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Time-cost-quality-risk Trade-off Project Scheduling Problem in Oil and Gas Construction Projects: Fuzzy Logic and Genetic Algorithm

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ABSTRACT

Time, cost and quality, known as project iron triangle, are among the important goals and objectives of any project. New agreements in construction industry, which pay more attention to the quality of project implementation while reducing time and cost, demonstrate the growing importance of these three primary objectives of projects. In this paper, an optimization model with three objective functions of cost, risk and quality considering their relationships with time is presented. In the cost objective function, the associated costs of compressing project activities together with the costs of delay are taken into account. The risk objective deals with the probability of risk occurrence and its impact on project other objectives. The quality objective function expresses the degree of reduction in the quality level of compressed activities. The model was also validated by solving the small-size problems with the exact method and NSGA-II algorithm (Non-dominated Sorting Genetic Algorithm). The proposed model was implemented in a construction project of oil storage tanks. Due to the NP-Hard and large-sized problem, the model was solved by using the metaheuristic NSGA-II algorithm. The results showed that the NSGA-II algorithm achieved close to the optimal solution. Therefore, the NSGA-II algorithm can be exploited for solving large-size problems with more confidence.

KEYWORDS: Multi-objective optimization, Time-cost-quality-risk trade-off, Fuzzy logic, Meta-heuristic algorithm, NSGA-II, Oil and gas construction project.

INTRODUCTION

The construction industry as one of the largest sectors is known as the cornerstone of economy in the world, since this industry requires relatively high human resources and significantly contributes to Gross Domestic Product (GDP). The construction industry is constantly facing challenging problems due to several uncertainties and changes throughout the different phases of the project life cycle. These changes affect the goals and objectives of a project. The design and implementation phases of the project are of significant importance due to their complexities and different stakeholders. The project success is often measured by main criteria, including completion time, total costs and quality of the project (Ibrahim and Elshwadfy, 2021). Project management often ensures that projects are completed within predefined time and budget as well as an acceptable quality level. Therefore, project managers are able to monitor and control the duration of each activity and, in case of deviation from the planned schedule, make the necessary decisions (Wong and Mohammed Ahmed, 2018). Project management as one of the most important and practical topics has attracted much more attention in recent years. Project schedule management as one of the knowledge areas of project management deals with managing the on-time completion of projects (PMBOK, 6th Edition, 2017; Ghafoori and Taghizadeh Yazdi, 2017; Hamta et al., 2018). Different goals and objectives are defined for projects; however, minimizing time and cost as well as maximizing quality are among the main goals of projects (Demeulemeester and Herroelen, 2006). Project

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managers can improve project quality with changing the durations and costs of activities which lead to the time-cost-quality trade-off project scheduling problem (Saif et al., 2015). Changes in time, cost and quality of projects are always associated with risk. Many project failures occur due to risks and uncertainties in the surrounding environment and inherent characteristics of projects (Liang, 2005). According to the definition of Project Management Institute (PMBOK, 6th Edition, 2017), project risk is an uncertain event that if it occurs, it may affect at least one of the project goals and objectives including quality, cost, time, … etc. Discovering the balance between the criteria of time, cost, quality and risk of the project and to what extent spending more costs will affect the duration of the project and its quality level is the main topic of this research.

Despite the high importance of risk management in construction projects, it is often neglected in projects due to its cost and high information requirements (Mubarak, 2015). Construction companies that carry out small-and medium-sized projects are less inclined to manage risk. One of the reasons for this reluctance is the fact that companies are forced to offer lower amounts for the project due to the highly competitive environment. Therefore, they cannot spend more money on risk management (Smith and Bohn, 1999). However, research shows that risk management can improve project performance in order to timely complete the project with the predetermined budget (Ali, 2000; Mills, 2001; Klemetti, 2006).

The contribution of the current study is in calculating the penalty for project delays. In addition, the actual project status and its deviation from the planned schedule together with project completion time can be determined by scheduling techniques and computing the negative floats at any time during the project implementation. Calculating the impact of activity compression on quality can be stated as another contribution of this study. Also, a new method was used to defuzzify the fuzzy numbers corresponding to linguistic variables. This article is organized as follows. The next section expresses the literature review. The methodology is then given, followed by illustrating the results and finally, the paper is concluded.

