AUT Journal of Modeling and Simulation

AUT J. Model. Simul., 54(2) (2022) 185-196
DOI: 10.22060/miscj.2023.20752.5266

A novel fuzzy Bayesian network-based approach for the project time-cost-quality trade-off problem

M.H.Haghighi [1], M. Ashrafi[1]*, E. Nazerfard[2]

[1] Amirkabir University of Technology, Department of Industrial Engineering and Management Systems,Tehran, Iran.
[2] Amirkabir University of Technology, Department of Computer Engineering, Tehran, Iran.

ABSTRACT: To successfully complete projects, it is essential to meet all the goals of the criteria that affect the project, such as time, cost, and quality. The time-cost-quality trade-off (TCQT) approach is considered a practical technique when project managers or customers tend to crash the total time of a project and create a balance within these criteria. On the other hand, due to the unique inherent of projects and various risks in the real world, using a certain framework for project management problems does not seem efficient. This paper presents a novel fuzzy Bayesian network-based approach to schedule a project and control real-world uncertainties. This novel approach applies the fuzzy opinions of several experts with regard to their weight. The presented fuzzy Bayesian model can calculate a project's total cost and duration in various uncertain situations. Consequently, this profound knowledge about the project's various conditions helps managers be aware of the different probable scenarios. To demonstrate the efficiency and application of the proposed model, a modified project example from the literature review is adopted and solved. A common technique in project management called PERT is applied to verify the proposed approach, and the results are compared. Finally, a comparative analysis with a recent related paper is presented.

Review History:

Received: Nov. 13, 2021
Revised: Jan. 07, 2023
Accepted: Jan. 14, 2023
Available Online: Feb. 28, 2023

Keywords:

Project management
time-cost-quality trade-off problem (TCQTP)
fuzzy bayesian network (BN)
risk, conditional probabilities

1- Introduction

The time-cost trade-off (TCT) approach is a beneficial technique in project management which is applied when the total time of a project is not accepted and it is required to be crashed [1]. Indeed, a project manager intends to reduce total time of the project through increasing the cost of activities by employing more manpower and equipment [2-5]. Because of the importance and applicability of the TCT approach, many studies have been performed in this area in recent years.

Leyman *et al.* [6] proposed a discrete TCT for project scheduling while optimizing project net present value. Ballesteros-Perez *et al.* [4] scrutinized on non-linear TCT models. Abdel-Basset *et al.* [7] proposed a linear TCT approach based on the neutrosophic set for uncertain parameters of a project. Panwar and Jha [8] integrated quality and safety in a TCT model. Orm and Jeunet [9] presented a survey for the assessment of quality in time-cost trade-off problems (TCTPs). Moreover, Mohammadipour and Sadjadi [10] presented a multi-objective model with cost, quality, and risk criteria under the time-constrained. Haghighi *et al.* [11] presented a new framework for TCTP considering quality loss cost under interval-valued fuzzy set. As well, Hosseini-Nasab *et al.* [12] used the trapezoidal fuzzy set in multi-mode time-cost-quality trade-off problem (TCQTP).

*Corresponding author's email: ashrafi.mm@aut.ac.ir

Project parameters are affected by different sources of risks [13]. Therefore, estimating the total cost and time of a project is a complex action. Some techniques, such as, regression [14], Artificial Neural Networks [15], Monte Carlo (MC) simulation [13] were presented to model risk. However, using a simple technique such as linear regression may not consider all aspects of a project and may miss a number of variables. The mentioned approaches are highly dependent on historical data, which in the context of projects, due to their unique nature, the existence of completely historical data seems unlikely. There are other effective approaches such as Bayesian network (BN) that can cover this weakness. It creates the possibility of applying expert judgment and historical data simultaneously, and its update as soon as data availability [16, 17].

One of the most efficient approaches for managing risks in projects is Bayesian approach. Since this approach has several advantages such as the possibility of structural learning, fast responsiveness, explicit treatment of uncertainty, and knowledge from different sources [2]. Covaliu and Soyer [18] presented a sequential Bayesian approach for a project with a few activities. Cho [19] proposed a linear Bayesian approach for duration of a project where it can be converted to full Bayesian with considering some assumptions. Nevertheless, most of these researches do not consider the dependencies between different elements of a project cost and time [20]. In spite of many merits of the BN approach, it has been criticized for using crisp probabilities in assessing uncertainty

Table 1. The most recent studies in TCTPs

Author(s)	Year	Time	Cost	Quality	Risk	Bayesian network (BN)	Fuzzy Bayesian network	Weight of decision maker
Kim et al. [29]	2012	✓	✓	✓				
Monghasemi et al. [30]	2015	✓	✓	✓				
He et al. [25]	2017	✓	✓					
Ghosh et al. [2]	2017	✓	✓			✓		
Tran and Long [31]	2018	✓	✓		✓			
Ballesteros-Perez et al. [4]	2019	✓	✓					
Liu et al. [26]	2020	✓	✓					
Jeunet and Orm [3]	2020	✓	✓	✓				
Panwar and Jha [8]	2021	✓	✓	✓				
This paper		✓	✓	✓	✓		✓	✓

[21], so the fuzzy BN methodology was presented to eliminate this weakness. Ferreira and Borenstein [22] presented a fuzzy-Bayesian model for supplier selection. Wan *et al.* [23] assessed maritime supply chain risks by a fuzzy Bayesian-based FMEA approach. Aliabadi *et al.* [24] applied a fuzzy BN for modeling risks in a hydrogen gasholder that introduced a new approach for determining the weight of each expert.

This paper develops a fuzzy full BN that can consider and manage risks related to the cost and time. On the other hand, this approach enables project managers to achieve profound knowledge by applying different scenarios of trade-off between time, cost, and quality for a project. Moreover, in order to increase the accuracy of the results in this research, the opinions of several experts are used to gather the necessary information about probabilities in fuzzy BN. Using different views of multiple experts can almost cover all aspects of the problem. To provide an exhaustive insight of the novelties of this paper, the main issues are mentioned as follows:

- To solve the project TCQTP, a novel fuzzy Bayesian network-based approach is proposed.
- A new probabilistic methodology is presented to manage the risks of the real world in the project environment.
- A fuzzy Bayesian network approach is developed within an expert group decision-making process, considering the weight of the expert's opinions.

