENT LAYOUT AND CORRESPONDING OCCUPANT NUMBER

Layout	Occupant number			
	Children	Male adults	Female adults	Elders
One-bedroom	0	1	1	0
Two-bedroom	1	1	1	0
Three-bedroom	1	1	1	2

TABLE III
RAW DATA AND NORMALIZED DATA (IN PARENTHESIS) OF ALL CRITERIA

Floor	A_1 (m)	A_2				A_3	A_4 (m)
		B_1	B_2	B_3	B_4		
47-50	2.4 (1.000)	5 (0.000)	7 (0.942)	7 (0.942)	6 (0.000)	25 (0.896)	39 (0.025)
51-54	2.4 (1.000)	3 (0.400)	7 (0.942)	7 (0.942)	6 (0.000)	23 (0.904)	39 (0.025)
55-58	2.4 (1.000)	4 (0.200)	6 (0.950)	6 (0.950)	4 (0.333)	20 (0.917)	33 (0.175)
59	2.4 (1.000)	0 (1.000)	108 (0.100)	108 (0.100)	0 (1.000)	216 (0.100)	29 (0.275)
60	2.4 (1.000)	0 (1.000)	70 (0.417)	70 (0.417)	0 (1.000)	140 (0.417)	29 (0.275)

III. RESULTS

Five experts have been asked to make their judgments of the pairwise comparison matrix using linguistic variables. As listed in Table IV, relative weights of A_1 to A_4 were calculated using (1)-(4). The weights of B_1 to B_4 were determined by the walking speed of different occupants given by Shi [13].

TABLE IV
RELATIVE WEIGHTS OF ALL CRITERIA

Creteia	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4
ω	0.346	0.161	0.336	0.157	0.232	0.266	0.279	0.223

The EC scores of all floors in each scenario were calculated with FAHP and TOPSIS separately and the evacuation simulations for each scenario were conducted with PF. All results are shown in Table V.

TABLE V
SCORES OF EC AND EVACUATION TIME FOR ALL FLOORS IN 3 SCENARIOS

Floor	FAHP			TOPSIS			PF (s)		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
47-50	0.73	0.73	0.73	0.95	0.96	0.77	40	40	40
51-54	0.75	0.58	0.75	0.96	0.69	0.82	38	39	38
55-58	0.78	0.61	0.78	0.98	0.71	0.91	29	31	29
59	0.50	0.33	0.70	0.05	0.04	0.21	154	350	79
60	0.64	0.47	0.76	0.35	0.21	0.58	72	240	34

IV. DISCUSSION

The weights of criteria in level 1 were acquired basing on the judgments of experts, and the rank of importance is $A_1, A_3, A_2,$ and A_4 , from highest to lowest. Furthermore, the importance of A_1 and A_3 are on the same level and so are A_2 and A_4 . This is compared with the equation given by Togawa [14]:

$$T_{move} = N_{tot} / (W_{eff} \times C) + L_{min} / V \tag{14}$$

where T_{move} is the evacuation time, N_{tot} is the total number of occupants to be evacuated, W_{eff} is the effective width of exit, C is a coefficient which shows the number of occupants passed an exit per meter per second, L_{min} is the distance between exit and the closest occupant, and V is the average walking speed of occupants. In this equation, the occupant number and the exit width are taken into account in one term and the distance and the walking speed in another. The factors in the same term could be regarded as criteria which affect the evacuation time in a similar way and may have nearly equal importance. This agrees, to some extent, with the results of criteria weights in this study.

In S1, all floors have the same exit width. Consequently, A_3 becomes the criterion of overwhelming importance. The values of A_3 for Floors 55-58 are the smallest of all floors, which makes their evacuation time the shortest. The values of A_3 have an apparent effect on evacuation time of other floors as well, and the effects of A_2 and A_4 are hard to recognize. The ranks of EC acquired by different methods are exactly the same for S1 (Fig. 3). It indicates that FAHP and TOPSIS both worked well in assessing the EC of all floors in this scenario.