LITERATURE REVIEW

It is often possible in project scheduling to speed up project completion time by reducing the durations of some activities and incurring additional costs. In general, the time-cost trade-off project scheduling problem has been extensively investigated by several researchers. Sequencing and scheduling of project activities considering limited resources are among the most substantial topics in the field of project management, which can considerably decrease the exorbitant costs of construction projects. Initially, the project scheduling problems were examined as single-objective optimization problems, so that the minimization of project completion time, total project costs or fluctuations in resource usage were broadly considered as the main objective functions (Falk and Horowitz, 1972). The time-cost trade-off problem was first introduced by Kelley (1961) who presented the linear programming model for compressing project activities in which the cost was linearly related to the activity duration. Falk and Horowitz (1972) developed a model to show the nonlinear relationship between cost and duration of each activity and proposed a solution method. Harvey and Patterson (1979) presented an enumerating algorithm for solving this problem. They introduced a zero-one mathematical programming model and validated it by solving a few examples. For the first time, Reda and Carr (1989) developed a multi-objective programming model for this type of project scheduling problem. Multi-objective optimization models mainly focus on finding optimal solutions that simultaneously minimize the total cost and duration of projects. Erenguc et al. (1993) presented an exact algorithm for solving the discrete time-cost trade-off problem with discounted cash flows. In the past, managerial decisions for expediting a project were limited to the considerations of time and cost, but recently it has been suggested that the quality of the project be taken into account. The time-cost-quality triangle has been constantly pursued by project managers throughout the project life cycle (Iranmanesh et al., 2008). Different expectations of project stakeholders and the changes happening during the course of the project may force managers to make changes to these goals. According to the time-cost-quality triangle, any changes of activity durations definitely lead to changes in cost and quality (Kerzner, 2017). The quality of the project as one of the basic criteria of project success is affected by compressing activity duration (Khang and Myint, 1999). Babu and Suresh (1996) proposed three linear programming models presented with three separate objective functions for time, cost and quality, each of which optimized only one objective function considering the other two objective functions as constraints. Thereafter, other researchers such as El-Rayes and Kandil (2005), Wang et al. (2019), Moghadam et al. (2020) and Luong et al. (2021) addressed the time-cost-quality trade-off problem. Wood (2017) implemented the time-cost-quality trade-off model in an oil and gas project and designed an algorithm consisting of 10 metaheuristic sub-algorithms to balance the local exploration and global exploration of the solution space.

Poh and Tah (2006) quantitatively analyzed project risks and investigated the impacts of risks on the durations and costs of project activities. Some researchers have particularly focused on risk management in the construction industry. These researchers have addressed topics such as identifying and evaluating risks in construction projects, determining key risk factors, studying the impacts of risks on project cost and quality and identifying barriers to risk management implementation (Chileshe and Yirenkyi-Fianko, 2012; Chileshe and Kikwasi, 2013; Hwang et al., 2014; Collins et al., 2017).

Reviewing the relevant literature shows some research gaps in modeling the time-cost-quality trade-off problem as well as providing solution approaches. Therefore, the existing shortcomings can be categorized into two groups: developing models closer to real-world projects and improving solution methods. In this paper, four aspects of time, cost, quality and risk in construction projects are examined. Hence, this research aims to develop a multi-objective optimization model considering the assumptions of real-world construction projects. Also, this study seeks to determine the execution mode of each critical project activity, so that the costs and risks of the project are reduced and the project quality is increased. Moreover, the effects of cost, risk and quality on project duration are analyzed. Furthermore, the fuzzy logic is used to deal with the uncertainty associated with the model parameters. Finally, the goal programming approach and NSGA-II metaheuristic algorithm are exploited to solve the proposed model.

MATHEMATICAL PROGRAMMING MODEL

There exist a number of execution modes for each project activity to choose, each of which has its own risk, duration, cost and quality. Optimizing time, cost and quality considering risk is an appropriate approach to find the optimal combinations of time, cost and quality for the project. In this study, a multi-objective mathematical programming model is presented to optimize the three objective functions of cost, risk and quality, considering activity compression. It should be noted that the proposed model attempts to minimize the degree of quality reduction by compressing activity duration, taking into account the relevant importance of the activity based on its duration, which ultimately increases the project quality.

