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Fuzzy AHP approach for selecting the suitable bridge construction method

Nang-Fei Pan *

Department of Civil Engineering, National Cheng Kung University, No. 1 University Road, Tainan 70101, Taiwan, ROC

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ABSTRACT

Selecting an appropriate bridge construction method is essential for the success of bridge construction projects. The Analytical Hierarchy Process (AHP) method has been widely used for solving multi-criteria decision-making problems. However, the conventional AHP method is incapable of handling the uncertainty and vagueness involving the mapping of one's preference to an exact number or ratio. This paper presents a fuzzy AHP model to overcome this problem. The proposed approach employs triangular and trapezoidal fuzzy numbers and the α-cut concept to deal with the imprecision inherent to the process of subjective judgment. A case study that evaluates bridge construction methods is presented to illustrate the use of the model and to demonstrate the capability of the model.

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1. Introduction

Bridges are important components of highway networks which need to provide adequate safety and serviceability for the public. Commonly used modern bridge construction methods include Full-span and Precast Launching Method, Advancing Shoring Method, Balanced Cantilever Method, Incremental Launching Method, and Precast Segmental Method, etc. Wardhana and Hadipriono conducted that 12 (7.6%) out of 157 bridge collapses excluding natural disasters and deterioration/obsolescence bridge failures in the United States between 1989 and 2000 were due to defective design and construction [1]. Catastrophic bridge failures such as bridge collapses during construction incurred by the use of inappropriate construction methods can cause considerable loss in terms of time, money, damage, and rework. For example, the West Gate Bridge collapsed during construction on 15 October 1970 in Melbourne, Victoria. Thirty-five construction workers were killed and 19 injured. It attributed the failure of the bridge to improper design and construction. The reconstructed bridge was completed after 10 years of construction and for USD $202 million [2]. Recently, at least 36 people were killed and dozens injured when a bridge felled while under construction in Fenghuang, Hunan, China [3].

Accordingly, selecting a desirable bridge construction technology is vital for the success of highway projects. In such a decision-making problem, the owner or project contractor usually needs to identify important decision criteria and evaluate their relative importance (weights) leading to determine the most preferred alternative. As indicated in the literatures [4–9], the selection of bridge construction methods consists of fundamental management criteria such as cost, quality, project duration, safety, and shape of bridge. These criteria can be characterized by their associated sub-criteria: direct cost (mainly, construction cost), indirect cost (e.g., damage cost), durability, productivity, site conditions (e.g., weather and traffic condition), geometry, landscape, and environmental preservation, etc. Determining an appropriate alternative encompasses a complex trade-off process which requires all the decision criteria to be considered simultaneously. The Analytic Hierarchy Process (AHP) initially developed by Saaty [10], an effective method for solving multi-criteria decision-making problem, has been used in various areas of construction management, such as evaluation of advanced automation construction technology [11,12], contractor prequalification and selection [13–15], project delivery measurement [16,17], assessment of construction safety [18], and dispute resolution/maintenance/equipment/building assembly selection [19–23]. However, the AHP approach is incapable of handling the inherent subjectivity and ambiguity associated with the mapping of one's perception to an exact number. Hence, Buckley developed a fuzzy AHP model to tackle this problem [24]. Following Buckley's work, various developments of fuzzy AHP methods and applications have been carried out [25–33]. To the best of the author's knowledge, no AHP and fuzzy AHP application was found regarding the selection of bridge construction method. Nevertheless, most of the existing fuzzy AHP models employ only triangular typed fuzzy numbers and complicated fuzzy arithmetic that require tremendous computational time. Generally, trapezoidal fuzzy numbers can better capture the most-likely situation while involving a great deal of uncertainty as compared to triangular fuzzy numbers.

This paper presents a fuzzy AHP approach to overcome the difficulties arising from that other fuzzy AHP methods involve complicated fuzzy mathematical calculations. In this proposed model, a combination of triangular fuzzy numbers and trapezoidal fuzzy

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* Tel./fax: +886 62758455.
E-mail address: nfpan@mail.ncku.edu.tw.

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numbers are utilized. To derive fuzzy weights from group evaluations, the max–min aggregation and center-of-gravity (COG) defuzzification techniques are utilized because of their simplicity and efficiency. Furthermore, the α-cut concept is applied to describe specific levels of uncertainty associated with the decision environment. As a result, the proposed approach is straightforward and its execution is faster than other fuzzy AHP models.

2. The proposed method

The proposed model is developed within the AHP framework. The analysis steps of the approach including the enhancements made to Buckley's model are discussed in the following subsections.

2.1. Construction of hierarchy

The typical fuzzy AHP decision problem consists of (1) a number of alternatives, M_i ($i=1, 2,\ldots, m$), (2) a set of evaluation criteria, C_j ($j=1, 2, \ldots, n$), (3) a linguistic judgment r_{ij} representing the relative importance of each pair criteria, and (4) a weighting vector, $\mathbf{w}=(w_1, w_2,\ldots, w_n)$. The first step of the proposed model is to determine all the important criteria and their relationship of the decision problem in the form of a hierarchy. This step is crucial because the selected criteria can influence the final choice. The hierarchy is structured from the top (the overall goal of the problem) through the intermediate levels (criteria and sub-criteria on which subsequent levels depend) to the bottom level (the list of alternatives).

