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M. Ammar Alzarrad
Bradley University

Gary P. Moynihan
The University of Alabama

Muhammad T. Hatamleh
The University of Alabama

Siyuan Song
University of Southern Mississippi

Hindawi
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Research Article

Fuzzy Multicriteria Decision-Making Model for Time-Cost-Risk Trade-Off Optimization in Construction Projects

M. Ammar Alzarrad,[1] **Gary P. Moynihan**,[2] **Muhammad T. Hatamleh**,[2] **and Siyuan Song**[3]

[1]*Department of Civil Engineering and Construction, Bradley University, Peoria, IL 61625, USA*
[2]*Department of Civil, Construction and Environmental Engineering, The University of Alabama, Tuscaloosa, AL 35487, USA*
[3]*School of Construction and Design, The University of Southern Mississippi, Hattiesburg, MS 39406, USA*

Correspondence should be addressed to M. Ammar Alzarrad; malzarrad@fsmail.bradley.edu

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As is often the case in project scheduling, when the project duration is shortened to decrease total cost, the total float is lost resulting in added critical or nearly critical activities. This, in turn, results in decreasing the probability of completing the project on time and increases the risk of schedule delays. To solve this problem, this research developed a fuzzy multicriteria decision-making (FMCDM) model. The objective of this model is to help project managers improve their decisions regarding time-cost-risk trade-offs (TCRTO) in construction projects. In this model, an optimization algorithm based on fuzzy logic and analytic hierarchy process (AHP) has been used to analyze the time-cost-risk trade-off alternatives and select the best one based on selected criteria. The algorithm was implemented in the MATLAB software and applied to two case studies to verify and validate the presented model. The presented FMCDM model could help produce a more reliable schedule and mitigate the risk of projects running overbudget or behind schedule. Further, this model is a powerful decision-making instrument to help managers reduce uncertainties and improve the accuracy of time-cost-risk trade-offs. The presented FMCDM model employed fuzzy linguistic terms, which provide decision-makers with the opportunity to give their judgments as intervals comparing to fixed value judgments. In conclusion, the presented FMCDM model has high robustness, and it is an attractive alternative to the traditional methods to solve the time-cost-risk trade-off problem in construction.

1. Introduction

Project management has a vital role in modern management. It is noted as the application of knowledge, skills, tools, and techniques in project activities to reach the project requirements [1]. In project management, the fundamental project concepts of time, cost, and risk are conflicting terms which should be appropriately assigned to project activities to achieve the desired objectives of project stakeholders [2]. There are many occasions where the owner informs the contractor that the schedule must be shortened. This action could lead to increases in total cost as well as risk. To accelerate the execution of a project, project managers need to reduce the scheduled execution time by hiring additional labor or using productive equipment. But, this idea will increase cost and risk, hence shortening the completion time of jobs on critical path network is needed.

Time-cost trade-off (TCT) is a common approach applied by project managers to reach the required completion time of the projects with the least extra cost [3]. In fact, TCT deals with modifying implementation time of project activities while doing a trade-off between the completion time and the project cost [4]. Several approaches were introduced in addressing risk in time-cost trade-off problems (TCTPs). He et al. addressed the preemptive time-cost-risk trade-off project scheduling through a multiobjective multimode model [5]. Hosseini-Nasab et al. applied variable neighborhood search and tabu search to handle the TCT problem [6]. Mohagheghi et al. introduced a multicriteria decision-making model for Time-cost-quality trade-off problem in construction projects [7]. The NSGA-II procedure was used to identify Pareto optimal solutions [7]. Eirgash et al. determined the optimal set of time-cost alternatives using a multiobjective teaching-learning-based optimization (TLBO) algorithm to successfully optimize small to medium projects [8]. Tran et al. presented fuzzy earned value management into a TCTP and used a statistical-based approach [9]. Tseng et al. proposed a two-phase differential evolution model to address construction project TCTP under resource-constrained limitations [10]. Zhang and Zhong, presented a multiobjective approach for solving discrete time-cost-risk trade-off problems with mode-identity and resource-constrained situations [11]. In this paper, a FMCDM model has been developed based on the fuzzy analytic hierarchy process (FAHP) algorithm. The objective of the presented model is to analyze the time-cost-risk trade-off alternatives and select the best one based on selected criteria. The presented algorithm was implemented in the MATLAB software and compared with other methods to qualify the magnitude of improvement that the proposed FMCDM model presents.

