Chapter 6

A New Model to Improve Project Time-Cost Trade-Off in Uncertain Environments

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Additional information is available at the end of the chapter

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Abstract

The time–cost trade-off problem (TCTP) is fundamental to project scheduling. Risks in estimation of project cost and duration are significant due to uncertainty. This uncertainty cannot be eliminated by any scheduling or estimation techniques. Therefore, a model that can represent uncertainty in the real world to solve time–cost trade-off problems is needed. In this chapter, fuzzy logic is utilized to consider affecting uncertainties in project duration and cost. An optimization algorithm based on time-driven activity-based costing (TDABC) is applied to provide a trade-off between project time and cost. The presented model could solve the time–cost trade-off problem while accounting for uncertainty in project cost and duration. This could help generate a more reliable schedule and mitigate the risk of projects running overbudget or behind schedule.

Keywords: scheduling, fuzzy logic, time–cost trade-off, cost estimating, risk management

1. Introduction

Operation management (OM) is vital to achieve success in many disciplines, particularly in a field which requires dealing with large amounts of information such as the construction industry. Most construction projects are a collection of different activities, processes and requirements, involving different factors and aspects to consider. In this way, making decisions in such environments can be a hard task. For these reasons, the need for OM to assist the characterization of such complex scenarios arises. OM could help project managers to improve their decision regarding project time–cost trade-offs (TCTP) [1]. To expedite the execution of a project, project managers need to reduce the scheduled execution time by hiring

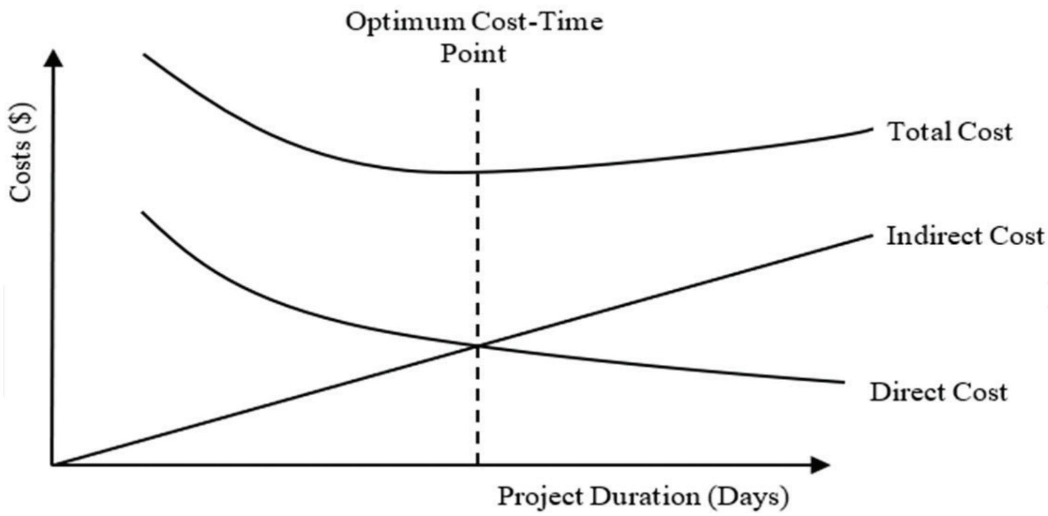

Figure 1. Project cost and time relationship.

extra labor or using productive equipment. But this idea will incur additional cost; hence, shortening the completion time of jobs on critical path network is needed. According to several researchers, time–cost trade-off problem (TCTP) is considered as one of the vital decisions in project accomplishment [2]. Usually, there is a trade-off between the duration and the direct cost to do an activity; the cheaper the resources, the larger the time needed to complete an activity. Reducing the time on an activity will usually increase its direct cost. Direct costs for the project contain materials cost, labor cost and equipment cost. Conversely, indirect costs are the necessary costs of doing work which cannot be related to a specific activity and in some cases, cannot be related to a specific project. The total project construction cost can be found by adding direct cost to indirect cost. When the trade-off of all the activities is considered in the project then the relationship between project duration and the total cost is developed as shown in **Figure 1**. **Figure 1** shows that when the duration for the project is reduced, the total cost becomes quite high and as the duration increases, the total cost increases [3]. The literature review of current practices reveals a shortage of existing tools and techniques specifically tailored to solve the time–cost trade-off problem while accounting for uncertainty in project time and cost. The objective of this research is to develop a model to find time–cost trade-off alternatives using TDABC and fuzzy logic. The next sections discuss these analytical methods.

2. Time-driven activity-based costing

The activity-based costing (ABC) concept was first defined in the late 1980s by Robert Kaplan and William Burns [4]. At first, ABC was utilized by the manufacturing industry where technological expansions and productivity developments had reduced the proportion of direct costs but increased the proportion of indirect costs [5].

ABC was developed as a method to address problems associated with traditional cost management systems, which tend to be usable to accurately determine actual production and service costs or provide useful information for operating decisions. ABC is defined as “a method for tracing costs within a process back to individual activities” [6].