Various approaches and mathematical models have been proposed to solve the TCTP, which have mostly considered time and cost criteria and ignored other success criteria of project [4, 25, 26]. On the other hand, the trend of new solution approaches is moving towards stochastic and fuzzy uncertainty approaches [2, 11, 27, 28]. The most recent studies for TCQTPs are mentioned in Table 1.

As can be seen in Table 1, in previous studies, the focus has only been on time and cost criteria. This paper considers three effective criteria time, cost, and quality in a project. On the other hand, due to the uncertain intrinsic nature of projects, setting a definite schedule and total cost does not seem to be accurate. In this paper, a fuzzy full BN for scheduling the project is proposed that can manage its uncertainties. In fact, the proposed approach in this paper can both manage the various uncertainties of a project associated with the occurrence of different scenarios and control the uncertainties that exist in the opinions of experts for determining the probabilities of BN. Moreover, in order to increase of accuracy of results, instead of one expert, opinions of several experts with considering weight of each expert, which is determined by the project manager, are applied in proposed methodology. The rest of this paper is organized as follows. Section 2 proposes the structure of the model. Afterward, an application example is presented in section 3. Finally, conclusions are presented in the last section.

2- Model description

A BN creates a probabilistic framework to consider the causal relationships and interactions under uncertainty [32]. Nowadays, this technique is applied to solve many real-world problems, such as, improving procurement performance in organizations [33], predicting delays in train operations [34], evaluating reliability in wind turbines [35], comparing maintenance strategies [36], forecasting stock market index daily direction [37], and modeling for supply chain risk propagation [38]. In a BN, nodes represent random variables and vectors represent the relationship between these variables [39, 40]. Three important categories of information is needed to form the framework of the new proposed approach. Figure 1

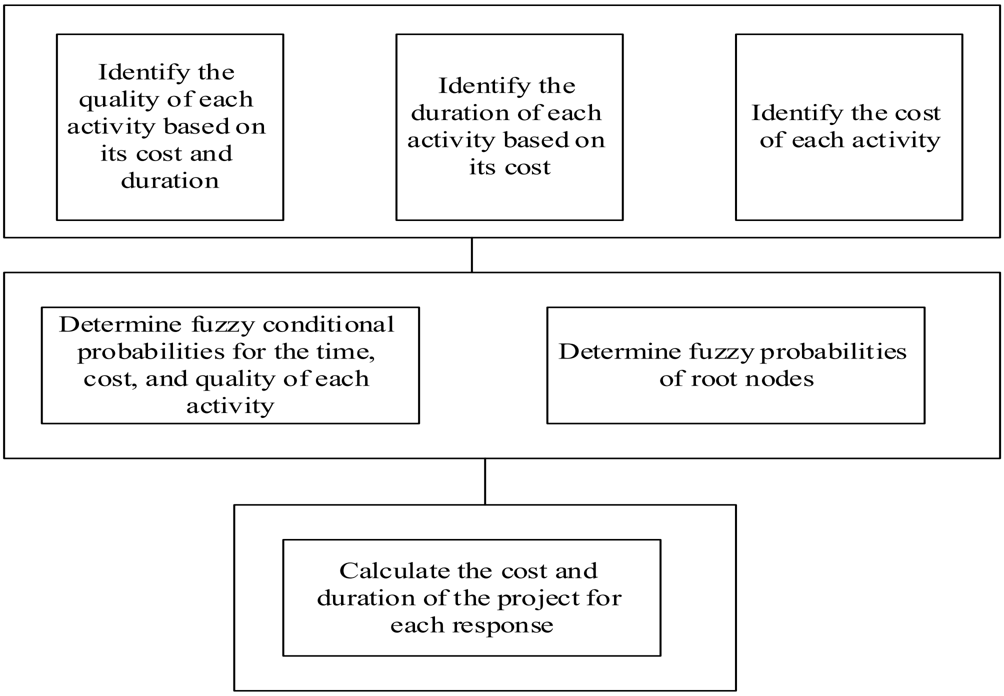


Fig. 1. The process of the proposed fuzzy Bayesian model

displays the proposed model framework for the TCQTP considering fuzzy BN.

2- 1- Inputs

The first category is model inputs, which include the project cost breakdown structure and the cost of performing activities (C_i ,$i=1,2,\ldots,n$), determining the execution time based on the cost of performing that activity (T_i ,$i=1,2,\ldots,n$), and also determining the quality of activities based on the assumed cost and duration of each activity (Q_i ,$i=1,2,\ldots,n$).

2- 2- Fuzzy Bayesian network (BN)

BN is a graphical model in which probabilities and dependencies between variables can be considered [17, 39, 41]. BN can consider accident paths in retrospective backward approach and analyze and predict various likely scenarios [32]. The second important category is related to data for creating fuzzy BN, which includes probabilities of root nodes as well as conditional probabilities of cost, time, and quality associated with other nodes. Indeed, the structure of the network is that the nodes represent the variables of time, cost and quality of project activities and ultimately the whole project, and the vectors represent the predecessor relationship as well as the dependency relationships between the variables.

2- 2- 1- Probability of root nodes

One of the most important parameters in BN is the probabilities of root nodes. Assume that a parent node N contains n states $S_1, S_2, \ldots, S_n$, so it is necessary to specify the probability of each state $Pr(S_i)$. Due to the lack of sufficient data and uncertainty in most projects, estimating a crisp value for the occurrence probability in a BN model is often very challenging [42, 43]. Fuzzy sets as efficient approaches can be applied to better manage uncertain environments [44, 45]. Because of these merits, some related research has applied fuzzy sets in their BN models [42, 43, 46, 47]. Indeed, this paper proposes a process that benefits of fuzzy set in the BN model and, ultimately, converts the occurrence possibility of the BN event into the occurrence probability to import data to the BN model.