2. Fuzzy Multicriteria Decision-Making (FMCDM)

Some decision situations involve a multitude of objectives or decision criteria that may be inaccurate and conflict with each other. Decision analysis considers the paradigm in which decision-makers contemplate a choice of action in a risky environment. Decision analysis is designed to help decision-makers choose between a set of predetermined alternatives [12]. The variety in the quality of the available data about a decision-related problem calls for models and tools that can help in data processing. The analytic hierarchy process (AHP) is a decision-making procedure to help decision-makers establish priorities to take the best possible decision. Analytic hierarchy process (AHP) is a system of measurement using pairwise comparisons and depends mainly on the experts' opinions [13]. Al-Harbi [14] led a study in which the AHP is applied as a decision-making technique to assess the problem of contractor qualification. The traditional AHP technique is not considered to be able to deal with the risks involved in the criteria [15]. There is an extensive literature which addresses the situation in the real world where the AHP comparison criteria are imprecise judgments. To reduce the bias associated with traditional AHP, this paper utilizes fuzzy analytic hierarchy process (FAHP) as a tool to provide decision support for construction project managers. The presented FAHP utilizes triangular fuzzy numbers (TFN) to capture expert opinions. A triangular fuzzy number (μ) can be defined as a triplet (a_1, a_M, a_2). This parameter (a_1, a_M, a_2) signifies the smallest possible value, the most promising value, and the largest possible value, respectively [12]. In FAHP, the pairwise evaluations of both criteria and the alternatives are completed using linguistic terms, which are represented by TFN. The α-cut method is a common technique to do arithmetic operations on a triangular membership function [16].

The α-cut signifies the degree of risk that the project managers are ready to take (i.e., no risk to full risk). Because the value of α could significantly affect the solution, it should be wisely chosen by project managers. Figure 1 shows a TFN with α-cut. The higher the value of α, the lower the risk ($\alpha = 1$ means no risk) [17].

In this paper, triangular fuzzy number with α-cut and analytic hierarchy process (AHP) is used to help decision-makers establish priorities to take the best possible decision regarding the TCRTO problem. The presented FMCDM model consists of four stages, as follows.

2.1. FMCDM Model Stage 1.

In stage one, the cost, time, and risk alternatives are calculated using the following objective functions:

$$\min f_1 = \sum_{i=1}^{n} t_{ij}\left(x_{ij}\right), \tag{1}$$

$$\min f_2 = \sum_{i=1}^{n} C_{ij}\left(x_{ij}\right) + \sum_{i-1}^{n} C_f, \tag{2}$$

$$\min f_3 = \sum_{i=1}^{n} R_{ij}, \tag{3}$$

$$S_j - S_i \geq t_{ij}\left(x_{ij}\right), \tag{4}$$

$$I_{ij} \leq X_{ij} \leq U_{ij}, \tag{5}$$

$$X_1 = 0, \tag{6}$$

$$\begin{aligned} C_R &\geq 0, \\ t_{ij}\left(x_{ij}\right) &\geq 0, \\ x_i &\geq 0. \end{aligned} \tag{7}$$

Equations (1)–(3) are the objective functions. They minimize the time, cost, and risk, respectively. The constraints are represented by equations (4) and (7). Equation (4) represents the precedence constraint. Equation (5) ensures normal and crash times represent the upper and lower limits of project duration which should not be violated. Equation (6) represents the start time which should always be zero. Equation (7) represents the nonnegativity constraint. The notations and variables used in the above equations are as follows:

i: index of activities
j: index of nodes in project network
t_{ij} (x_{ij}): expected duration of an activity
C_{ij} (x_{ij}): the normal cost of an activity
R_{ij}: total value of risk for project activities
S_i: start time of activity i
S_j: start time of node j