ABC has been used in the construction industry for cost estimating [7]. Further, ABC has been used to forecast the optimum duration of a project as well as the optimum resources required to complete a defined quantity of work in a timely and cost-effective manner [8]. Although traditional ABC systems provide construction managers with valuable information, many have been abandoned or never were implemented fully [3]. The traditional ABC system is costly to build, requires time to process, is difficult to maintain and is inflexible when needing modification [3]. These problems are particularly acute for small companies that are not likely to have a sophisticated information processing system. Further, ABC is very expensive for medium-sized-to-large companies.

To overcome the difficulties inherent in traditional ABC, Kaplan and Steven presented a new method called "time-driven activity-based costing (TDABC)." The new TDABC has overcome traditional ABC difficulties, offering a clear, accessible methodology that is easy to implement and update [4]. TDABC relies only on simple time estimates that, for example, can be established based on direct observation of processes [9].

TDABC utilizes time equations that directly allocate resource costs to the activities performed and transactions processed. Only two values need to be estimated: the capacity cost rate for the project (Eq. (1)) and the capacity usage by each activity in the project (Eq. (2)). Both values can be estimated easily and accurately [4]. Kaplan and Steven (2007) further define the capacity cost rate and the capacity usage as follows:

$$\text{Capacity cost rate} = \text{Total estimated cost} \div (\text{Working hours} \times \text{Efficiency rate}) \tag{1}$$

$$\text{Capacity usage rate} = \text{Capacity cost rate} \times \text{Activity duration} \times \text{Quantity} \tag{2}$$

Although TDABC has many advantages over ABC, TDABC is not flawless. There are many difficulties associated with this deterministic TDABC approach. TDABC is unable of accounting for any variation or uncertainty in the project cost and duration (Hoozée and Hansen, 2015). Research carried out in TDABC, so far, has applied deterministic approaches. But, because of uncertainty present in the estimation of project cost and duration, a fuzzy TDABC would lead to more accurate results [10].

3. Fuzzy logic

Fuzzy logic is a technique that provides a definite conclusion from vague and inaccurate information. Fuzzy set theory was first introduced by Zadeh in 1965. He was motivated after witnessing that human reasoning can utilize concepts and knowledge that do not have well-defined boundaries [11].

A useful method for investigating many everyday problems is fuzzy approximate reasoning or fuzzy logic. This technique is founded on the fuzzy set theory that allows the elements of a set to have variable degrees of membership, from a non-membership grade of 0 to a full membership of 1.0 [12]. This smooth gradation of values is what makes fuzzy logic tie well with the ambiguity and uncertainty of many everyday problems.

Fuzzy logic has become an important tool for many different applications ranging from the control of engineering systems to artificial intelligence. Fuzzy logic has been extended to handle the concept of partial truth, where the truth value may range between completely true and false [13]. Fuzzy logic and fuzzy hybrid techniques have been used to capture and model uncertainty in construction, thereby improving workforce and project management. Fuzzy logic can effectively capture expert knowledge and engineering judgment and combine these subjective elements with project data to improve construction decision-making, performance and productivity [14].

Among the various shapes of fuzzy numbers, the triangular fuzzy numbers (TFNs) are the most popular [15]. A triangular fuzzy number μA(x) can be defined as a triplet (a_1, a_M, a_2). Its membership function is defined as follows [16]:

$$\mu A(x) = \begin{cases} \frac{x - a_1}{a_M - a_1} & \text{for } a_1 \le x \le a_M \\ \frac{x - a_2}{a_M - a_2} & \text{for } a_M \le x \le a_2 \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

where $[a_1, a_2]$ is the interval of possible fuzzy numbers and the point $(a_M, 1)$ is the peak. This parameter (a_1, a_M, a_2) signifies the smallest possible value, the most promising value and the largest possible value, respectively [17]. **Figure 2** illustrates a TFN.

4. Fuzzy time-driven activity-based costing model

This model utilizes TDABC as a tool for tracing costs and time within a project back to individual activities. TFNs are proposed as a logical approach to manage uncertainty in the deterministic TDABC system. TFNs were used to signify vagueness of TDABC because of their simplification to formulate in a fuzzy environment. Further, they are potentially more intuitive than other complicated types of fuzzy numbers such as trapezoidal or bell-shaped fuzzy numbers [16]. This model has the ability to fuzzify the project cost and duration by

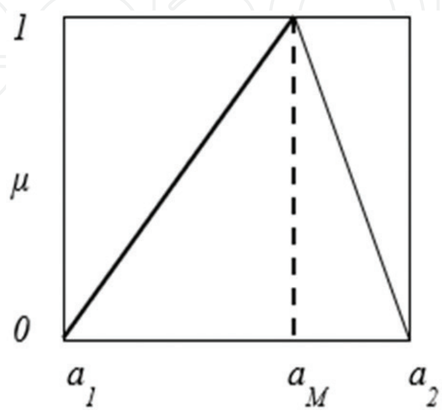

Figure 2. Triangular fuzzy number.