In this approach, trapezoidal fuzzy possibilities of root nodes and trapezoidal fuzzy conditional possibilities of other nodes, introduced in the next section, are determined based on the opinion of three experts according to the weight of each expert. Indeed, using fuzzy sets in determining possibilities can improve the results since these sets can manage circumstances with incomplete data and doubts in experts' opinions. Considering several experts and the weight of each expert in the project decision-making environment can enhance the accuracy of the results. In fact, the project manager first gathers all data about possibilities from the experts and then determines a weight for each expert based on their resumes. Eventually, by considering the weight of each expert, the aggregated possibilities are computed by Eq. (1). The process of determining the weight of each expert is presented in Appendix 1. Afterward, the defuzzified values of aggregated possibilities (based on Yucesan et al. [48]) are calculated by Eq. (2). In the next step, the aggregated possibilities convert into probabilities by Eq. (3) inspired by Onisawa [49]. Finally, the normalized defuzzified values of aggregated prob-

Table 2. Example information

Activity	Predecessor	Duration (day)		Cost ($)		Quality (%)	
		Normal	Crashed	Normal	Crashed	Normal	Crashed
A	-	5	3	7500	8000 10000	90	95 85
B	-	8	7	12000	18000	95	90
C	A,B	5	2	2000	5400 6000 7000	85	95 90 85
D	A,B	17	15	35000	50000 60000	90	95 85
E	B	9	-	20000	-	100	-
F	C,D,E	25	22 20	60000	85000 90000	85	90 80

abilities are determined by Eq. (4) and applied for all the root nodes probabilities and conditional probabilities in the BN.

$$\widetilde{APs}=W_1\otimes \widetilde{Ps_1} + W_2\otimes \widetilde{Ps_2} + W_3\otimes \widetilde{Ps_3} + \cdots \quad (1)$$

Defuzzified value (DFPs) =

$$\frac{1}{3}\left(\frac{\left((APs)_4+(APs)_3\right)^2-\left((APs)_4\times(APs)_3\right)}{(APs)_4+(APs)_3-(APs)_1-(APs)_2}+\frac{-\left((APs)_1+(APs)_2\right)^2+\left((APs)_1\times(APs)_2\right)}{(APs)_4+(APs)_3-(APs)_1-(APs)_2}\right) \quad (2)$$

$$Pr_i=\begin{cases}\frac{1}{10^K}\ if\ Ps\neq 0\\ 0\ \ if\ Ps=0\end{cases} \qquad K=2.301*\left[\left(\frac{100-DFPs_i}{DFPs_i}\right)\right]^{\frac{1}{3}} \quad (3)$$

Normalized probability (NPr)=

$$\frac{Pr_i}{\sum_i^n Pr_i}\times 100\ , \qquad i=1,\dots,n \quad (4)$$

Where:
W_e : The weight of each expert (e=1, 2, …, h)
APs_i : The aggregated possibilities
$DFPs_i$: Defuzzified value of aggregated possibilities
NPr_i = The normalized probabilities

2- 2- 2- Conditional probabilities of other nodes

BN is based on Bayesian theory. This approach can manage uncertainty based on the dependence of conditional probabilities between variables [36]. In a BN analysis, for n unique parameters i = 1, 2,…, n, the probabilities are calculated using the following Eq. (5):

$$P(O_i|E)=\frac{P(E|O_i)*P(O_i)}{\sum_j P(E|O_j)P(O_j)} \quad (5)$$

Where $P(O\,|\,E)$ indicates the probability of occurring O if E occurs. $P(O)$ indicates the probability of occurrence of O. $P(E\,|O)$ also indicates the probability of occurring E if O occurs.

2- 3- Outputs

The last category is related the outputs of the proposed model, which include the total cost, the total duration, and also total quality of the project with their probabilities for different scenarios.

3- Fuzzy BN model development for an application example

In order to depict the application and efficiency of the proposed model, a modified numerical example from the research of Ghosh et al. [2] is adopted and solved in this section. This example displays a project whose information is given in Table 2. Table 2 presents the names of the activities and their predecessors, the normal and crashed duration of the activities, as well as the cost and quality of the activities in the normal and crashed conditions.

According to the project information, Figure 2 depicts BN related to this project. In this network, variables (cost, time, and quality) related to all activities are located in the nodes. Activity cost nodes A and B (Cost of A, Cost of B) are the root nodes and the probabilities of the other nodes are calculated as conditional probabilities. In this network, mentioning two