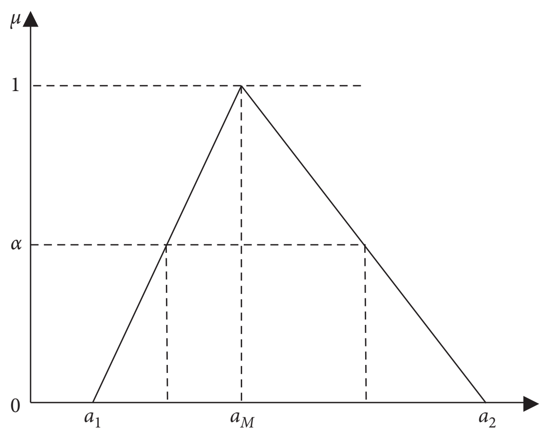

Figure 1: Triangular fuzzy number with α-cut [7].

This step generates ten alternatives for cost, time, and risk based on different α-cut values that range from 0.1 to 1 with an increment of 10%.

2.2. FMCDM Model Stage 2. In stage two, data are gathered from decision-makers to compare alternatives based on a fuzzy scale. In traditional AHP, a scale of real numbers from one to nine is used to assign preferences [13]. When comparing two alternatives, the significance of the assigned number can be gauged by using the pairwise comparison measurement scale shown in Table 1 as suggested by Saaty [13]. Intermediate numbers are used to add further resolution to the judgments.

To fuzzify this numeric scale, TFN is used to represent uncertainty in the traditional AHP approach. This model uses the linguistic variables and the fuzzy triangular scale that are shown in Table 2, as suggested by Alzarrad and Fonseca [12].

The decision-makers compare the criteria or alternatives using the linguistic terms shown in Table 2, according to the matching TFN of these terms. For example, if the decision-makers state, "Time (criterion 1) is very strongly favored compared to cost (criterion 2)," then it takes the scale of (6, 7, 8). Conversely, comparison of cost (criterion 2) to time (criterion 1) will take the scale of (1/8, 1/7, 1/6). This step involves two objectives:

(1) Compare the alternatives with respect to criteria

(2) Compare the criteria with respect to the goal

2.3. FMCDM Model Stage 3. The third stage is to develop pairwise fuzzy comparison matrices. This consists of matrices of pairwise assessments of the contribution of elements at one level, to achieve the objectives of the next higher level. The diagonal elements of all three matrices are (1, 1, 1) because they are the result of comparing identical criteria. A pairwise fuzzy comparison matrix ($\widetilde{A}$) is shown as follows:

Table 1: Traditional AHP numerical scale.

Location	Saaty scale
Extremely favored (E. Fav)	9
Very strong favored (V.S. Fav)	7
Strongly favored (S. Fav)	5
Moderately favored (M. Fav)	3
Equal (equal)	1
Moderately disfavored (M. Disfav)	1/3
Strongly disfavored (S. Disfav)	1/5
Very strongly disfavored (V.S. Disfav)	1/7
Extremely disfavored (E. Disfav)	1/9
Intermediate values	2, 4, 6, 8

Table 2: Fuzzy triangular scale for fuzzy AHP.

Location	Saaty scale
Extremely favored (E. Fav)	(9, 9, 9)
Very strong favored (V.S. Fav)	(6, 7, 8)
Strongly favored (S. Fav)	(4, 5, 6)
Moderately favored (M. Fav)	(2, 3, 4)
Equal (equal)	(1, 1, 1)
Moderately disfavored (M. Disfav)	(1/4, 1/3, 1/2)
Strongly disfavored (S. Disfav)	(1/6, 1/5, 1/4)
Very strongly disfavored (V.S. Disfav)	(1/8, 1/7, 1/6)
Extremely disfavored (E. Disfav)	(1/9, 1/9, 1/9)
Middle value of 1 and 3	(1, 2, 3)
Middle value of 3 and 5	(3, 4, 5)
Middle value of 5 and 7	(5, 6, 7)
Middle value of 7 and 9	(7, 8, 9)

$$\widetilde{A} = \begin{bmatrix} d_{11} & d_{12} & \dots & d_{1n} \\ d_{21} & d_{22} & \dots & d_{2n} \\ \dots & \dots & \dots & \dots \\ d_{n1} & d_{n2} & \dots & d_{nn} \end{bmatrix}, \quad (8)$$

where d_{ij} indicates the decision maker's preference of i^{th} criterion over j^{th} criterion through TFN.