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transferring these values from crisp numbers to fuzzy sets. A crisp number has a specific value while a fuzzy set has a possible range of values [15]. Then after applying a fuzzy rule, the model will defuzzify the cost and duration of the project to transfer these values back to crisp numbers. **Figure 3** shows the fuzzy logic process that has been used in this model, as suggested by [14]. The fuzzy TDABC model consists of three stages as follows:

4.1. Model stage one

The first step in stage one is to transfer the three-point estimate of project duration from crisp values to the fuzzy set. This can be done by calculating the estimated project duration using one of the traditional scheduling techniques (i.e., CPM) [18]. This value will be called the moderate duration and will use the notation D_M. Then the pessimistic duration (the maximum project duration) should be calculated using expert opinion. The pessimistic duration notation is D_P. Finally, the optimistic duration (the minimum project duration) should be calculated also using expert opinion. The optimistic duration notation is D_O.

The second step is to transfer the three-points estimate of project cost from crisp values to the fuzzy set. This can be done by calculating the estimated project cost using one of the traditional cost estimation techniques (i.e., unit area cost estimate, unit volume cost estimate or parameter cost estimate) [18]. This value will be called the moderate cost and will use the notation C_M. Then, the pessimistic cost (the maximum project cost) should be calculated using expert opinion. The pessimistic cost notation is C_P. Finally, the optimistic cost (the minimum project cost) should be calculated also using expert opinion. The optimistic cost notation is C_O.

During this step, each activity's moderate duration, optimistic duration and pessimistic duration should be determined. The notations for an activity moderate duration, optimistic duration and pessimistic duration are d_m, d_o and $d_{p,}$ respectively. The third step is to calculate the fuzzy capacity cost rate (CCR) using Eq. (4):

$$CCR = \left(\frac{C_P}{D_O}, \frac{C_M}{D_M}, \frac{C_O}{D_P}\right) \tag{4}$$

Then, the fuzzy capacity usage rate (CUR) should be calculated as a triangular membership function (TMF) using the following equations:

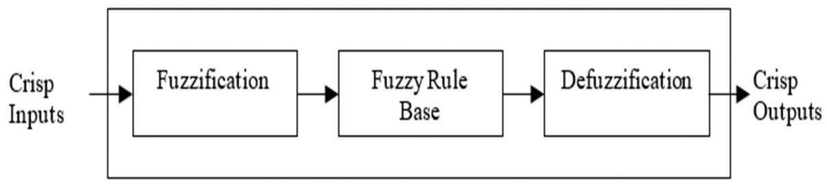

Figure 3. Fuzzy logic controller.

$$\mathrm{CUR} = \begin{pmatrix} \frac{C_P}{D_O} \\ \frac{C_M}{D_M} \\ \frac{C_O}{D_P} \end{pmatrix} * \begin{pmatrix} d_o \\ d_m \\ d_p \end{pmatrix} * \begin{pmatrix} Q \\ Q \\ Q \end{pmatrix} \tag{5}$$

$$\mathrm{CUR} = \left\{ \left(\frac{C_P}{D_O} * \mathbf{d_o} * \mathbf{Q} \right), \left(\frac{C_M}{D_M} * \mathbf{d_m} * \mathbf{Q} \right), \left(\frac{C_O}{D_P} * \mathbf{d_p} * \mathbf{Q} \right) \right\} \tag{6}$$

where Q = Number of Each Activity (quantity).

The fourth step is to defuzzify the triangular membership function (TMF) to get crisp CUR values. Available defuzzification techniques include a max-membership principle, a centroid method, a weighted average method, a mean-max membership method, a center of sums, a center of largest area, the first of maxima or last of maxima [19]. Among these, a centroid method (also called Center of Gravity [COG]) is the most prevalent and physically appealing method [20]. The α-cut method is a standard method for performing arithmetic operations on a Triangular Membership Function [21]. The α-cut signifies the degree of risk that the decision-makers are prepared to take (i.e., no risk to full risk). Since the value of α could severely influence the solution, its choice should be carefully considered by decision-makers. **Figure 4** shows a TFN with α-cut. The higher the value of α, the greater the confidence ($\alpha = 1$ means no risk) [21].

By using the center of gravity (COG) defuzzification technique and $\propto = 0.1$, crisp CUR values (cost values) can be calculated for each activity using the following formula:

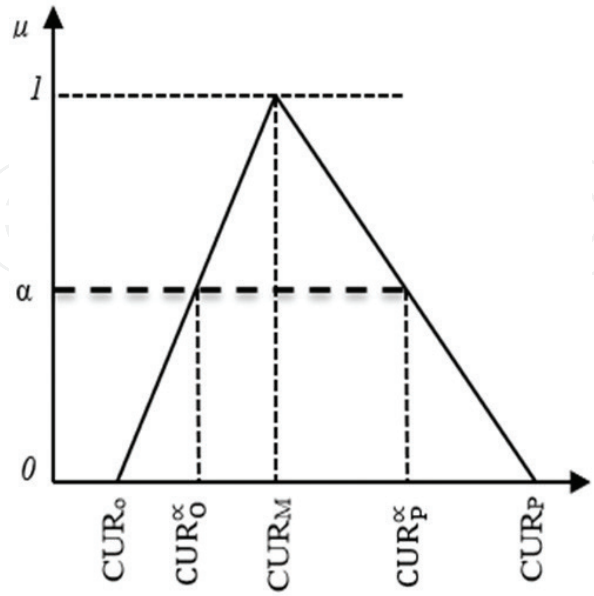

Figure 4. Triangular fuzzy number with α-cut.