2.2. Evaluation of fuzzy pairwise comparison

Once the hierarchy is established, the pairwise comparison evaluation takes place. All the criteria on the same level of the hierarchy are compared to each of the criterion of the preceding (upper) level. A pairwise comparison is performed by using linguistic terms. Based on the modification of Chen's definition [29], five linguistic terms, "Very Unimportant"(VU),"Less Important" (LI), "EquallyImportant" (EI), "More Important" (MI) and "Very Important"(VI) ranging 0–10 are used to develop fuzzy comparison matrices. These five linguistic variables are described by fuzzy numbers as denoted in Table 1 or by membership functions as illustrated in Fig. 1. It can be found in the figure that "Very Unimportant"and "VeryImportant"are represented by half trapezoidal membership functions; whereas the remaining levels are characterized by symmetric triangular membership functions.

Fuzzy comparison matrix, $\tilde{\boldsymbol{A}}$, representing fuzzy relative importance of each pair elements is given by

$$\tilde{\boldsymbol{A}} = \begin{bmatrix} 1 & \tilde{r}_{12} & \tilde{r}_{13} & \cdots & \tilde{r}_{1n} \\ \tilde{r}_{21} & 1 & \tilde{r}_{23} & \cdots & \tilde{r}_{2n} \\ \vdots & \vdots & \ddots & & \vdots \\ \tilde{r}_{n1} & \tilde{r}_{n2} & \cdots\cdots & & 1 \end{bmatrix} \tag{1}$$

In Buckley's method, the element of the negative judgment is treated as an inverse and reversed order of the fuzzy number of the corresponding positive judgment. For example, suppose that criterion A compared to criterion B is "more important"denoted by fuzzy number (6, 7.5, 9), so that the negative judgment, "less important", is described by (1/9, 1/7.5, 1/6). Thus, it requires careful checks to avoid errors arising from such tedious manipulations while constructing a reciprocal matrix. To overcome this difficulty, each negative reciprocal element is characterized by its own representative fuzzy number as defined in Table 1.

Table 1
Fuzzy importance scale

Verbal judgment	Explanation	Fuzzy number
Very Unimportant (VU)	A criterion is strongly inferior to another	(0, 0, 1, 2)
Less Important (LI)	A criterion is slightly inferior to another	(1, 2.5, 4)
Equally Important (EI)	Two criteria contribute equally to the object	(3, 5, 7)
More Important (MI)	Judgment slightly favor one criterion over another	(6, 7.5, 9)
Very Important (VI)	Judgment strongly favor one criterion over another	(8, 9, 10, 10)

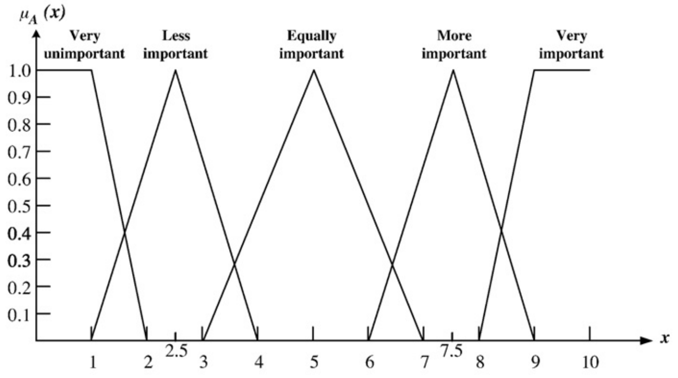

Fig. 1. Membership functions for linguistic values.

To reflect particular degrees of uncertainty regarding the decision-making process, the α-cut concept is applied. This is another enhancement of the proposed method made to Buckley's model. The value of α is between 0 and 1.$\alpha=0$ and $\alpha=1$, signify the degree of uncertainty is greatest and least, respectively. In practical applications, $\alpha=0$, $\alpha=0.5$, and $\alpha=1$ are used to indicate the decision-making condition that has pessimistic, moderate, and optimistic view, respectively. Fig. 2 shows that a triangular fuzzy number regarding a given value can be denoted by $(X_{\alpha,\mathrm{L}}, X_{\alpha,\mathrm{M}}, X_{\alpha,\mathrm{R}})$. $X_{\alpha,\mathrm{M}}$, $X_{\alpha,\mathrm{L}}$, and $X_{\alpha,\mathrm{R}}$ represents the most-likely value, minimum value, and maximum value of the fuzzy number, respectively.