2.4. FMCDM Model Stage 4. This step involves the determination of the relative priorities of each element, at a specific level, with respect to the level immediately above. The relative weights of all the elements at the various levels are aggregated in order to find a vector of composite weights, which will serve as a rating of the decision alternatives to attain the general goal of the problem. The relative weights are denoted by a vector (w) called the priority vector. There are a number of techniques to determine the relative weights. The most commonly used technique is the eigenvalue method [18]. According to the eigenvalue method, the relative priorities of each element at a particular level can be calculated using the following steps:

(1) Find the geometric mean of fuzzy comparison values of each criterion and alternative using the following equation:

$$r_i = \left(\prod_{j=1}^{n} d_{ij} \right)^{1/n}, \quad (9)$$

where r_i = geometric mean and n = number of criteria or alternatives

(2) Find the reciprocal value of the r_i summation ($1/\sum r_i$) and arrange these values in increasing order

(3) The priority vector (w_i) for each criterion or alternative can be calculated using the following equation:

$$w_i = r_i * \left(\frac{1}{\sum r_i} \right). \quad (10)$$

(4) Since w_i are still TFN, they need to defuzzified by the Centre of Gravity method via applying the following equation:

$$w_{\text{crisp}} = \frac{lw_i + mw_i + hw_i}{3}, \quad (11)$$

where lw_i = the low value of w_i in the comparison rating, mw_i = the medium value of w_i in the comparison rating, hw_i = the high value of w_i in the comparison rating, and w_{crisp} = the defuzzified value priority vector (w_i) for each criterion or alternative

(5) Normalize w_{crisp} by using the following equation:

$$w_n = \frac{w_{\text{crisp}}}{\sum w_{\text{crisp}}}. \quad (12)$$

By using these five steps, the normalized weights can be found. Then, the scores for each alternative can be calculated. Finally, the alternative with the largest score is recommended as the first priority of decision-makers.

3. Verification and Validation

To illustrate an implementation of the FMCDM model, two case studies are used to verify and validate the model.

3.1. Case One. The first case study is proposed initially by Gen and Cheng [19]. The FMCDM model is applied to this case to help the decision-makers determine the project optimal time-cost-risk balance. The case study shows a construction project that has seven activities as shown in Table 3. The calculated project duration is 60, 81, and 92 days for the optimistic, moderate, and pessimistic times, respectively. The calculated project cost is $270K, $245K, and $220K for pessimistic, moderate, and optimistic.

The presented model generates the result as shown in Table 4.

Table 3: Activity duration and cost.

Activity	Predecessor	Optimistic time	Moderate time	Pessimistic time
A	—	14	20	24
B	A	15	18	20
C	A	15	22	33
D	A	12	16	20
E	B, C	22	24	28
F	D	14	18	24
G	E, F	9	15	18

Based on the results in Table 4, alternative 10 has the largest total score which is 0.255. Therefore, it is recommended as the best choice to minimize the risk and maintain the time-cost balance. To evaluate the result, a software called Expert Choice © is used. Expert Choice is a decision-making software that uses traditional AHP to select the best choice from a group of existing options [20].

Figure 2 shows a comparison between the Expert Choice result and the result obtained by using the FMCDM model.

At first glance, the results look similar, but to further compare the results, a test called Wilcoxon signed-rank test is performed. The method to perform the Wilcoxon test starts with two hypotheses. A null hypothesis (H_0) states that the results obtained from the two approaches are the same. An alternative hypothesis (H_1) states that the results obtained from the two approaches are not the same [21]. Table 5 shows the Wilcoxon signed-rank test result.