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$$CUR^{\propto}_{COST} = \frac{\int_{CUR^{\propto}_{O}}^{CUR_{M}} \boldsymbol{\mu} A(\mathbf{x}) x dx + \int_{CUR_{M}}^{CUR^{\propto}_{P}} \boldsymbol{\mu} A(\mathbf{x}) x dx}{\int_{CUR^{\propto}_{O}}^{CUR_{M}} \boldsymbol{\mu} A(\mathbf{x}) dx + \int_{CUR_{M}}^{CUR^{\propto}_{P}} \boldsymbol{\mu} A(\mathbf{x}) dx} \quad (7)$$

where:

$$CUR^{\propto}_{COST} = \text{Improved cost estimate of an activity at } \propto = 0.1$$

$$CUR^{\propto}_{O} = \left(\frac{C_P}{D_o} * d_O * Q\right) = \text{Optimistic cost at } \propto = 0.1$$

$$CUR^{\propto}_{P} = \left(\frac{C_O}{D_P} * d_P * Q\right) = \text{Pessimistic cost at } \propto = 0.1$$

$$CUR_{M} = \left(\frac{C_M}{D_M} * d_m * Q\right) = \text{Moderate cost}$$

The crisp $CUR^{\propto}_{COST}$ value that is calculated in this step is the improved cost estimate for an activity at $\propto = 0.1$ and its notation is $(iac_{0.1})$.

The fifth step is to repeat the same process to get the improved cost estimate for all project activities. Finally, add the improved cost estimate for all the activities to get an improved cost estimate for the project at $\propto = 0.1$. The project improved cost estimate will be abbreviated as $IPC_{0.1}$

$$IPC_{0.1} = \sum_{i}^{\text{Project}} \text{improved activities cost at } \propto = 0.1 \quad (8)$$

4.2. Model stage two

The first step in stage two is to calculate the fuzzy capacity cost rate (CCR) using the new $IPC_{0.1}$ cost and the following equation:

$$CCR = \left(\frac{\mathbf{D_O}}{\mathbf{IPC_{0.1}}}, \frac{\mathbf{D_M}}{\mathbf{IPC_{0.1}}}, \frac{\mathbf{D_P}}{\mathbf{IPC_{0.1}}}\right) \quad (9)$$

The second step is to calculate the fuzzy capacity usage rate (CUR) as a triangular fuzzy function using the following equation:

$$CUR = \begin{pmatrix} \frac{\mathbf{D_O}}{\mathbf{IPC_{0.1}}} \\ \frac{\mathbf{D_M}}{\mathbf{IPC_{0.1}}} \\ \frac{\mathbf{D_P}}{\mathbf{IPC_{0.1}}} \end{pmatrix} * \begin{pmatrix} iac_{\mathbf{0.1}} \\ iac_{\mathbf{0.1}} \\ iac_{\mathbf{0.1}} \end{pmatrix} * \begin{pmatrix} \mathbf{Q} \\ \mathbf{Q} \\ \mathbf{Q} \end{pmatrix} \quad (10)$$

$$\mathrm{CUR} = \left\{ \left(\frac{\mathbf{D_O}}{\mathrm{IPC}_{\mathbf{0.1}}} * \mathrm{iac}_{\mathbf{0.1}} * \mathbf{Q} \right), \ \left(\frac{\mathbf{D_M}}{\mathrm{IPC}_{\mathbf{0.1}}} * \mathrm{iac}_{\mathbf{0.1}} * \mathbf{Q} \right), \ \left(\frac{\mathbf{D_P}}{\mathrm{IPC}_{\mathbf{0.1}}} * \mathrm{iac}_{\mathbf{0.1}} * \mathbf{Q} \right) \right\} \tag{11}$$

where $\mathrm{iac}_{0.1}$ = The improved activity cost at $\propto = 0.1$ (it is already calculated in stage one).

The third step is to defuzzify the triangular membership function (TMF) using the center of gravity (COG) defuzzification technique. Using COG and $\propto = 0.1$, a crisp CUR value (time value) can be calculated for each activity using the following formula:

$$\mathrm{CUR}^{\propto}_{\mathrm{TIME}} = \frac{\int_{\mathrm{CUR}^{\propto}_{O}}^{\mathrm{CUR}_{M}} \mu A(\mathbf{x}) x dx + \int_{\mathrm{CUR}_{M}}^{\mathrm{CUR}^{\propto}_{P}} \mu A(\mathbf{x}) x dx}{\int_{\mathrm{CUR}^{\propto}_{O}}^{\mathrm{CUR}_{M}} \mu A(\mathbf{x}) dx + \int_{\mathrm{CUR}_{M}}^{\mathrm{CUR}^{\propto}_{P}} \mu A(\mathbf{x}) dx} \tag{12}$$

where:

$$\mathrm{CUR}^{\propto}_{\mathrm{TIME}} = \text{Improved time estimate of an activity at } \propto = 0.1$$

$$\mathrm{CUR}^{\propto}_{O} = \left(\frac{D_O}{\mathrm{IPC}_{0.1}} * \mathrm{iac}_{0.1} * Q \right) = \text{Optimistic time at } \propto = 0.1$$

$$\mathrm{CUR}^{\propto}_{P} = \left(\frac{D_P}{\mathrm{IPC}_{0.1}} * \mathrm{iac}_{0.1} * Q \right) = \text{Pessimistic time at } \propto = 0.1$$

$$\mathrm{CUR}_{M} = \left(\frac{D_M}{\mathrm{IPC}_{0.1}} * \mathrm{iac}_{0.1} * Q \right) = \text{Moderate time}$$