The five membership functions shown in Fig. 1 can also be mathematically expressed through Eqs. (2)–(5).

$$X(\alpha)_{\text{Very unimportant}} = \begin{cases} X_{\alpha,\mathrm{L}} = 0 \\ X_{\alpha,\mathrm{M}} = \dfrac{0.5 + (X_{\alpha,\mathrm{L}} - 1)\left[(X_{\alpha,\mathrm{L}} - 1)(0.33 + 0.17\alpha) + 1\right]}{1 + (0.5X_{\alpha,\mathrm{L}} - 0.5)(1+\alpha)} \\ X_{\alpha,\mathrm{R}} = 2 - \alpha \end{cases} \tag{2}$$

$$X(\alpha)_{\text{Less unimportant}} = \begin{cases} X_{\alpha,\mathrm{L}} = 1 + 1.5\alpha \\ X_{\alpha,\mathrm{M}} = 2.5 \\ X_{\alpha,\mathrm{R}} = 4 - 1.5\alpha \end{cases} \tag{3}$$

$$X(\alpha)_{\text{Equally important}} = \begin{cases} X_{\alpha,\mathrm{L}} = 3 + 2\alpha \\ X_{\alpha,\mathrm{M}} = 5 \\ X_{\alpha,\mathrm{R}} = 7 - 2\alpha \end{cases} \tag{4}$$

$$X(\alpha)_{\text{More important}} = \begin{cases} X_{\alpha,\mathrm{L}} = 6 + 1.5\alpha \\ X_{\alpha,\mathrm{M}} = 7.5 \\ X_{\alpha,\mathrm{R}} = 9 - 1.5\alpha \end{cases} \tag{5}$$

$$X(\alpha)_{\text{Very important}} = \begin{cases} X_{(\alpha,\mathrm{L})} = 8 + \alpha \\ X_{(\alpha,\mathrm{M})} = 8 + \dfrac{1.5 + (9 - X_{(\alpha,\mathrm{L})})\left[(9 - X_{(\alpha,\mathrm{L})})(0.67 + 0.17\alpha) + 0.5\right]}{1 + (4.5 - 0.5X_{(\alpha,\mathrm{L})})(1+\alpha)} \\ X_{(\alpha,\mathrm{R})} = 10 \end{cases} \tag{6}$$

Accordingly, a fuzzy comparison matrix can be defined as follows:

$$\tilde{A} = \begin{bmatrix} 1 & (x_{12,\mathrm{L}}, x_{12,\mathrm{M}}, x_{12,\mathrm{U}}) & \cdots & (x_{1n,\mathrm{L}}, x_{1n,\mathrm{M}}, x_{1n,\mathrm{U}}) \\ (x_{21,\mathrm{L}}, x_{21,\mathrm{M}}, x_{21,\mathrm{U}}) & 1 & \cdots & (x_{2n,\mathrm{L}}, x_{2n,\mathrm{M}}, x_{2n,\mathrm{U}}) \\ \cdots & \cdots & \cdots & \cdots \\ (x_{n1,\mathrm{L}}, x_{n1,\mathrm{M}}, x_{21,\mathrm{U}}) & \cdots & \cdots & 1 \end{bmatrix} \tag{7}$$

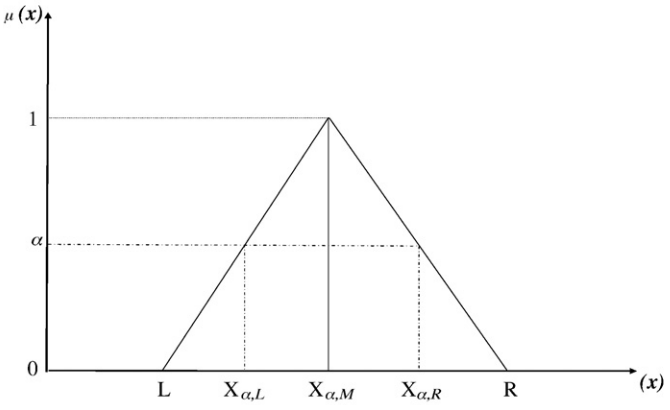

Fig. 2. Triangular fuzzy intervals under α-cut.

For instance, $(x_{12,\mathrm{L}}, x_{12,\mathrm{M}}, x_{12,\mathrm{U}})$ in Eq. (7) shows the lower, middle and upper value of the 1st element compared with the 2nd element at the higher level, respectively. To facilitate fuzzy weight computations, matrix $\tilde{\boldsymbol{A}}$ is further decomposed into three crisp matrices: the lower-bound matrix ($\boldsymbol{A}_\mathrm{L}$), most-likely matrix, ($\boldsymbol{A}_\mathrm{M}$), and upper-bound matrix ($\boldsymbol{A}_\mathrm{U}$). Concerning $\boldsymbol{A}_\mathrm{U}$ as an example, $\boldsymbol{A}_\mathrm{U}$ is defined by

$$A_\mathrm{U} = \begin{bmatrix} 1 & x_{21,\mathrm{U}} & \ldots & x_{1n,\mathrm{U}} \\ x_{21,\mathrm{U}} & 1 & \ldots & x_{2n,\mathrm{U}} \\ \ldots & \ldots & \ldots & \ldots \\ x_{n1,\mathrm{U}} & \ldots & \ldots & 1 \end{bmatrix} \tag{8}$$

2.3. Calculation of element weight

The Normalization of the Geometric Mean (NGM) method used in Buckley's model is applied to compute local weights and given by [24,28]

$$w_i = \frac{g_i}{\sum_{i=1}^{n} g_i} \tag{9}$$

where

$$g_i = \left(\Pi_{j=1}^{n} r_{ij}\right)^{1/n} \tag{10}$$

In the above equations, g_i is geometric mean of criterion i. r_{ij} is the comparison value of criterion i to criterion j. w_i is the ith criterion's weight, where $w_i > 0$ and $\sum_{i=1}^{n} w_i = 1$, $1 \le i \le n$.

