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Fuzzy AHP approach for selecting the suitable bridge construction method

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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.

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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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,…, m), (2) a set of evaluation criteria, C_j (j=1, 2, …, 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, $\tilde{A}$, representing fuzzy relative importance of each pair elements is given by

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

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)

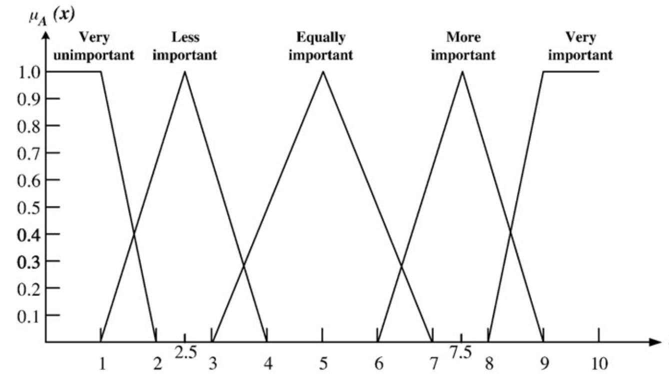

Fig. 1. Membership functions for linguistic values.

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.α=0 and α=1, signify the degree of uncertainty is greatest and least, respectively. In practical applications, α=0, α=0.5, and α=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 ($X_{\alpha,L}$, $X_{\alpha,M}$, $X_{\alpha,R}$). $X_{\alpha,M}$, $X_{\alpha,L}$, and $X_{\alpha,R}$ 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).

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

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

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

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

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

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

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