The crisp $\mathrm{CUR}^{\propto}_{\mathrm{TIME}}$ value that is calculated in this step is the improves duration for an activity at $\propto = 0.1$ and its notation is $(\mathrm{iad}_{0.1})$.

The fourth step is to repeat the same process to get the improved duration for all project activities. Finally, add the improved duration for all the activities to get an improved duration for the project. The project improved duration will be abbreviated as $\mathrm{IPD}_{0.1}$

$$\mathrm{IPD}_{0.1} = \sum_{i}^{\mathrm{Project}} \text{improved activities duration at } \propto = 0.1 \tag{13}$$

4.3. Model stage three

In stage three, a sensitivity analysis should be performed to investigate the variability of the results obtained with respect to the choice of the α-cut value. Sensitivity analysis is "the study of how the uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input" [22]. One of the simplest and most common approaches to sensitivity analysis is changing the α-cut value, to see what effect this produces on the project cost and duration. To achieve that, stage one and two should be repeated using α-cut values equal to 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0. The results obtained from the different α-cut values will be saved as shown in **Table 1**. The sensitivity analysis will help investigate various levels of confidence associated with each time–cost alternative.

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α-cut	Improved project cost	Improved project duration
0.1	$IPC_{0.1}$	$IPD_{0.1}$
0.2	$IPC_{0.2}$	$IPD_{0.2}$
0.3	$IPC_{0.3}$	$IPD_{0.3}$
0.4	$IPC_{0.4}$	$IPD_{0.4}$
0.5	$IPC_{0.5}$	$IPD_{0.5}$
0.6	$IPC_{0.6}$	$IPD_{0.6}$
0.7	$IPC_{0.7}$	$IPD_{0.7}$
0.8	$IPC_{0.8}$	$IPD_{0.8}$
0.9	$IPC_{0.9}$	$IPD_{0.9}$
1.0	$IPC_{1.0}$	$IPD_{1.0}$

Table 1. Project time and cost at each α-cut.

5. Fuzzy time-driven model verification and validation

To illustrate an application of the fuzzy TDABC model, a case study of seven activities proposed initially by Zheng et al. (2004) was used [23]. The case study illustrates a construction project that has seven activities as shown in **Table 2**. The letters O, M and P in **Table 2** signify optimistic, moderate and pessimistic time and direct cost. The assumed value for indirect cost per day is \$1000, \$1150 and \$2000 for optimistic, moderate and pessimistic values, respectively. The calculated project duration is (60, 81 and 92) days for optimistic, moderate and pessimistic, respectively.

The first step is to calculate the total cost of the project by adding the indirect cost to the direct cost. **Table 3** shows the optimistic, moderate and pessimistic total cost.

Applying stage one of the fuzzy TDABC model begins by using Eq. (4) to calculate the fuzzy CCR as shown in **Table 4**.

Activity	Predecessor	Time (Days)			Direct cost ($)		
		O	M	P	O	M	P
A	—	14	20	24	23,000	18,000	12,000
B	A	15	18	20	3000	2400	1800
C	A	15	22	33	4500	4000	3200
D	A	12	16	20	45,000	35,000	30,000
E	B, C	22	24	28	20,000	17,500	15,000
F	D	14	18	24	40,000	32,000	18,000
G	E, F	9	15	18	30,000	24,000	22,000

Table 2. Activities duration and cost.

Total cost ($)		
P	M	O
296,772	238,169	205,192

Table 3. Project total cost.

CCR ($): Phase I		
O	M	P
2938	1791	1229

Table 4. Fuzzy capacity cost rate (CCR).

Then, the fuzzy capacity usage rate (CUR) is calculated as a cost function using Eq. (5). **Table 5** shows the CUR values.

Next, α-cut values of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0 are applied to the CUR values in **Table 5**. This will generate new CUR values associated with each α-cut. **Table 6** shows the CUR values that are associated with each α-cut for each activity in the project.

Using Eq. (7), crisp CUR values associated with each α-cut are determined for each activity. These CUR values are the improved cost estimate for each activity at the associated α-cut. By adding the improved activities' costs, the project improved cost estimates are determined as shown in **Table 7**.

At this point, stage one of the model is done and stage two begins. By using the improved project costs that have been calculated in **Table 7**, the fuzzy capacity cost rates (CCR) are calculated using Eq. (9). **Table 8** shows the CCR value associated with each α-cut.