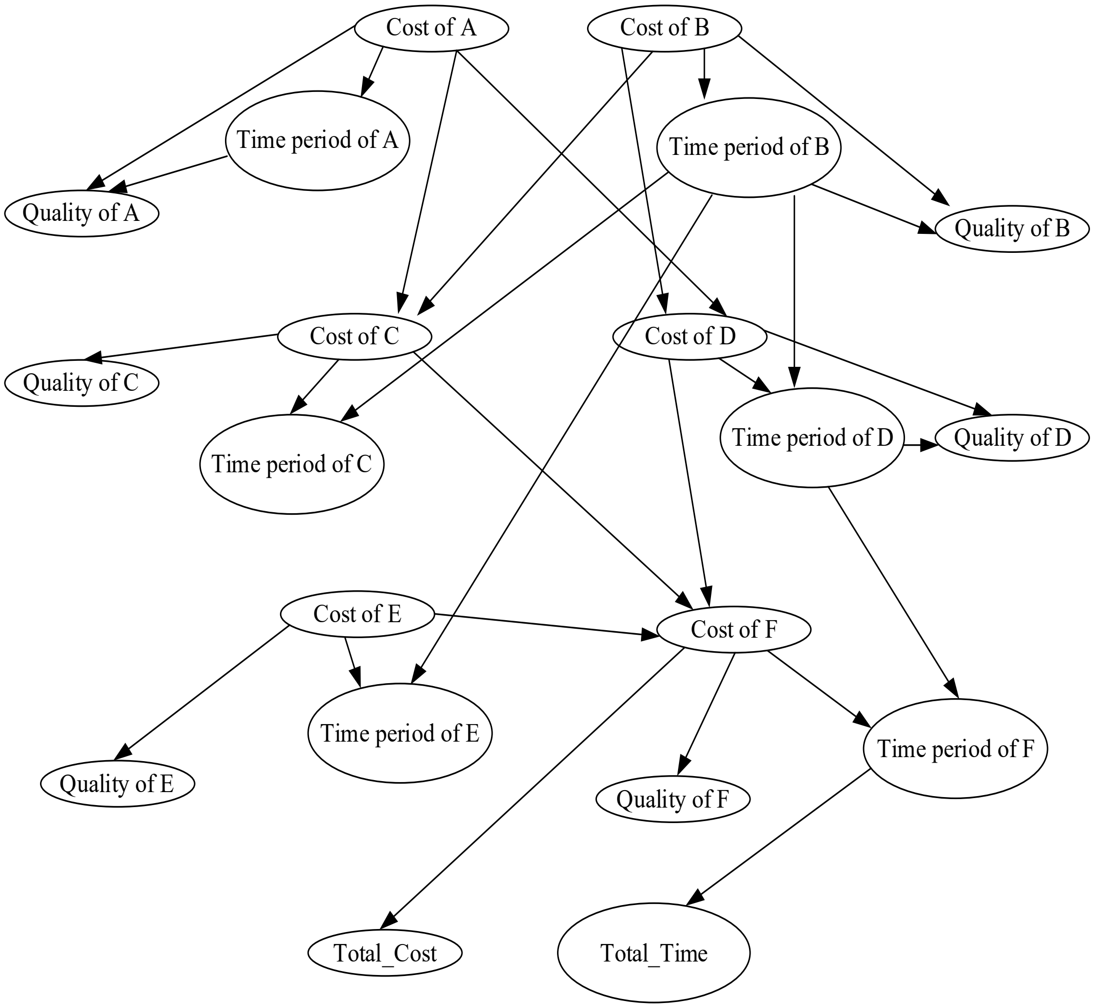


Fig. 2. BN of the instance project

points is vital. First, we must know that the time period of an activity is based on the cumulative time derived from the predecessors of that activity. The second point concerns the relationships between activities, so that, for example, if an activity has two predecessors and one predecessor in all cases has a maximum time, we avoid mentioning another predecessor. For example, activity C, has two predecessors A and B, which activity B has the maximum of time in all cases (normal and crashed), so the relationship between A and C is not drawn.

Now, the opinions of each expert in order to determine root nodes probabilities and also conditional probabilities of other nodes are gathered in form of trapezoidal fuzzy numbers. For example Table 3 depicts probabilities of cost of activity C (cost of C node). This node has two parent nodes (cost of A and cost of B). Each expert determines probability of each state of cost C.

In the next step, all opinions regarding the weight of each expert are aggregated by Eq. (1) and presented in Table 4.

Afterward, aggregated possibilities are defuzzified by Eq. (2). Then, the aggregated possibilities are converted into final probability by Eq. (3). Ultimately, defuzzified values of aggregated probabilities are normalized by Eq. (4) and applied for calculations in BN. Table 5 depicts the defuzzified aggregated possibilities and probabilities. Indeed, If the costs of 'A' and 'B' be \$7500 and \$12000, respectively, there is a 92% chance of Cost C having the value \$7,000, an 7.5% chance for the value \$6,000, a 0.4% chance of the value \$5,400, and a 0.1% chance of the value \$2,000. The sum of the probabilities in a row is 100%.

Table 6 shows the results of the proposed model. All calculations are performed by Netika software. In this model, calculations have been performed for different scenarios. In the first scenario, all activities are in maximum crashing mode. The whole project's maximum cost and minimum time are obtained in this case. In the second scenario, all activities are performed at their normal time and cost, in which the maximum time and minimum cost are calculated. In the third scenario, the completion time and cost of the project are computed for the situation where the maximum quality of the project is considered. In the last scenario, the cost and time of the whole project are calculated in a favorable state.

Table 3. Cost of C node

Cost of A	Cost of B	Possibility (%) of states of cost of C			
		7000	**6000**	**5400**	**2000**
7500	**12000**	DM_1: (47,49,52,57) DM_2: (44,45,48,50) DM_3: (49,53,55,60)	DM_1: (20,24,27,30) DM_2: (25,28,31,33) DM_3: (15,17,19,22)	DM_1: (5,8,10,11) DM_2: (10,13,14,18) DM_3: (7,9,12,17)	DM_1: (4,6,7,10) DM_2: (5,8,11,13) DM_3: (6,7,10,13)
7500	**18000**	DM_1: (13,15,17,19) DM_2: (14,17,20,21) DM_3: (15,17,19,20)	DM_1: (22,24,26,28) DM_2: (20,22,25,27) DM_3: (18,23,25,27)	DM_1: (16,18,20,23) DM_2: (22,24,25,26) DM_3: (25,28,30,32)	DM_1: (34,38,42,45) DM_2: (33,35,38,40) DM_3: (37,39,43,45)
8000	**12000**	DM_1: (45,47,51,53) DM_2: (39,43,48,53) DM_3: (52,54,55,59)	DM_1: (17,20,22,25) DM_2: (17,19,21,23) DM_3: (15,18,20,21)	DM_1: (15,18,19,20) DM_2: (10,14,15,16) DM_3: (13,15,17,19)	DM_1: (6,7,8,9) DM_2: (8,10,12,14) DM_3: (5,7,9,11)
8000	**18000**	DM_1: (10,12,14,16) DM_2: (8,10,11,12) DM_3: (17,19,20,21)	DM_1: (19,22,24,26) DM_2: (19,21,23,25) DM_3: (14,15,16,18)	DM_1: (24,25,26,28) DM_2: (26,27,29,30) DM_3: (28,29,30,31)	DM_1: (36,39,41,42) DM_2: (38,41,44,46) DM_3: (29,33,35,38)
10000	**12000**	DM_1: (33,36,38,39) DM_2: (30,32,36,37) DM_3: (29,33,35,38)	DM_1: (16,18,20,21) DM_2: (9,11,13,17) DM_3: (11,14,16,17)	DM_1: (16,18,20,21) DM_2: (12,14,15,18) DM_3: (14,16,17,19)	DM_1: (29,33,35,38) DM_2: (36,38,39,40) DM_3: (30,33,36,39)
10000	**18000**	DM_1: (4,6,8,10) DM_2: (8,11,13,15) DM_3: (5,8,11,12)	DM_1: (18,20,22,24) DM_2: (12,15,17,20) DM_3: (20,21,23,24)	DM_1: (26,28,30,31) DM_2: (24,26,29,32) DM_3: (28,30,32,34)	DM_1: (36,38,39,43) DM_2: (37,39,43,45) DM_3: (29,31,34,38)