For group evaluation, it is required to aggregate manifold evaluators' opinions into one. The aggregate of multiple experts' evaluations encompasses a range of membership values that must be defuzzified in order to resolve a single representative value. In Buckley's model, fuzzy addition and fuzzy multiplication are used to derive fuzzy weights from group judgment, which are complicated and require considerable computational time. Instead, the proposed model employs the fuzzy max–min operator and center-of-gravity (COG) techniques because of their simplicity and efficiency. Fuzzy max–min operator is given by [34]

$$\mu_A(x) = \max\{\min[\mu_1(x), \mu_2(x), \ldots, \mu_n(x)]\} \tag{11}$$

where $\mu_A(x)$ is the membership value of the element x in the aggregated subset A; $\mu_1(x)$, $\mu_2(x)$,... $\mu_n(x)$ are membership grades representing the 1st, 2nd, …, and the nth evaluator's judgment, respectively.

The COG method is given by the following expression [35]

$$z^* = \frac{\int \mu(z) \cdot z dz}{\int \mu(z) dz} \tag{12}$$

where $\mu(z)$ is the membership value; z^* is the weighted average.

Accordingly, the overall weight of the lth sub-criterion, S_l, can be computed by

$$S_l = \sum_{i=1}^{L} w_k \times S_{lk} \tag{13}$$

where w_k is the weight of the kth main-criterion; S_{lk} is the local weight of the l^{th} sub-criterion with respect to the kth main-criterion.

Similarly, the overall weight of the mth alternative regarding the lth sub-criterion, R_m, is given by

$$R_m = \sum_{m=1}^{M} S_l \times R_{ml} \tag{14}$$

3. A case study

A new bridge construction project of the National Taiwan Secondary Freeway Project located in Tainan area was applied. The project owner, the Taiwan National Expressway Engineering Bureau, attempted to choose the most appropriate bridge construction method among Full-span and Pre-cast Launching Method, Advancing Shoring Method, Balanced Cantilever Method. Figs. 3–5 show these three operations. According to the report from the Taiwan National Expressway

Fig. 3. Full-span and Pre-cast Launching Method.

Fig. 4. Advancing Shoring Method.

Fig. 5. Balanced Cantilever Method.

Engineering Bureau [36], 34 (21%), 62 (38%), and 43 (26%) out of 157 new bridges over the past 10 years were constructed by using Full-span and Pre-cast Launching Method, Advancing Shoring Method, and Balanced Cantilever Method, respectively. Notably, these three technologies were preassigned feasible alternatives after a preliminary study conducted by the owner. A decision-making group was formed which was made up of eight domain experts who were in charge of the project and had worked on numerous similar bridge projects in Taiwan for a minimum of ten years. Four members were from the Engineering Bureau; and the remainders were from the corporation including project contractors and senior bridge engineers. Sufficient practice experience and suitable level of knowledge are the two criteria in identifying them as domain experts.

The basic hierarchy of the decision problem was constructed based on the experts' suggestions derived by using Delphi approach. That is, each expert was asked to identify possible factors that could somehow affect the final decision through several surveys, questionnaires and discussions until a consensus was reached. [37]. Also, the criteria used in the hierarchy were obtained and checked through the discussion process using Delphi approach and based on the suggestions from the references in [4–9]. As shown in Fig. 6, the top level and the lowest level of the hierarchy denote the overall objective (selecting the most appropriate bridge construction method) and the candidates, respectively. The five main criteria, namely quality, cost, safety, duration, and shape of bridge were included at the second level. The main criteria were further broken down into sub-criteria. Quality was characterized by durability and suitability. Cost was divided into construction cost and damage cost. Safety was associated with traffic conflict and site condition. Duration criterion was broken down into weather condition and constructability that affects productivity. Shape was divided into landscape, geometry, and environmental preservation. It should be noted that the criteria selected in the hierarchy may not be exhausted and absolute.