Then, the fuzzy capacity usage rate (CUR) is calculated as a time function using Eq. (10). **Table 9** shows the CUR values.

Activity	CUR ($): Phase I		
	O	M	P
A	41,137	35,815	29,489
B	44,075	32,233	24,574
C	44,075	39,396	40,547
D	35,260	28,652	24,574
E	64,643	42,978	34,403
F	41,137	32,233	29,489
G	26,445	26,861	22,117

Table 5. Fuzzy capacity usage rate (CUR).

α	Fuzzy CUR ($)	Activities						
		A	B	C	D	E	F	G
0.1	CUR_o	40,604	42,891	43,607	34,599	62,477	40,246	26,487
	CUR_M	35,815	32,233	39,396	28,652	42,978	32,233	26,861
	CUR_P	30,121	25,340	40,432	24,982	35,261	29,763	22,591
0.2	CUR_o	40,072	41,707	43,139	33,938	60,310	39,356	26,528
	CUR_M	35,815	32,233	39,396	28,652	42,978	32,233	26,861
	CUR_P	30,754	26,106	40,317	25,390	36,118	30,038	23,065
0.3	CUR_o	39,540	40,523	42,671	33,278	58,144	38,466	26,570
	CUR_M	35,815	32,233	39,396	28,652	42,978	32,233	26,861
	CUR_P	31,387	26,872	40,202	25,797	36,976	30,312	23,540
0.4	CUR_o	39,008	39,338	42,204	32,617	55,977	37,575	26,611
	CUR_M	35,815	32,233	39,396	28,652	42,978	32,233	26,861
	CUR_P	32,019	27,638	40,087	26,205	37,833	30,587	24,014
0.5	CUR_o	38,476	38,154	41,736	31,956	53,811	36,685	26,653
	CUR_M	35,815	32,233	39,396	28,652	42,978	32,233	26,861
	CUR_P	32,652	28,404	39,972	26,613	38,691	30,861	24,489
0.6	CUR_o	37,944	36,970	41,268	31,295	51,644	35,795	26,695
	CUR_M	35,815	32,233	39,396	28,652	42,978	32,233	26,861
	CUR_P	33,284	29,170	39,857	27,021	39,548	31,135	24,963
0.7	CUR_o	37,411	35,786	40,800	30,634	49,477	34,904	26,736
	CUR_M	35,815	32,233	39,396	28,652	42,978	32,233	26,861
	CUR_P	33,917	29,936	39,741	27,428	40,405	31,410	25,438
0.8	CUR_o	36,879	34,602	40,332	29,973	47,311	34,014	26,778
	CUR_M	35,815	32,233	39,396	28,652	42,978	32,233	26,861
	CUR_P	34,550	30,701	39,626	27,836	41,263	31,684	25,912
0.9	CUR_o	36,347	33,418	39,864	29,313	45,144	33,124	26,820
	CUR_M	35,815	32,233	39,396	28,652	42,978	32,233	26,861
	CUR_P	35,182	31,467	39,511	28,244	42,120	31,959	26,387
1.0	CUR_o	35,815	32,233	39,396	28,652	42,978	32,233	26,861
	CUR_M	35,815	32,233	39,396	28,652	42,978	32,233	26,861
	CUR_P	35,815	32,233	39,396	28,652	42,978	32,233	26,861

Table 6. CUR value at each α-cut ($): Phase I.

Using Eq. (12), new crisp CUR values associated with each α-cut are determined for each activity. These CUR values are the improved duration for each activity at the associated α-cut. By adding the improved activities' durations, the project improved durations are determined as shown in **Table 10**.

Crisp CUR Values ($) - Phase I								
α-cut	Activities							Improved project cost ($)
	A	B	C	D	E	F	G	
0.1	35,622	34,868	42,040	30,049	50,132	35,266	24,590	252,567
0.2	35,617	34,504	41,744	29,869	49,226	34,905	24,837	250,703
0.3	35,620	34,158	41,449	29,695	48,345	34,550	25,085	248,902
0.4	35,628	33,829	41,154	29,527	47,490	34,200	25,335	247,164
0.5	35,643	33,517	40,860	29,366	46,663	33,857	25,586	245,491
0.6	35,665	33,223	40,566	29,210	45,863	33,519	25,839	243,885
0.7	35,693	32,947	40,273	29,061	45,094	33,188	26,092	242,348
0.8	35,727	32,690	39,980	28,918	44,356	32,863	26,347	240,882
0.9	35,768	32,452	39,688	28,782	43,650	32,545	26,604	239,488
1.0	35,815	32,233	39,396	28,652	42,978	32,233	26,861	238,169

Table 7. Project improved cost estimates.

Using the results in **Tables 7** and **10**, the improved project cost and the improved project duration associated with each α-cut are summarized in **Table 11**.