Table 5 shows that the p value is 0.006 which is less than the significance level of 0.05. As a result, there is enough evidence to reject the H_0 hypothesis and to conclude that the difference between the results obtained from the two approaches is significant. Although alternative 10 is recommended as the best choice by both the presented model and the Expert Choice software, the scores assigned by each approach are different.

3.2. Case Two. Case two is a concrete bridge project, which was first introduced by Zhang and Zhong [11]. This case consists of six activities as shown in Table 6. The calculated project duration is 180, 199, and 217 days for the optimistic, moderate, and pessimistic times, respectively. The calculated project cost is $1500, $1900, and $2500 for pessimistic, moderate, and optimistic, respectively.

The presented model generates the result as shown in Table 7.

Based on the results in Table 7, alternative one has the highest score, which is 0.240. Therefore, it is recommended as the best choice. Expert Choice has been used to evaluate the result of the presented model. Figure 3 shows a comparison between the Expert Choice result and the result obtained by using the FMCDM model. Wilcoxon test has been used to further evaluate the results. Table 8 shows the Wilcoxon signed-rank test result.

Table 8 shows that the P value is 0.005 which is less than the significance level of 0.05. As a result, there is enough evidence to conclude that the difference between the results obtained from the two approaches is significant. Although

Table 4: Results of the FMCDM model (case one).

	Weights	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7	Alt. 8	Alt. 9	Alt. 10
Time	0.111	0.290	0.242	0.148	0.107	0.070	0.047	0.038	0.028	0.017	0.013
Cost	0.111	0.013	0.016	0.027	0.037	0.058	0.084	0.105	0.144	0.231	0.286
Risk	0.777	0.013	0.016	0.027	0.037	0.058	0.084	0.105	0.144	0.231	0.286
Total scores		**0.044**	**0.041**	**0.040**	**0.044**	**0.059**	**0.080**	**0.097**	**0.131**	**0.207**	**0.255**

The bold values represent the total weight score for each alternative.

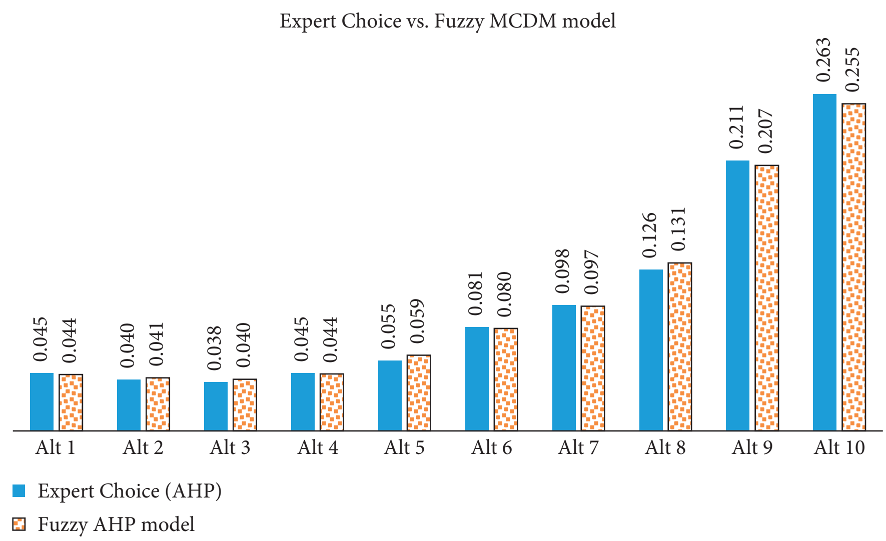

Figure 2: Expert Choice results vs FMCDM model results (case one).

Table 5: Activity duration and cost.

Source	N	Wilcoxon statistic	P value	Estimated median
FMCDM	10	55.0	0.006	0.086
Expert Choice	10	55.0	0.006	0.083

Table 6: Activity duration.

Activity	Optimistic time	Moderate time	Pessimistic time
A	26	28	30
B	40	42	46
C	36	38	40
D	83	85	87
E	18	20	22
F	22	25	28

Table 7: Results of the FMCDM model (case two).