The indices and parameters are presented as follows:

Indices

i: Predecessor of activity *j*

j: Activity

k: Successor of activity *j*

r: Impact of risk associated with crashing the duration of activity *j* on project goals

t: The amount of reduced duration of activity *j*

l: The dummy finish activity

y: Project delay

Parameters

C_j: Increased cost of performing activity *j* corresponding with reducing duration of activity *j*

C_p: Delay cost for a client or employer claim

f_0: Planned project finish time or deadline

d_j: Duration of activity *j*

TR_j^{max}: Maximum reduced duration of activity *j*

FS_{ij}^{min}: The lowest lag or lead between activities *i* and *j* with the FS predecessor relationship

SS_{ij}^{min}: The lowest lag or lead between activities *i* and *j* with the SS predecessor relationship

FF_{ij}^{min}: The lowest lag or lead between activities *i* and *j* with the FF predecessor relationship

SF_{ij}^{min}: The lowest lag or lead between activities i and j with the SF predecessor relationship
P_{jt}: Probability of risk occurring while reducing t unit of time from the duration of activity *j*
I_{jrt}: The scale of risk occurring on the *r* factor of the project by decreasing t time unit for the duration of activity *j*
W_{dj}: The weight of activity j based on its duration
S_j^E: The earliest start time of activity *j*
f_j^l: The latest finish time of activity *j*
f_n^l: The actual finish time of the project

Decision variable

X_{jt}: The binary variable; 1 If the duration of activity *j* is reduced by *t* units of time and 0 otherwise

Mathematical Programming Model

$$\min Z_1 = y * C_p + \sum_{j=1}^{n}\sum_{t=1}^{TR_j^{max}} t.C_j.X_{jt} \tag{1}$$

$$\min Z_2 = \sum_{r=1}^{m}\sum_{j=1}^{n}\sum_{t=1}^{TR_j^{max}} P_{jt}.I_{rjt}.X_{jt} \tag{2}$$

$$\min Z_3 = \sum_{j=1}^{n}\sum_{t=1}^{TR_j^{max}} W_{dj}.(1 - q_{jt}) \tag{3}$$

$$\sum_{t=1}^{TR_j^{max}} X_{jt} \leq 1 \tag{4}$$

$$y = \begin{cases} f_n^l - f_0 > f_0 \\ 0 & else \end{cases} \tag{5}$$

$$f_j^l - S_j^E \geq (d_j - \sum_{t=1}^{TR_j^{max}} t.X_{jt})\forall_j \tag{6}$$

$$S_j^E - S_i^E \geq (d_j - \sum_{t=1}^{TR_j^{max}} t.X_{jt}) + FS_{ij}^{min} \tag{7}$$

$$f_k^l - f_j^l \geq (d_k - \sum_{t=1}^{TR_k^{max}} t.X_{kt}) + FS_{jk}^{min}\forall_{i,j\in FS} \tag{8}$$

$$S_j^E - S_i^E \geq SS_{ij}^{min} \tag{9}$$

$$f_k^l - f_j^l \geq \left(d_k - \sum_{t=1}^{TR_k^{max}} t.X_{kt}\right) - (d_j - \sum_{t=1}^{TR_j^{max}} t.X_{jt}) + SS_{jk}^{min} \tag{10}$$

$$f_k^l - f_j^l \geq FF_{jk}^{min} \tag{11}$$

$$S_j^E - S_i^E \geq SF_{ij}^{min} - (d_j - \sum_{t=1}^{TR_j^{max}} t.X_{jt})x \tag{12}$$

$$f_k^l - f_j^l \geq SF_{jk}^{min} - (d_j - \sum_{t=1}^{TR_j^{max}} t.X_{jt}) \tag{13}$$

$$S_j^E \text{and} f_j^l \geq 0 \tag{14}$$

$$X_{jt} \in \{0, 1\} \tag{15}$$

$$0 \leq q_{jt} \leq 1 \tag{16}$$

$$\sum_{j=1}^{n} W_{dj} = 1 \tag{17}$$

$$0 \leq P_{jt} \leq 1 \tag{18}$$

Eq. 1 seeks to minimize the cost objective function which equals all incurred costs related to crashing activities, plus a delay cost. In fact, the amount of project delay is calculated by the difference between actual finish time and planned project finish time shown in constraint 5. The amount of project delay, is multiplied by the associated costs. It should be noted that in case of project delay, the total project float is negative. In other words, this objective function first seeks to minimize the total costs of the project by minimizing the costs of the activities selected for crashing. These activities are selected based on their floats. Eq. 2 seeks to minimize the risk objective function which is equal to the product of the probability of occurrence of the risk and its impact, as well as the main project factors that will be affected by risk. One of the important steps of risk management is the formation of probability and effect matrix (PMBOK, 6th edition, 2017). The probability of occurrence of each risk and its impact on project objectives are determined. Risks are prioritized based on their potential impacts on project objectives.