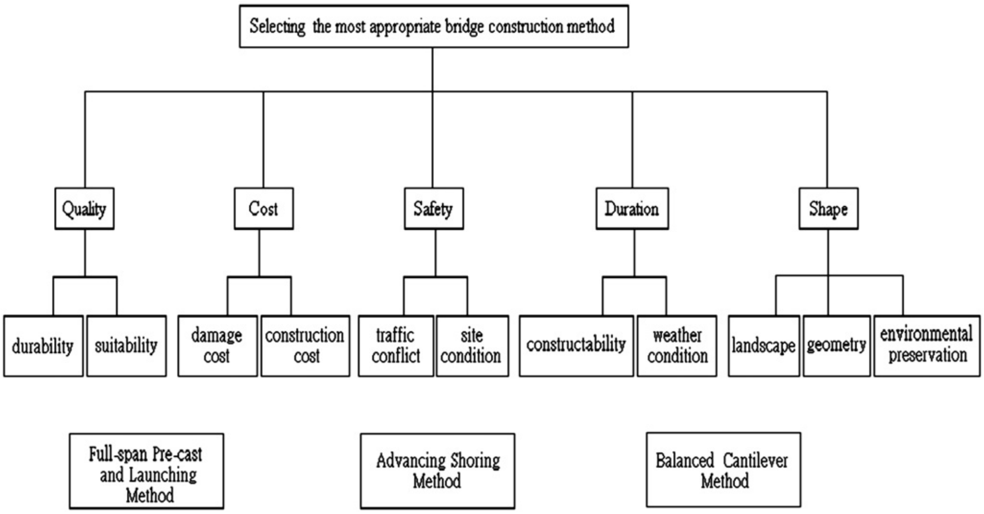

Fig. 6. The hierarchy for selecting bridge construction methods.

Table 2
Questionnaire used to assess main criteria

With respect to the overall goal “selection of the most desirable bridge construction method”
Q1. How important is *quality* (C_1) when it is compared to *cost* (C_2)?
Q2. How important is *quality* (C_1) when it is compared to *safety* (C_3)?
Q3. How important is *quality* (C_1)when it is compared to *duration* (C_4)?
Q4. How important is *quality* (C_1)when it is compared to *shape* (C_5)?
Q5. How important is *cost* (C_2) when it is compared to *safety* (C_3)?
Q6. How important is *cost* (C_2) when it is compared to *duration* (C_4)?
Q7. How important is *cost* (C_2) when it is compared to *shape* (C_5)?
Q8. How important is *safety* (C_3) when it is compared to *duration* (C_4)?
Q9. How important is *safety* (C_3) when it is compared to *shape* (C_5)?
Q10. How important is *duration* (C_4) when it is compared to *shape* (C_5)?

Once the hierarchy was established, experts' knowledge was elicited through interviews and questionnaires. A series of questionnaires were designed and used to direct pairwise comparison judgments. As an example, Table 2 depicts a particular questionnaire for evaluating main criteria with respect to the overall goal. By the use of Table 2, each expert performed a pairwise comparison to indicate his or her preference for each criterion. The assessment result can be found in Table 3. Similarly, the evaluation results of the sub-criteria relating to each main-criterion and the alternatives regarding each sub-criterion are shown in Tables 4 and 5, respectively.

To better illustrate the use of the proposed model, only the first and the second expert's assessment in Table 3 is exemplified. First, the fuzzy comparison matrix based on the first expert's judgment is given by

$$\tilde{A}^1 = \begin{bmatrix} 1 & (8,9,10,10) & (6,7.5,9) & (8,9,10,10) & (8,9,10,10) \\ (0,0,1,2) & 1 & (1,2.5,4) & (6,7.5,9) & (1,2.5,4) \\ (1,2.5,4) & (6,7.5,9) & 1 & (8,9,10,10) & (8,9,10,10) \\ (0,0,1,2) & (1,2.5,4) & (0,0,1,2) & 1 & (1,2.5,4) \\ (0,0,1,2) & (6,7.5,9) & (0,0,1,2) & (6,7.5,9) & 1 \end{bmatrix} \tag{15}$$

Thus, the upper-bound comparison matrix is given by

$$A_U^1 = \begin{bmatrix} 1 & 10 & 9 & 10 & 10 \\ 2 & 1 & 4 & 9 & 4 \\ 4 & 9 & 1 & 10 & 10 \\ 2 & 4 & 2 & 1 & 4 \\ 2 & 9 & 2 & 9 & 1 \end{bmatrix} \tag{16}$$

Next, the geometric mean of quality (C_1) with regard to cost (C_2), safety (C_3), duration (C_4), and shape (C_5) can be calculated by using Eq. (9) to produce the following

$$u_1 = (1 \times 10 \times 9 \times 10 \times 10)^{1/5} = 6.178 \tag{17}$$

By the same manner, the geometric mean for C_2, C_3, C_4, and C_5 yields 3.104, 5.143, 2.297, and 3.178, respectively. Hence, the relative

Table 3
Evaluation results of the main criteria with respect to the overall goal

Pairwise criteria	Results							
	1st expert	2nd expert	3rd expert	4th expert	5th expert	6th expert	7th expert	8th expert
Quality vs. Cost	VI	MI	VI	MI	VI	EI	EI	MI
Quality vs. Safety	MI	EI	EI	LI	EI	EI	EI	EI
Quality vs. Duration	VI	MI	VI	MI	EI	EI	MI	EI
Quality vs. Shape	VI	MI	MI	VI	MI	MI	MI	EI
Cost vs. Safety	LI	LI	LI	VU	EI	EI	EI	LI
Cost vs. Duration	MI	EI	EI	EI	EI	EI	EI	EI
Cost vs. Shape	LI	MI	MI	EI	MI	MI	EI	LI
Safety vs. Duration	VI	MI	MI	VI	EI	EI	MI	MI
Safety vs. Shape	VI	MI	VI	VI	MI	VI	VI	EI
Duration vs. Shape	LI	EI	EI	EI	MI	MI	MI	EI