	Weights	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7	Alt. 8	Alt. 9	Alt. 10
Time	0.819	0.290	0.242	0.148	0.107	0.070	0.047	0.038	0.028	0.017	0.013
Cost	0.091	0.013	0.016	0.027	0.037	0.058	0.084	0.105	0.144	0.231	0.286
Risk	0.091	0.013	0.016	0.027	0.037	0.058	0.084	0.105	0.144	0.231	0.286
Total scores		**0.240**	**0.201**	**0.126**	**0.094**	**0.068**	**0.054**	**0.050**	**0.049**	**0.055**	**0.063**

The bold values represent the total weight score for each alternative.

Alternative one is recommended as the best choice by both the presented model and the Expert Choice software, and the scores assigned by each approach are different. Further, the proposed FMCDM model allows better modeling of the uncertainty, and it takes care of more decision-makers' preferences compared with classical AHP.

4. Results and Limitations

In this paper, a FMCDM model is presented and compared with the classical AHP method that is implemented by use of the Expert Choice software. Two case studies have been used to verify and validate the presented model. Using the first

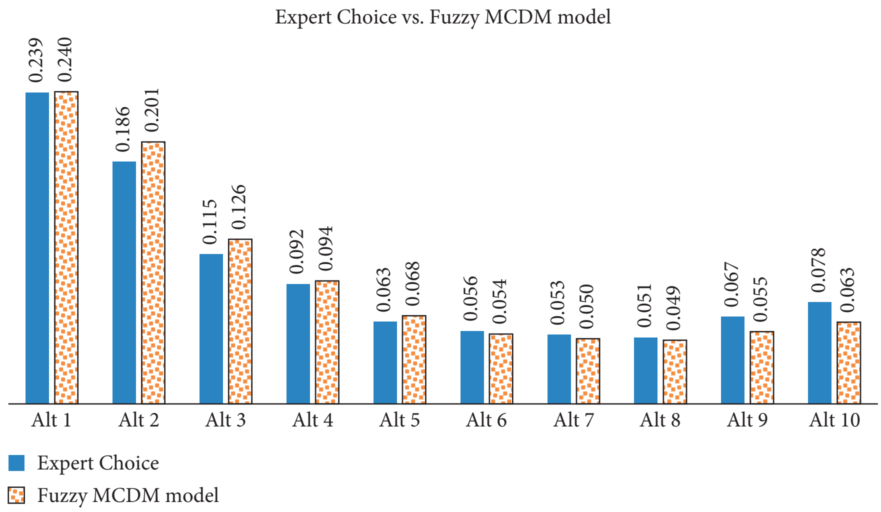

Figure 3: Expert Choice results vs FMCDM model results (case two).

Table 8: Activity duration and cost.

Source	N	Wilcoxon statistic	P value	Estimated median
FMCDM	10	55.0	0.005	0.0840
Expert choice ©	10	55.0	0.005	0.0875

case study data, the result of the FMCDM model shows that alternative ten has higher priority (0.255) than the other alternatives. The result of the Expert Choice software also shows that alternative ten has higher priority (0.263) than the other alternatives. Using the second case study data, the result of the FMCDM model shows that alternative one has higher priority (0.240) than the other alternatives. The result of the Expert Choice software also shows that alternative one has higher priority (0.239) than the other alternatives. However, the statistical analysis of the results obtained by the presented model and the Expert Choice software shows that there is a significant difference between the two approaches. The presented model is better than other available methods because it used fuzzy linguistic variables for enabling the comparisons between the criteria. This provides decision-makers with the opportunity to provide their judgments as intervals compared to the fixed value judgments. The presented model is much easier to use because the decision-makers feel much more comfortable with using linguistic variables compared to providing precise, crisp judgments [22]. The main limitation of the proposed model is the α-cut values that have been used in this research. Further research could be done to evaluate α-cut effect on the FMCDM model results. This will help investigate further the sensitivity of the model to α-cut change. Finally, the presented FMCDM model is a flexible decision-making model to help managers reduce uncertainties and improve the accuracy of their decision.

Data Availability

The data used in this study can be accessed at DOI: 10.1002/9780470172261.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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