Table 4. Aggregated possibility of states of cost of C

Cost of A	Cost of B	Aggregated possibility (%) of states of cost of C			
		7000	6000	5400	2000
7500	12000	(46.7,49,51.7,55.8)*	(20,23.1,25.8,28.5)	(7.1,9.8,11.8,14.9)	(4.9,6.9,9.1,11.8)
7500	18000	(13.9,16.2,18.5,19.9)	(20.2,23.1,25.4,27.4)	(20.5,22.8,24.5,26.6)	(34.6,37.4,41.1,43.5)
8000	12000	(45.3,47.9,51.3,54.8)	(16.4,19.1,21.1,23.2)	(12.9,15.9,17.2,18.5)	(6.3,7.9,9.5,11.1)
8000	18000	(11.5,13.5,14.9,16.3)	(17.5,19.6,21.3,23.3)	(25.8,26.8,28.1,29.5)	(34.5,37.8,40.1,42)
10000	12000	(30.9,33.9,36.5,38.1)	(12.4,14.7,16.7,18.6)	(14.2,16.2,17.6,19.5)	(31.4,34.5,36.5,38.9)
10000	18000	(5.5,8.1,10.4,12.1)	(16.8,18.8,20.8,22.8)	(26,28,30.3,32.2)	(34.2,36.2,38.7,42.1)

$^{*}\widetilde{APs}=(0.4)\otimes(47,49,52,57)+(0.3)\otimes(44,45,48,50)+(0.3)\otimes(49,53,55,60)=(46.7,49,51.7,55.8)$

Table 5. Defuzzified aggregated possibility and probability of states of cost of C

Cost of A	Cost of B	Defuzzified aggregated possibility (%) of states of cost of C				K				Defuzzified aggregated probability (%) of states of cost of C			
		7000	**6000**	**5400**	**2000**	**7000**	**6000**	**5400**	**2000**	**7000**	**6000**	**5400**	**2000**
7500	**12000**	50.88*	24.33	10.92	8.2	2.27	3.36	4.63	5.15	92	7.5	0.4	0.1
7500	**18000**	17.09	23.98	23.59	39.13	3.89	3.38	3.4	2.67	4	13	13	70
8000	**12000**	49.86	19.92	16.04	8.7	2.3	3.66	3.99	5.03	93.8	4	2	0.2
8000	**18000**	14.02	20.42	27.56	38.53	4.21	3.62	3.17	2.69	2	8	22	68
10000	**12000**	34.79	15.58	16.87	35.29	2.84	4.04	3.92	2.82	45	3	4	48
10000	**18000**	8.99	19.8	29.12	37.86	4.98	3.67	3.09	2.71	0.4	7	27	65.6

Defuzzified value (DFPs) =

$$\frac{1}{3}\frac{(55.8+51.7)^2-(55.8\times51.7)-(46.7+49)^2+(46.7\times49)}{55.8+51.7-46.7-49}=50.88$$

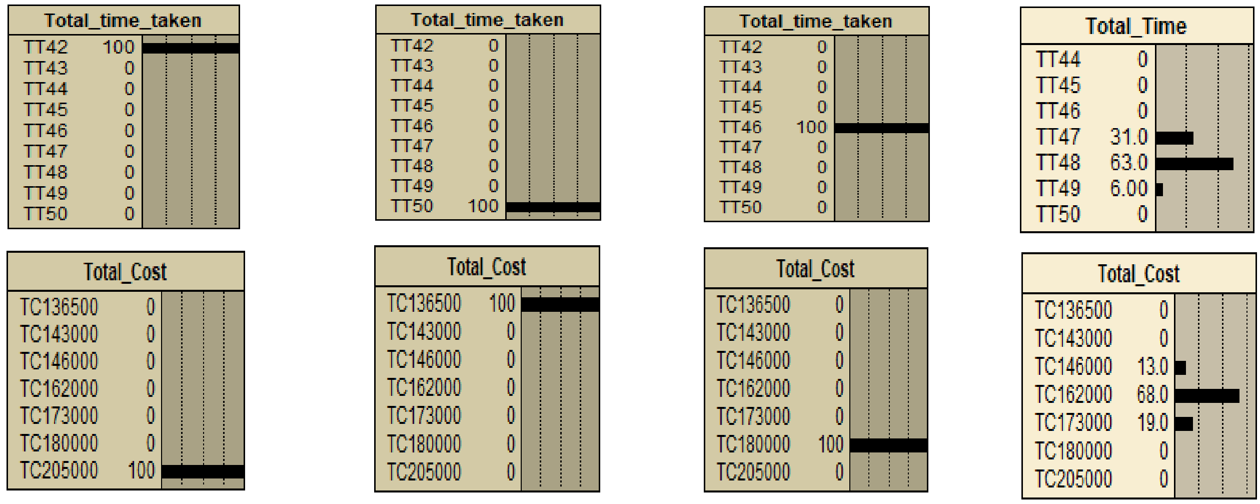
Table 6. The results of different scenarios using fuzzy BN model

Node	Fully crashed	Normal time	Best quality	Favorable state
Cost of A	10000	7500	8000	8000
Time period of A	3	5	4	4
Quality of A	85	90	95	95
Cost of B	18000	12000	12000	18000
Time period of B	7	8	8	7
Quality of B	90	95	95	90
Cost of C	7000	2000	5400	6000
Time period of C	9	13	12	10
Quality of C	85	85	95	90
Cost of D	60000	35000	50000	50000
Time period of D	22	25	25	23
Quality of D	85	90	95	95
Cost of E	20000	20000	20000	20000
Time period of E	16	17	17	16
Quality of E	100	100	100	100
Cost of F	90000	60000	85000	60000
Time period of F	42	50	50	48
Quality of F	80	85	90	85