Table 4
Evaluation results of the sub-criteria regarding the main criteria

Pairwise criteria	Results							
	1st expert	2nd expert	3rd expert	4th expert	5th expert	6th expert	7th expert	8th expert
Durability vs. suitability	EI	MI	EI	MI	MI	EI	EI	EI
Damage cost vs. construction cost	EI	LI	EI	LI	EI	EI	EI	EI
Traffic conflict vs. site condition	MI	EI	EI	EI	EI	VI	MI	EI
Constructability vs. weather condition	VI	EI	EI	VI	MI	MI	MI	MI
Landscape vs. geometry	VI	EI	EI	MI	MI	EI	MI	MI
Landscape vs. environmental	LI	EI	EI	EI	EI	EI	MI	EI
Preservation geometry vs. environmental preservation	VU	LI	EI	LI	LI	EI	LI	EI

Table 5
Judgment results for the alternatives with respect to the sub-criteria

Sub-criteria	Results							
	1st expert	2nd expert	3rd expert	4th expert	5th expert	6th expert	7th expert	8th expert
Durability*1	LI	LI	EI	LI	EI	VU	EI	EI
Durability*2	MI	EI	EI	MI	EI	VI	EI	EI
Durability*3	MI	MI	EI	MI	MI	MI	EI	EI
Suitability*1	LI	LI	EI	VU	EI	LI	EI	EI
Suitability*2	EI	MI	LI	MI	EI	MI	EI	EI
Suitability*3	MI	MI	MI	MI	EI	MI	MI	EI
Damage cost*1	VU	EI	LI	LI	EI	LI	LI	LI
Damage cost *2	LI	LI	EI	MI	EI	LI	EI	LI
Damage cost 3	MI	MI	MI	MI	EI	MI	VI	VI
Construction cost*1	VI	VI	MI	MI	MI	EI	MI	MI
Construction cost *2	VI	VI	MI	VI	MI	EI	LI	LI
Construction cost *3	LI	EI	EI	MI	MI	EI	EI	LI
Traffic conflict*1	LI	EI	EI	EI	EI	EI	MI	MI
Traffic conflict *2	MI	EI	LI	EI	EI	EI	MI	MI
Traffic conflict *3	VI	EI	MI	EI	EI	MI	EI	MI
Site condition*1	EI	MI	MI	EI	EI	EI	EI	EI
Site condition *2	EI	MI	MI	LI	LI	EI	MI	LI
Site condition *3	LI	MI	MI	LI	MI	EI	EI	LI
Constructability*1	EI	LI	EI	EI	LI	LI	EI	LI
Constructability *2	EI	MI	EI	EI	EI	EI	EI	EI
Constructability *3	EI	MI	EI	EI	EI	MI	MI	EI
Weather condition*1	LI	LI	LI	VU	EI	EI	EI	EI
Weather condition *2	LI	EI	LI	LI	LI	EI	EI	MI
Weather condition *3	LI	MI	EI	MI	EI	EI	MI	EI
Landscape*1	LI	MI	EI	LI	EI	EI	MI	EI
Landscape *2	VU	EI	LI	VU	EI	EI	EI	LI
Landscape *3	VU	EI	LI	LI	EI	EI	EI	LI
Geometry*1	LI	MI	EI	LI	EI	EI	EI	EI
Geometry *2	VU	EI	LI	VU	EI	EI	EI	LI
Geometry *3	VU	EI	LI	LI	EI	EI	EI	LI
Environmental preservation*1	VI	EI	EI	EI	EI	EI	MI	EI
Environmental preservation *2	MI	EI	EI	LI	EI	EI	MI	LI
Environmental preservation *3	VU	EI	LI	LI	EI	EI	EI	LI

Note: *1 denotes the relative importance of Full-span and Pre-cast Launching Method when it compared to Advancing Shoring Method regarding the sub-criterion.
*2 denotes the relative importance of Full-span and Pre-cast Launching Method when it compared to Balanced Cantilever Method regarding the sub-criterion.
*3 denotes the relative importance of Advancing Shoring Method when it compared to Balanced Cantilever Method regarding the sub-criterion.

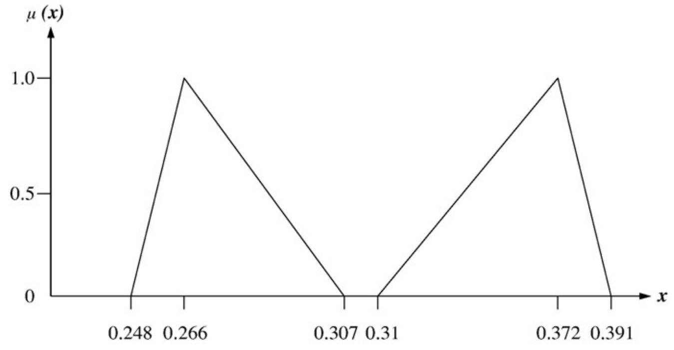

Fig. 7. Aggregation of two evaluators' assessments regarding quality.

weight of C_1 can be estimated by using Eq. (10) to the produce following:

$$w_1 = 6.178/(3.104 + 5.143 + 2.297 + 3.718) = 0.310 \tag{18}$$

Similarly, the weights for C_2, C_3, C_4, and C_5 yield 0.156, 0.260, 0.115, and 0.161, respectively. Also, regarding A^1_M and A^1_L, the weights for C_1, C_2, C_3, C_4, and C_5 result in (0.372, 0.144, 0.258, 0.096, 0.160) and (0.391, 0.112, 0.240, 0.078, 0.149), respectively. Consequently, the minimum, mean, and maximum weight of C_1 yields (0.310, 0.372, 0.391).