Using **Table 11**, a plot of the improved project costs versus the improved project durations is created as shown in **Figure 5**. The robustness of the new proposed TDABC model is compared with two previous models:

1. Gen and Cheng (2000) model.
2. Zheng et al. (2004) model.

Activity	CCR - Phase II		
	O	M	P
0.1	0.000238	0.000321	0.000364
0.2	0.000239	0.000323	0.000367
0.3	0.000241	0.000325	0.000370
0.4	0.000243	0.000328	0.000372
0.5	0.000244	0.000330	0.000375
0.6	0.000246	0.000332	0.000377
0.7	0.000248	0.000334	0.000380
0.8	0.000249	0.000336	0.000382
0.9	0.000251	0.000338	0.000384
1.0	0.000252	0.000340	0.000386

Table 8. The CCR value associated with each α-cut.

α	Fuzzy CUR (Days)	Activities						
		A	**B**	**C**	**D**	**E**	**F**	**G**
0.1	CUR_o	9	9	10	7	12	9	6
	CUR_M	11	11	13	10	16	11	8
	CUR_P	13	13	15	11	18	13	9
0.2	CUR_o	9	9	11	8	13	9	6
	CUR_M	12	11	13	10	16	11	8
	CUR_P	13	12	15	11	18	13	9
0.3	CUR_o	9	9	11	8	13	9	6
	CUR_M	12	11	13	10	16	11	8
	CUR_P	13	12	15	11	18	12	9
0.4	CUR_o	10	9	11	8	14	10	7
	CUR_M	12	11	13	10	16	11	8
	CUR_P	12	12	15	10	17	12	9
0.5	CUR_o	10	10	12	8	14	10	7
	CUR_M	12	11	13	10	15	11	8
	CUR_P	12	12	14	10	17	12	8
0.6	CUR_o	10	10	12	9	14	10	7
	CUR_M	12	11	13	10	15	11	9
	CUR_P	12	12	14	10	17	12	8
0.7	CUR_o	11	10	12	9	15	10	7
	CUR_M	12	11	13	10	15	11	9
	CUR_P	12	12	14	10	17	12	8
0.8	CUR_o	11	11	13	9	15	11	7
	CUR_M	12	11	13	10	15	11	9
	CUR_P	12	11	14	10	17	12	8
0.9	CUR_o	11	11	13	9	16	11	8
	CUR_M	12	11	13	10	15	11	9
	CUR_P	12	11	14	10	16	11	8
1.0	CUR_o	11	11	13	10	16	11	8
	CUR_M	12	11	13	10	15	11	9
	CUR_P	11	11	13	10	16	11	8

Table 9. CUR value at each α-cut (days): Phase II.

Gen and Cheng (2004) used a genetic algorithm (GA) approach to find the best Time–Cost Trade-Offs. GA is a search method used for finding optimized solutions to problems based on the natural selection theory and biological evolution [24]. The Zheng et al. model used the modified adaptive weight approach with GA to solve the time–cost trade-off problem. The

Crisp CUR (Days): Phase II								
α-cut	Activities							Improved project duration (Days)
	A	B	C	D	E	F	G	
0.1	10.9	10.7	12.9	9.2	15.4	10.8	7.5	77.4
0.2	11.0	10.7	12.9	9.2	15.4	10.9	7.6	77.7
0.3	11.0	10.8	13.0	9.3	15.5	10.9	7.6	78.0
0.4	11.1	10.8	13.0	9.3	15.6	10.9	7.6	78.4
0.5	11.1	10.9	13.1	9.4	15.6	11.0	7.7	78.8
0.6	11.2	10.9	13.2	9.4	15.7	11.1	7.7	79.2
0.7	11.2	11.0	13.2	9.5	15.8	11.1	7.7	79.6
0.8	10.9	10.7	12.9	9.2	15.4	10.8	7.5	77.4
0.9	11.0	10.7	12.9	9.2	15.4	10.9	7.6	77.7
1.0	11.0	10.8	13.0	9.3	15.5	10.9	7.6	78.0

Table 10. Project improved duration.

modified adaptive weight approach is a method to represent the importance of each function by assigning different weights to different functions [23].

The results of these two models are compared with the fuzzy TDABC model in **Table 12**.

Figure 6 compares between the fuzzy TDABC result and the results obtained by Gen and Cheng (2004) and Zheng et al. (2004).

Table 12 and **Figure 6** show that the fuzzy TDABC obtains better values of time and cost compared to the result obtained by Gen and Cheng (2000). However, the result obtained by Zheng (2004) is better than the fuzzy TDABC result.

α-cut	Improved project cost ($)	Improved project duration (Days)
0.1	252,567	77.4
0.2	250,703	77.7
0.3	248,902	78.0
0.4	247,164	78.4
0.5	245,491	78.8
0.6	243,885	79.2
0.7	242,348	79.6
0.8	240,882	80.0
0.9	239,488	80.5
1.0	238,169	81.0

Table 11. Improved project cost and duration associated with each α-cut.