As can be seen in Figure 3, in maximum crashing mode, the duration and total cost of the project are 42 days and 205000$, respectively. In fact, this time is minimum completion time of the project with maximum cost. On the other side, in normal time mode, the duration of the project is 50 days and total cost is 136500$. The minimum cost occurs in this mode. In maximum quality mode, the duration and total cost of the project are 46 days and 180000$. Ultimately, the results of favorable decisions of experts are located in favorable mode,

In order to evaluate the obtained results, the introduced project is compared with one of the old and common methods of project management, called Program Evaluation and Review Technique (PERT). PERT considers optimistic, pessimistic, and most likely values in calculations. Then, to determine the expected value, Eq. (6) is introduced:

$$\text{Expected value} = \frac{(\text{optimistic value} + 4\times \text{most likely value} + \text{pessimistic value})}{6} \quad (6)$$



A. Maximum crashing mode   B. Normal time mode   C. Maximum quality mode   D. Favorable mode

Fig. 3. All calculations for different scenarios in the proposed project

Table 7. Solution of the proposed project via PERT

Activity	Optimistic time	Most likely time	Pessimistic time	Expected time	Corresponding cost	Corresponding quality	Aggregate time
A	3	4	5	4	8000	95	4
B	7	7/5	8	7.5 (8)	12000	95	8
C	2	3	5	3.17 (3)	6000	90	11(8+3)
D	15	16	17	16	50000	95	24(8+16)
E	9	9	9	9	20000	100	17(8+9)
F	20	22	25	22.17 (22)	85000	90	46(24+22)

As can be seen in table 7, an activity with fractional expected time is rounded and then, corresponding cost and quality of that activity is determined. As a result, the total time, cost, and quality of the project with PERT are computed 46, 181000, and 94.17 respectively. The proposed BN has advantages over PERT:

1- In the proposed BN, it is possible to simultaneously model time, cost, and quality and to simultaneously determine event probabilities, but in PERT, only the time criterion is discussed, and other criteria are determined according to the activity time.

2- In the presented BN, the results are reported with considering uncertainty until the last stage, and the project manager knows with what probabilities the time, cost, and quality of the project will occur, but in PERT, in the first stage, the uncertain parameters become a crisp number. It may cause data loss.

3- In the presented BN, in addition to considering the predecessors' relations of activities that are also considered in PERT, it can consider the interrelationship between time, cost, and quality of various activities (nodes).

4- In the presented BN, different probability distributions can be considered for the uncertain parameters, while only one mode is possible in PERT.

5- The presented BN is an efficient method when there is sufficient data to determine the distributions of uncertain parameters and when there is no historical data. When there is no historical data, it can create effective solutions using experts' opinions and fuzzy sets. Due to the unique inherent of projects, the lack of enough data is common.

Table 8. A summary of the advantages of the presented method and comparative analysis with Ghosh et al. [2] 1.

Aspects of the comparisons	Results of the comparisons
Quality criterion	In the presented methodology, the quality criterion as a vital criterion in project success is considered, but Ghosh et al. [2] did not consider this important subject.
Considering group decision-making	Considering a set of experts, instead of individual expert, can result more accurate decisions, since they can comprehensively control various aspects of the decision-making process and create fair and reasonable evaluation results. Ghosh et al. [2] did not pay attention to this note.
Weight of each expert	It is important to compute the weight of each DM in a group decision-making due to the achievement of better solutions. Ghosh et al. [2] did not pay attention to this note.
Fuzzy uncertainty	One of the novelties of this method is to consider fuzzy uncertainty instead of crisp values to address the probability of the BN model. This action can better express the doubts of expert opinions and better handle the group decision-making process due to advantages of fuzzy concepts. Ghosh et al. [2] did not consider this important subject.

3- 1- Comparative analysis

To depict the advantages of the presented methodology, a comparative analysis with a recent paper Ghosh et al. [2] that is accounted as the basic paper of this paper is provided. In Table 8, the superiorities of the presented methodology are clearly expressed in more detail and compared with each other.

The presented methodology has some advantages that make it powerful and appropriate. In this paper, the quality criterion, known as one of the most vital criteria for project success, has been considered. Moreover, this methodology benefits from the group decision-making process and the weight of expert opinion. It can improve the accuracy of the results due to considering various aspects of the problem. Fuzzy uncertainty is applied to better manage the uncertainty of real world and the experts' vagueness in determining the BN model's probability.

4- Conclusion and summary

The project scheduling problem is considered as one of the most important problems in project management. In this paper, a novel approach based on fuzzy Bayesian network (BN) was presented to solve the time-cost-quality trade-off problem (TCQTP). This approach can schedule a project through managing real-world uncertainty. To implement the approach, the experts' opinions, which are in form of the trapezoidal fuzzy, according to the weight of each expert were applied to calculate the probabilities of root nodes and conditional probabilities of other nodes of BN. Indeed, the presented approach can both manage the various uncertainties of a project associated with the occurrence of different scenarios and control the uncertainties that exist in the opinions of experts to determine the required probabilities of BN. On the other hand, the proposed fuzzy BN approach, unlike many previous approaches that relied severely upon historical data, can work with historical data as well as expert opinions. Furthermore, the existence of an active system in order to implement the necessary changes with the emergence of the effects of new factors, the possibility of the existence of discrete and continuous variables in the model, and also the possibility of considering different distributions are the other advantages of the presented methodology. To demonstrate the application and efficiency of the proposed model, a modified project example from the literature review was selected and solved by the proposed approach. All results were calculated using Netica software for four scenarios fully crashed, normal time, best quality, and favorable state. The results obtained can be so helpful for project managers, since they achieve comprehensive information about the time, cost, and quality of the project in different situations and scenarios. To verify the proposed methodology, the computed results were compared with the PERT approach. To develop this research, it is worth mentioning that one of the problems in managing projects is an accurate estimation of project parameters, which are also known as model inputs. In order to develop this research, it is required to provide the model with an accurate estimation method for the input parameters. Moreover, other components for ensuring project success such as project resources can be inserted into the model. A dynamic BN can be applied to solve the introduced problem. Finally, other approaches except experts' opinions approach can also be applied to calculate probabilities in BN.