By the same manner, the weight of C_1 deriving from the second expert's judgment yields (0.248, 0.266, 0.307). By using Eq. (11), the aggregate of the two experts' evaluations can be obtained as shown in Fig. 7. Thus, the representative weight of quality (C_1), z^*, can be found by using Eq. (12) to produce the following

$$\begin{aligned} Z^*_{\text{quality}} = & \left\{ \int_{0.310}^{0.372} \frac{1-0}{0.372-0.310}(x-0.310)xdx + \int_{0.372}^{0.391} \left(\frac{0-1}{0.391-0.372}(x-0.372)+1 \right) xdx \right. \\ & \left. + \int_{0.248}^{0.266} \frac{1-0}{0.266-0.248}(x-0.248)xdx + \int_{0.266}^{0.307} \left(\frac{0-1}{0.307-0.266}(x-0.266)+1 \right) xdx \right\} \\ & \div \left\{ \int_{0.310}^{0.372} \frac{1-0}{0.372-0.310}(x-0.310)dx + \int_{0.372}^{0.391} \left(\frac{0-1}{0.391-0.372}(x-0.372)+1 \right) dx \right. \\ & \left. + \int_{0.248}^{0.266} \frac{0-1}{0.266-0.248}(x-0.248)dx + \int_{0.266}^{0.307} \left(\frac{0-1}{0.307-0.266}(x-0.266)+1 \right) dx \right\} \\ = & \ 0.322 \end{aligned} \tag{19}$$

By using the foregoing procedures and the whole experts' evaluations (Table 3), the weights for quality, cost, safety, duration, and shape yield (0.297, 0.156, 0.294, 0.142, 0.139), (0.298, 0.163, 0.293, 0.146, 0.124), and (0.276, 0.159, 0.277, 0.155, 0.133) regarding α=0, α=0.5 and α=1, respectively. The results indicate that quality and safety are the two most important main criteria for selecting a bridge construction technique in this case study; whereas bridge shape is least important. Based on the main criteria weights, the overall weights of sub-criteria can be estimated by using Table 4 and Eq. (13). Table 6 displays the results. Applying Tables 5 and 6 and Eq. (14), the alternative weight can be obtained as shown in Table 7. Consequently, the final alternative weight can be derived by summing all the weights up. It can be found in the bottom row of Table 7, the weights for Full-span and Pre-cast Launching Method, Advancing Shoring Method, Balanced Cantilever Method regarding α=0, 0.5, and 1 are (0.352, 0.380, 0.294), (0.361, 0.387, 0.289) and (0.328, 0.370, 0.294), respectively. The result suggests that Advancing Shoring Method is the most appropriate alternative. The result also reflects the fact that this operation is dominant (38% of usage) in Taiwan [37].

Table 7
Overall weights of the alternatives estimated by the proposed model

Sub-criteria	Method			
	α	Full-span Pre-cast & Launching Method	Advance Shoring Method	Incremental Launching Method
Durability	0	0.055	0.077	0.045
	0.5	0.055	0.075	0.04
	1	0.048	0.067	0.040
Suitability	0	0.033	0.048	0.026
	0.5	0.035	0.055	0.029
	1	0.036	0.053	0.031
Damage cost	0	0.015	0.027	0.015
	0.5	0.016	0.031	0.017
	1	0.018	0.035	0.020
Construction cost	0	0.047	0.024	0.033
	0.5	0.048	0.025	0.028
	1	0.040	0.022	0.025
Traffic conflict	0	0.075	0.076	0.043
	0.5	0.063	0.057	0.033
	1	0.057	0.058	0.043
Site condition	0	0.040	0.034	0.035
	0.5	0.059	0.047	0.045
	1	0.042	0.036	0.040
Constructability	0	0.021	0.030	0.018
	0.5	0.028	0.041	0.024
	1	0.028	0.037	0.027
Weather condition	0	0.018	0.030	0.018
	0.5	0.015	0.023	0.019
	1	0.017	0.025	0.022
Landscape	0	0.009	0.010	0.018
	0.5	0.013	0.013	0.022
	1	0.015	0.014	0.017
Geometry	0	0.008	0.008	0.014
	0.5	0.007	0.008	0.013
	1	0.009	0.009	0.014
Environmental preservation	0	0.031	0.016	0.029
	0.5	0.022	0.012	0.019
	1	0.018	0.014	0.015
Sum of weights	0	0.352	0.380	0.294
	0.5	0.361	0.387	0.289
	1	0.328	0.370	0.294

4. Discussions

To justify the capability of the approach, Buckley's model was used to analyze this case problem. Note that the α-cut concept was employed in Buckley's method by the author to enable this method to deal with various values. Table 8 displays the final alternative weights estimated by Buckley's method. As shown in the table, the weights of criteria and alternatives assessed by the two models are similar. However, the proposed model is easier and faster than Buckley's model.