Table 1. The impacts of risks on project objectives

Project objective	**Relative or numerical scales**				
	Very low (0.05)	Low (0.1)	Medium (0.2)	High (0.4)	Very high (0.8)
Cost	Slight cost increase	Cost increase of less than 10%	10 to 20 percent increase in costs	20 to 40 percent increase in costs	More than 40% increase in costs
Time	Slight time increase	Time increase of less than 5%	5 to 10 percent increase in time	10 to 20 percent increase in time	More than 20% increase in costs
Scope	Slight scope decrease	Small areas of the scope are affected	The main areas of the scope are affected	Reducing the scope is unacceptable for the sponsor	The final project deliverables are completely useless
Quality	Slight quality decrease	Only high-demand applications are affected	Quality reduction requires the approval. of the sponsor	Quality reduction is unacceptable for the sponsor	The final project deliverables are completely useless

In the quality objective function (Eq. 3), the quality reduction degrees of compressed activities are expressed with fuzzy numbers at five different levels. Each of these levels that are expressed using linguistic variables is converted into crisp numbers by the E_φ method. Then, the weights of these activities are calculated. Eq. 4 shows the project delay and states that if the project is completed later than the deadline, the amount of delay (in terms of time unit) is multiplied by the associated penalty cost for each unit of time specified in the contract. Eqs. 5 to 14 relate to the critical path and the allowable amount of time for reducing the durations of activities considering the floats and the precedence relationships between activities. Eq. 15 represents the binary decision variable. Eq. 16 defines the quality level of the project between 0 and 1. Eq. 17 indicates that the sum of the weights is equal to 1 and Eq. 18 dictates that the probability must be between 0 and 1.

Subsequently, the proposed model is solved by the NSGA-II algorithm. The flowchart of the algorithm is presented in Figure 1.

In addition, the goal programming method is applied for validation of the algorithm. Goal programming method is used to formulate and solve problems that require multiple goals. This method needs two values of goal and weight, each of which is denoted by w and b, respectively. The objective functions are rewritten as follows:

$$\text{Min } G \tag{19}$$

Subject to:

$$\left(y * C_p + \sum_{j=1}^{n} \sum_{t=1}^{TR_j^{max}} t.C_j.X_{jt}\right) - {}^{1}\!/_{3}\, G \leq b_1 \tag{20}$$

$$\left(\sum_{r=1}^{m} \sum_{j=1}^{n} \sum_{t=1}^{TR_j^{max}} P_{jt}.I_{rjt}.X_{jt}\right) - {}^{1}\!/_{3}\, G \leq b_2 \tag{21}$$

$$\left(\sum_{j=1}^{n} \sum_{t=1}^{TR_j^{max}} W_{dj}.(1 - q_{jt})\right) - {}^{1}\!/_{3}\, G \leq b_3 \tag{22}$$

Eq. 19 expresses the cost objective function. This function minimizes the deviation from achieving project goals. Eq. 20 denotes the cost constraint (determines its value by considering equal weights for 3 factors and setting a goal). Eq. 21 shows the risk constraint (determines its value by considering equal weights for 3 factors and setting a goal). Eq. 22 states the quality constraint (determines its value by considering the equal weights for the 3 factors and setting a goal). The above model seeks to optimize these three objective functions with equal weights.