References

[1] Bettemir, Ö. H., & Birgönül, M. T. (2017). Network analysis algorithm for the solution of discrete time-cost trade-off problem. KSCE Journal of Civil Engineering, 21(4), 1047-1=058.

[2] Ghosh, M., Kabir, G., & Hasin, M. A. A. (2017). Project time–cost trade-off: a Bayesian approach to update project time and cost estimates. International Journal of Management Science and Engineering Management, 12(3), 206-215.

[3] Jeunet, J., & Orm, M. B. (2020). Optimizing temporary work and overtime in the Time Cost Quality Trade-off Problem. European Journal of Operational Research, 284(2), 743-761.

[4] Ballesteros-Perez, P., Elamrousy, K. M., & González-Cruz, M. C. (2019). Non-linear time-cost trade-off models of activity crashing: Application to construction scheduling and project compression with fast-tracking. Automation in Construction, 97, 229-240.

[5] El-Sayegh, S. M., & Al-Haj, R. (2017). A new framework for time-cost trade-off considering float loss impact. Journal of Financial Management of Property and Construction, 22(1), 20-36.

[6] Leyman, P., Van Driessche, N., Vanhoucke, M., & De Causmaecker, P. (2019). The impact of solution representations on heuristic net present value optimization in discrete time/cost trade-off project scheduling with multiple cash flow and payment models. Computers & Operations Research, 103, 184-197.

[7] Abdel-Basset, M., Ali, M., & Atef, A. (2020). Uncertainty assessments of linear time-cost tradeoffs using neutrosophic set. Computers & Industrial Engineering, 141, 106286.

[8] Panwar, A., & Jha, K. N. (2021). Integrating Quality and Safety in Construction Scheduling Time-Cost Trade-Off Model. Journal of Construction Engineering and Management, 147(2), 04020160.

[9] Orm, M. B., & Jeunet, J. (2018). Time cost quality trade-off problems: A survey exploring the assessment of quality. Computers & Industrial Engineering, 118, 319-328.

[10] Mohammadipour, F., & Sadjadi, S. J. (2016). Project cost-quality-risk trade-off analysis in a time-constrained problem. Computers & Industrial Engineering, 95, 111-121.

[11] Haghighi, M. H., Mousavi, S. M., Antuchevičienė, J., & Mohagheghi, V. (2019). A new analytical methodology to handle time-cost trade-off problem with considering quality loss cost under interval-valued fuzzy uncertainty. Technological and economic development of economy, 25(2), 277-299.

[12] Hosseini-Nasab, H., Pourkheradmand, M., & Shahsavaripour, N. (2017). Solving Multi-Mode Time-Cost-Quality Trade-off Problem in Uncertainty Condition Using a Novel Genetic Algorithm. International Journal of Management and Fuzzy Systems, 3(3), 32.

[13] Chapman, C., & Ward, S. (2011). How to manage project opportunity and risk: Why uncertainty management can be a much better approach than risk management. New York, NY: Wiley.

[14] Salman, Baris. (2011). Infrastructure management and deterioration risk assessment of wastewater collection systems (PhD Dissertation). University of Cincinnati, p. 210.

[15] Naik, M., & Kumar, D. (2015). Construction project cost and duration optimization using artificial neural network. American Society of Civil Engineers, 2015, 433–444.

[16] Ashrafi, M., & Anzabi Zadeh, S. (2017). Lifecycle risk assessment of a technological system using dynamic Bayesian networks. Quality and Reliability Engineering International, 33(8), 2497-2520.

[17] Sanchez, F., Steria, S., Bonjour, E., Micaelli, J. P., & Monticolo, D. (2020). An approach based on bayesian network for improving project management maturity: An application to reduce cost overrun risks in engineering projects. Computers in Industry, 119, 103227.

[18] Covaliu, Z., & Soyer, R. (1996). Bayesian project management. In: Procreation Conference ASA Section on Bayesian Statistical Science, pp. 208–213.

[19] Cho, S. (2009). A linear Bayesian stochastic approximation to update project duration estimates. European Journal of Operational Research, 196, 585–593.

[20] Chou, J. S., Yang, I. T., & Chong, W. K. (2009). Probabilistic simulation for developing likelihood distribution of engineering project cost. Automation in Construction, 18, 570–577.

[21] Zarei, E., Khakzad, N., Cozzani, V., & Reniers, G. (2019). Safety analysis of process systems using Fuzzy Bayesian Network (FBN). Journal of loss prevention in the process industries, 57, 7-16.

[22] Ferreira, L., & Borenstein, D. (2012). A fuzzy-Bayesian model for supplier selection. Expert Systems with Applications, 39(9), 7834-7844.

[23] Wan, C., Yan, X., Zhang, D., Qu, Z., & Yang, Z. (2019). An advanced fuzzy Bayesian-based FMEA approach for assessing maritime supply chain risks. Transportation Research Part E: Logistics and Transportation Review, 125, 222-240.

[24] Aliabadi, M. M., Pourhasan, A., & Mohammadfam, I. (2020). Risk modelling of a hydrogen gasholder using Fuzzy Bayesian Network (FBN). International Journal of Hydrogen Energy, 45(1), 1177-1186.

[25] He, Z., He, H., Liu, R., & Wang, N. (2017). Variable neighbourhood search and tabu search for a discrete time-cost trade-off problem to minimize the maximal cash flow gap. Computers & Operations Research, 78(1), 564-577.

[26] Liu, D., Li, H., Wang, H., Qi, C., & Rose, T. (2020).

Discrete symbiotic organisms search method for solving large-scale time-cost trade-off problem in construction scheduling. Expert Systems with Applications, 148, 113230.

[27] Bossaghzadeh, I., Hejazi, S. R., & Pirmoradi, Z. (2015). Developing robust project scheduling methods for uncertain parameters. AUT Journal of Modeling and Simulation, 47(1), 21-32.

[28] Nabipoor Afruzi, E., & Aghaie, A. (2019). A Hybridized Metaheuristic Algorithm to Solve the Robust Resource Constrained Multi-Project Scheduling Problem. AUT Journal of Modeling and Simulation, 51(1), 15-32.