To guarantee the performance of the model, the model was also evaluated by ten potential end-users from Taiwan and the United States for various criteria such as applicability, similarity, efficiency, and the overall performance of the approach. Each of these criteria

Table 6
Overall sub-criteria weights under α=0, 0.5, and 1

α	Durability	Suitability	Damage cost	Construction cost	Traffic conflict	Site condition	Constructability	Weather condition	Landscape	Geometry	Environmental preservation
0	0.186	0.111	0.059	0.098	0.193	0.101	0.073	0.069	0.036	0.029	0.074
0.5	0.178	0.120	0.066	0.097	0.150	0.143	0.092	0.054	0.046	0.026	0.051
1	0.155	0.121	0.072	0.086	0.158	0.118	0.092	0.064	0.051	0.032	0.051

Table 8
Overall weights of the alternatives estimated by Buckley's method

Sub-criteria	Method			
	α	Full-span Pre-cast & Launching Method	Advance Shoring Method	Incremental Launching Method
Durability	0	0.055	0.077	0.045
	0.5	0.053	0.074	0.038
	1	0.045	0.063	0.039
Suitability	0	0.033	0.048	0.026
	0.5	0.036	0.058	0.029
	1	0.037	0.052	0.030
Damage cost	0	0.015	0.027	0.015
	0.5	0.017	0.038	0.019
	1	0.014	0.032	0.020
Construction cost	0	0.047	0.024	0.033
	0.5	0.052	0.032	0.025
	1	0.043	0.030	0.023
Traffic conflict	0	0.075	0.076	0.043
	0.5	0.068	0.063	0.034
	1	0.061	0.063	0.030
Site condition	0	0.040	0.034	0.035
	0.5	0.056	0.048	0.041
	1	0.046	0.042	0.040
Constructability	0	0.021	0.030	0.018
	0.5	0.028	0.043	0.022
	1	0.028	0.041	0.024
Weather condition	0	0.018	0.030	0.018
	0.5	0.013	0.021	0.018
	1	0.020	0.025	0.022
Landscape	0	0.009	0.010	0.018
	0.5	0.015	0.015	0.024
	1	0.013	0.014	0.019
Geometry	0	0.008	0.008	0.014
	0.5	0.008	0.008	0.015
	1	0.007	0.008	0.013
Environmental preservation	0	0.031	0.016	0.029
	0.5	0.025	0.014	0.017
	1	0.020	0.015	0.016
Sum of weights	0	0.352	0.380	0.294
	0.5	0.371	0.414	0.282
	1	0.334	0.385	0.276

and the overall performance of the model were rated in a range between good and very good. This demonstrates the effectiveness and practicability of the approach.

5. Conclusions

Accurately choosing the most suitable bridge construction operation is vital for the success of a bridge project. This paper presents a fuzzy AHP model to tackle the problem of the AHP model arising from transforming one's imprecise judgment into an exact number. In this approach, both of triangular and trapezoidal typed fuzzy numbers are utilized to overcome the difficulties of other fuzzy AHP methods which cannot simultaneously handle these two types of fuzzy numbers. Also, each negative reciprocal element in the comparison matrix is directly characterized by its own fuzzy number rather than a tedious inverse and reversed order of the corresponding positive fuzzy number used in Buckley's model. Besides, the α-cut concept is applied to adequately measure different levels of uncertainty involving the decision process. Moreover, the max–min aggregation and COG defuzzification techniques are utilized to avoid complicated fuzzy arithmetic. Consequently, the approach is simpler, faster and more efficient.

The outputs produced by the model are the weights of sub-criteria, main criteria, and alternatives. The input requirements include (1) the hierarchy of the decision problem, and (2) the pairwise comparison judgments. Since these are dependent on the expert's assessments, the expert's inputs to problem solving are essential for the approach. Moreover, a suitable level of experience on the part of the expert is crucial because the expert usually relies heavily on experiences and knowledge while evaluating alternatives. Likewise, a judgment of the quality of information regarding design and construction, and sufficient knowledge of the expertise is also significant for the assessments.

A case study involving an actual highway project was presented to illustrate the use of the proposed model which allows users to simulate experts' judgment. The result demonstrates the capability and effectiveness of the model that can assist project contractors to better evaluate bridge construction methods.

Notably, the use of the proposed model is not restricted to the types and numbers of bridge construction methods. The three bridge construction methods considered in the study is simply because they are preassigned alternatives. Also, the list of the selected criteria and alternatives may not be an inclusive list in the case study. Thus, one may comprise more bridge alternatives, establish more hierarchies or consider the problem in more detail. Furthermore, the model provides a structured and systematic approach for effectively identifying the preferred bridge construction technique. It may be applied for different areas of construction management and solving a large-scale decision-making problem. However, it could lead to a great deal of calculations as the numbers of criteria and alternatives increase considerably. Therefore, developments of a computer system or a decision support system (e.g., expert system) are useful to facilitate the process of analysis. These are suggestions for future studies.

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