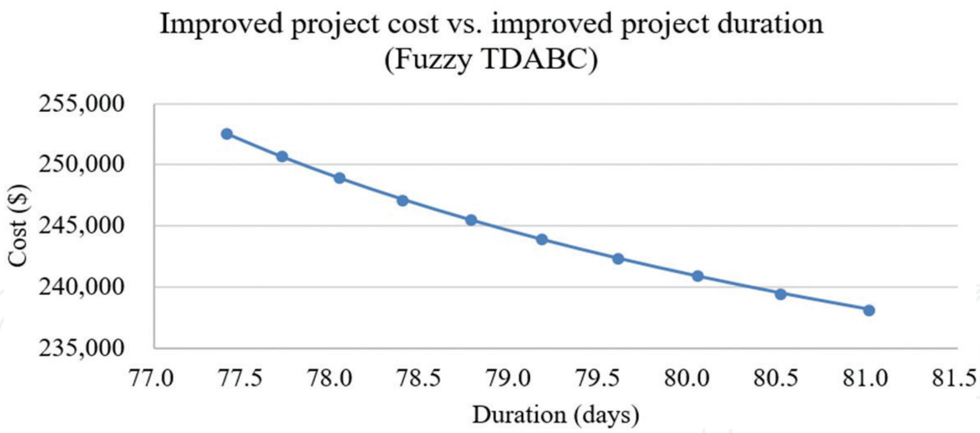

Figure 5. Improved project cost versus project durations.

To further compare the results of the fuzzy TDABC model with the past published results, a test called Wilcoxon signed-ranks test is performed. The Wilcoxon Signed-Ranks test is a non-parametric analysis that statistically compared the average of two dependent samples and assessed for significant differences. Wilcoxon signed-ranks test does not assume normality of the differences of the compered groups [25]. The Wilcoxon test has been selected because the datasets in this case do not follow normal distribution. The method to perform Wilcoxon test starts with two hypotheses. A null hypothesis (H_0) assumes that the results obtained from the three approaches are the same. An alternative hypothesis (H_1) assumes that the results obtained from the three approaches are not the same. **Table 13** shows the Wilcoxon signed-ranks test result.

Table 13 shows that the p-value is 0.036. The p-value, or calculated probability, assesses if the sample data support the argument that the null hypothesis (H_0) is true. A small p-value (less or equal to 0.05) indicates solid evidence against the null hypothesis, so the null hypothesis should be rejected. A large p-value (larger than 0.05) indicates weak evidence against the null hypothesis, so the null hypothesis should not be rejected [25]. The p-value is 0.036, in this case, which is less than the significance level of 0.05. As a result, there is enough evidence to reject the null hypothesis and to conclude that the difference between the results obtained from the three approaches is significant.

Approaches	Criteria		Target
	Time (days)	Cost ($)	
Gen and Cheng (2000)	83	243,500	Least cost
	79	256,400	Least time
Zheng et al. (2004)	73	236,500	Least cost
	66	251,500	Least time
Fuzzy TDABC	81	238,169	Least cost
(This research)	77	252,567	Least time

Table 12. Fuzzy TDABC result vs. previous research results.

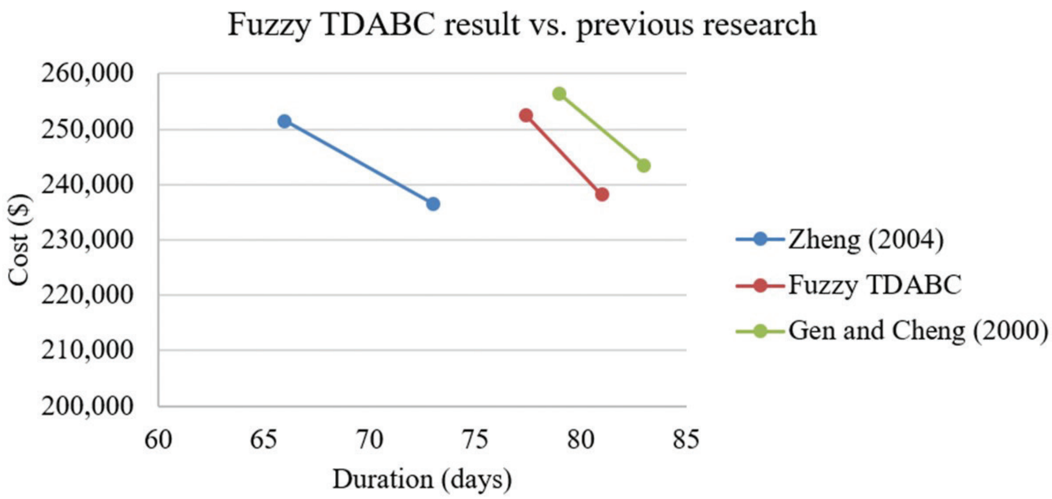

Figure 6. Fuzzy TDABC result versus previous research results.

Source	N	Wilcoxon Statistic	P-Value	Estimated median
Time	6	21.0	0.036	77 Day
Cost	6	21.0	0.036	$246,450

Table 13. Wilcoxon signed-ranks test result.

6. Conclusion

The objective of this research is to develop a model to find time–cost trade-off alternatives while accounting for uncertainty in project time and cost. The presented fuzzy TDABC model provides an attractive alternative for the traditional solutions of the time–cost trade-offs optimization problem. The presented model is simple and easy to apply compared with other approaches. Further, this model obtained a better solution when compared to the GA model that is presented by Gen and Cheng (2000). The fuzzy TDABC model could improve the reliability of the time–cost trade-off decisions. This could help construction companies mitigate the risk of projects running over budget or behind schedule.

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