[29] Kim, J., Kang, C., & Hwang, I. (2012). A practical approach to project scheduling: considering the potential quality loss cost in the time-cost trade-off problem. International Journal of Project Management, 30(2), 264-272.

[30] Monghasemi, S., Nikoo, M. R., Fasaee, M. A. K., & Adamowski, J. (2015). A novel multi-criteria decision-making model for optimizing time-cost-quality trade-off problems in construction projects. Expert Systems with Applications, 42(6), 3089-3104.

[31] Tran, D. H., & Long, L. D. (2018). Project scheduling with time, cost and risk trade-off using adaptive multiple objective differential evolution. Engineering, Construction and Architectural Management, 25(5), 623-638.

[32] Ashrafi, M., Davoudpour, H., & Khodakarami, V. (2015). Risk assessment of wind turbines: Transition from pure mechanistic paradigm to modern complexity paradigm. Renewable and Sustainable Energy Reviews, 51, 347-355.

[33] Abolbashari, M. H., Chang, E., Hussain, O. K., & Saberi, M. (2018). Smart buyer: a Bayesian network modelling approach for measuring and improving procurement performance in organisations. Knowledge-Based Systems, 142, 127-148.

[34] Lessan, J., Fu, L., & Wen, C. (2019). A hybrid Bayesian network model for predicting delays in train operations. Computers & Industrial Engineering, 127, 1214-1222.

[35] Ashrafi, M., Davoudpour, H., & Khodakarami, V. (2016). A Bayesian network based framework to evaluate reliability in wind turbines. Wind and Structures, 22(5), 543–553.

[36] Ashrafi, M., & Davoudpour, H. (2019). A hierarchical bayesian network to compare maintenance strategies based on cost and reliability: A case of onshore wind turbines. International Journal of Industrial Engineering, 26(3).

[37] Malagrino, L. S., Roman, N. T., & Monteiro, A. M. (2018). Forecasting stock market index daily direction: A Bayesian Network approach. Expert Systems with Applications, 105, 11-22.

[38] Ojha, R., Ghadge, A., Tiwari, M. K., & Bititci, U. S. (2018). Bayesian network modelling for supply chain risk propagation. International Journal of Production Research, 56(17), 5795-5819.

[39] Kabir, G., Tesfamariam, S., Francisque, A., & Sadiq, R. (2015). Evaluating risk of water mains failure using a Bayesian belief network model. European Journal of Operational Research, 240, 220–234.

[40] Ashrafi, M. (2021). Forward and backward risk assessment throughout a system life cycle using dynamic Bayesian networks: A case in a petroleum refinery. Quality and Reliability Engineering International, 37(1), 309-334.

[41] Pearl, J. (1988). Probabilistic reasoning in Intelligent Systems: Networks of plausible inference. San Francisco: Morgan Kaufmann , Incorporation.

[42] Zarei, E., Khakzad, N., Cozzani, V., & Reniers, G. (2019). Safety analysis of process systems using Fuzzy Bayesian Network (FBN). Journal of loss prevention in the process industries, 57, 7-16.

[43] Shan, X., Liu, K., & Sun, P. L. (2017). Risk analysis on leakage failure of natural gas pipelines by fuzzy Bayesian network with a bow-tie model. Scientific programming, 2017.

[44] Haghighi, M. H., Mousavi, S. M., & Mohagheghi, V. (2019). A new soft computing model based on linear assignment and linear programming technique for multidimensional analysis of preference with interval type-2 fuzzy sets. Applied Soft Computing, 77, 780-796.

[45] Haghighi, M. H., & Ashrafi, M. (2022). A new qualitative and quantitative analytical approach for risk management in energy project time-cost trade-off problem under interval type-2 fuzzy uncertainty: A case study in the gas industry. Energy Reports, 8, 12668-12685.

[46] Rostamabadi, A., Jahangiri, M., Zarei, E., Kamalinia, M., & Alimohammadlou, M. (2020). A novel Fuzzy Bayesian Network approach for safety analysis of process systems; An application of HFACS and SHIPP methodology. Journal of Cleaner Production, 244, 118761.

[47] Lavasani, S. M., Ramzali, N., Sabzalipour, F., & Akyuz, E. (2015). Utilisation of Fuzzy Fault Tree Analysis (FFTA) for quantified risk analysis of leakage in abandoned oil and natural-gas wells. Ocean Engineering, 108, 729-737.

[48] Yucesan, M., Gul, M., & Celik, E. (2021). A holistic FMEA approach by fuzzy-based Bayesian network and best–worst method. Complex & Intelligent Systems, 1-18.

[49] Onisawa, T. (1988). An approach to human reliability in man-machine systems using error possibility. Fuzzy sets and Systems, 27(2), 87-103.

Appendix 1:

In a group decision-making process, various experts were different in their knowledge structure, ability, and experience. Consequently, considering the weight of experts' opinions can cause more reliable results. In this paper, first, ten prominent experts who had both research backgrounds and work experiences have been selected. All experts have both high academic experience and industrial experience in project management. In the next step, the three experts with upper scores regarding operational experience, work experience, managerial job responsibility, and research background are determined. The scores range from 1 to 10. Ultimately the project manager determines the weight of opinion for each DM according to the obtained average score. These three different experts have been able to consider the various aspects of a problem and there is not any bias in the results.

Table 1. Scores of each expert

	Operational experience	Work experience	Managerial job responsibility	Research experience	Average
Ex_1	5	7	6	6	6
Ex_2	8	7	9	10	8.5
Ex_3	4	8	6	7	6.25
Ex_4	6	6	6	8	6.5
Ex_5	9	5	5	6	6.25
Ex_6	5	5	5	6	5.25
Ex7	7	6	5	4	5.5
Ex_8	6	10	7	8	7.75
Ex_9	7	6	7	7	6.75
Ex_{10}	10	10	8	9	9.25

HOW TO CITE THIS ARTICLE

M.H.Haghighi, M. Ashrafi, E. Nazerfard, A novel fuzzy Bayesian network-based approach for the project time-cost-quality trade-off problem. AUT J. Model. Simul., 54(2) (2022) 185-196.

DOI: 10.22060/miscj.2023.20752.5266