The values of A_1 for floors 51-60 become 1.2 m for S2. The result of simulation shows that the evacuation time of floors 59-60 increase significantly, whereas the evacuation time for floors 51-58 remain nearly the same as in S1 although the exit

width is halved. This is mainly because that for floors 59-60, the stair size is not large enough to contain all occupants simultaneously and the congestion on the stairs prevents occupants from entering the stair cores. However, for floors 55-58, the occupants are so few that they can reach the exit without queuing even the exit width is only 50% of S1, and that's why their simulation results vary slightly. Fig. 4 shows the ranks of EC acquired by different methods for all floors in S2. The rank in S2 is the same as in S1 according to the evacuation time: floors 59-60 are still the last two and the other floors are almost unaffected by the change of exit width. However, the EC scores calculated with both FAHP and TOPSIS don't agree well with the simulation results. The EC scores for floors 51-58 are lower than that in S1 because of the lower exit width, which actually has limited effect on evacuation time for these floors. This indicates that both FAHP and TOPSIS can't correctly deal with this kind of situation where the exit width changes while the occupants are few.

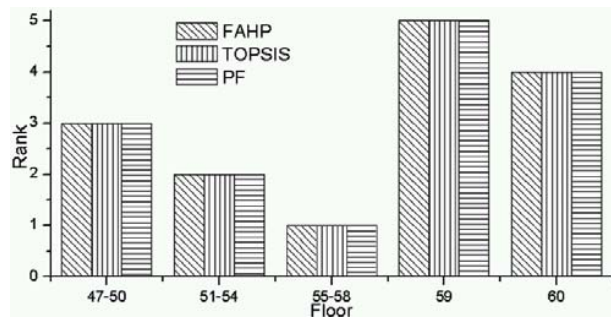


Fig. 3 Ranks of EC acquired by different methods for all floors in S1

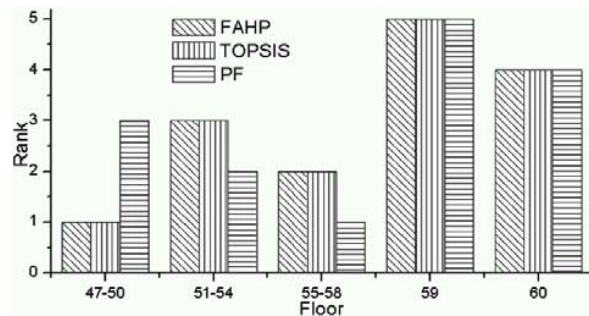


Fig. 4 Ranks of EC acquired by different methods for all floors in S2

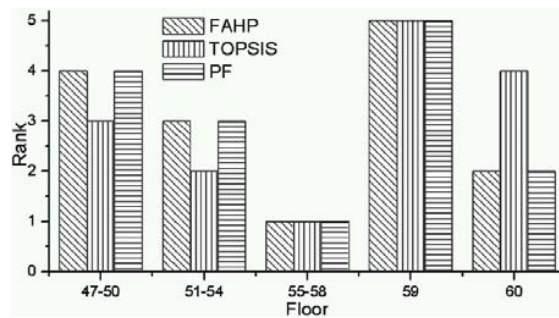


Fig. 5 Ranks of EC acquired by different methods for all floors in S3

Fig. 5 shows the ranks of EC of all floors in S3. The evacuation time for floors 59 and 60 in S3 is about 50% of that in S1. It's easy to understand because the occupants on them are halved. Floor 60 remains the last when ranking, whereas floor 59 moves up to the second. The occupant number of floor 59 is not the second least, but shorter evacuation distance and no slow occupants (i.e. children and elders) make it surpass floors 47-54. PF and FAHP ranked all floors in the same order, but TOPSIS didn't appropriately handle the influences of A_2 and A_4 on EC.

The comparison of results demonstrates that FAHP performs better than TOPSIS in accuracy of EC assessment of high-rise buildings. Besides, we believe that the FAHP is superior to TOPSIS in following aspects.

Firstly, both FAHP and TOPSIS need the weights of all criteria for assessment, but FAHP can handle a multi-level hierarchical structure by determining the weights with pairwise comparisons. Although TOPSIS works well for single level hierarchy, in order to deal with more complex problems, researchers have developed other extensions of TOPSIS [15], [16] which tackle the difficulty of determining the weights by combining TOPSIS with other methods, such as FAHP.

Furthermore, after determining the weights and normalizing the data, FAHP appears to be more practical, because addition and multiplication involved in FAHP are much easier than extraction of a root needed in TOPSIS.

V. CONCLUSION

The EC of floors 47-60 of a high-rise building in Jinan were assessed with 3 scenarios considered. A hierarchical structure of EC was constructed and the relative weights of all criteria were calculated based on the judgments of experts. The EC scores of all floors in the each scenario were calculated with FAHP and TOPSIS separately. The evacuation time were also simulated with PF. The results were compared with each other and following conclusions have been drawn.

The relative weights of criteria in level 1 indicate that exit width and occupant number are more important than occupant type and the distance to exit in evacuation of high-rise buildings. The comparisons of ranks of floors in 3 scenarios show that FAHP performs better than TOPSIS for EC assessment in the aspect of handling the effects of occupant type and distance to exit, tackling complex problems with multi-level structure of criteria, and requiring less computation. However, both FAHP and TOPSIS fail to correctly deal with the situation where the exit width changes while the occupants are few.

ACKNOWLEDGMENT

This research was supported by National Natural Science Foundation of China (No. 91024027). The authors deeply appreciate the support.

REFERENCES

- [1] UNFPA, *State of world population 2010*. New York: UNFPA, 2010.
- [2] S. Gwynne, E. R. Galea, M. Owen, P. J. Lawrence, and L. Filippidis, "A review of the methodologies used in the computer simulation of evacuation from the built environment," *Build. Environ.*, vol. 34, pp. 741-749, 1999.
- [3] S. Gwynne, E. R. Galea, M. Owen, and L. Filippidis, "A systematic comparison of model predictions produced by the buildingEXODUS evacuation model and the Tsukuba pavilion evacuation data," *J. Appl. Fire Sci.*, vol. 7, no. 3, pp. 235-266, 1998.
- [4] P. A. Thompson, E. W. Marchant, "A computer-model for the evacuation of large building populations," *Fire Safety J.*, vol. 24, no. 2, pp. 131-148, 1995.
- [5] S. M. Lo, Z. Fang, P. Lin, G. S. Zhi, "An evacuation model: the SGEM package," *Fire Safety J.*, vol. 39, no. 3, pp. 169-190, 2004.
- [6] J. P. Yuan, Z. Fang, Y. C. Wang, S. M. Lo, P. Wang, "Integrated network approach of evacuation simulation for large complex buildings," *Fire Safety J.*, vol. 44, no. 2, pp. 266-275, 2009.
- [7] T. L. Saaty, *The analytic hierarchy process*. New York: McGraw-Hill, 1980.
- [8] L. A. Zadeh, "Fuzzy sets," *Inform. Control*, vol. 8, pp. 338-353, 1965.
- [9] R. R. Yager, S. Ovchinnikov, R. M. Tong, H. T. Nguyen, *L.A. Zadeh: Selected Papers on Fuzzy Sets and Applications*. New York: John Wiley & Sons, 1987.
- [10] P. J. M. Van Laarhoven, W. Pedrycz, "A fuzzy extension of Saary's priority theory," *Fuzzy Set Syst.*, vol. 11, no. 3, pp. 229-241, 1983.
- [11] T. L. Saaty, "How to make a decision-the analytic hierarchy process," *Interfaces*, vol. 24, no. 6, pp. 19-43, 1994.
- [12] C. L. Hwang, and K. Yoon, *Multiple attribute decision making: Methods and applications*. New York: Springer-Verlag, 1981.
- [13] L. Shi, Q. Y. Xie, X. D. Cheng, L. Chen, Y. Zhou, and R. F. Zhang, "Developing a Database for Emergency Evacuation Model," *Build. Environ.*, vol. 44, pp. 1724-1729, 2009.
- [14] K. Togawa, 1955. Study on Fire Escapes Based on the Observation of Multitude Currents. Japanese Building Research Institute Report 14, Tokyo.
- [15] C. Kahraman, S. Cevik, N. Y. Ates, and M. Gulbay, "Fuzzy multi-criteria evaluation of industrial robotic systems," *Comput. Ind. Eng.*, vol. 52, pp. 143-168, 2007.
- [16] J. W. Wang, C. H. Cheng, K. C. Huang, "Fuzzy hierarchical TOPSIS for supplier selection," *Appl. Soft Comput.*, vol. 9, pp. 377-386, 2009.