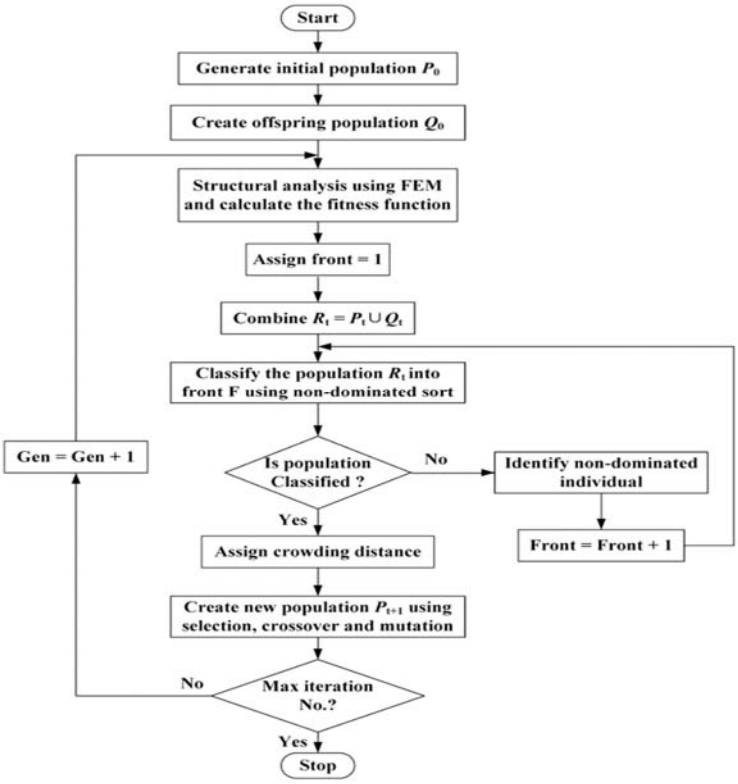

Figure (1): The algorithm flowchart

RESULTS

The proposed mathematical programming model was implemented in a construction project of oil storage tanks. First, with the assistance of engineering, business and construction teams together with the review of the documents of completed similar projects, the durations of activities, their precedence relationships and sequencing were determined. The actual project duration was 158 days, 7 days more than the planned duration stated in the contract. Therefore, the project float is negative and the project is 7 days behind the schedule. The problem of this study is how to compress the project duration, taking the three goals of cost, risk and quality into account. Therefore, the activities that have negative floats should be considered for crashing. According to the characteristics of each activity and the human resources required for performing, the compression cost of each selected activity is calculated and the results are shown in Table 2.

Table 2. Maximum reduction in duration for selected activities

Code	Activity Name	Duration	Maximum Reduction	Cost ($)
A1	Vendor Print Index & Schedule (VPIS)	10	7	100
A2	Process/Mechanical Data Sheet 1	10	7	100
A3	Process/Mechanical Data Sheet 2	10	7	100
A4	Deviation Confirmation	10	7	100
A5	General Arrangement and Detail Drawing	20	15	100
A6	General Arrangement and Detail Drawing	20	15	100
A7	Boot Attachments Fit-up & Welding	20	16	25
A8	Fitting & Welding of Legs	12	8	80
A9	Hydrostatic Test	7	5	120
A10	Sand Blast & Primer Coating	12	8	90

Table 3 shows the probability of occurrence for each risk based on previously completed similar projects.

Since quality is expressed using linguistic and verbal variables, fuzzy numbers are used to deal with vagueness of variables. The method proposed by Abdullah and Khadiah (2011) for measuring the customer satisfaction levels based on linguistic variables is employed in this study. Five quality levels are considered, as shown in Table 4.

Table 3. Probabilities of occurrence of different risks

I_{rjt}	P_{jt}
0/05	0/19
0/1	0/21
0/2	0/18
0/4	0/22
0/8	0/2

Table 4. Weight of importance for each criterion (quality factor)

Linguistic Variable	**Weight, W_i**		
	l	*m*	*u*
Very Low	3	3	8
Low	3	8	13
Middle	8	13	18
High	13	18	23
Very High	18	23	23

These intervals are converted by using Eq. 23 into intervals corresponding to quality (Amirfakhrian, 2012).

$$0 \leq {}^{\alpha - 3}/_{20} \leq 1 \tag{23}$$

The final fuzzy intervals are shown in Table 5.

Table 5. Quality degrees in 5 levels after conversion into the interval between 0 and 1

	l	***m***	***u***
Very Low	0	0	1/4
Low	0	1/4	1/2
Middle	1/4	1/2	3/4
High	1/2	3/4	1
Very High	3/4	1	1

Next, the E_{φ} method is used for defuzzification and converting the fuzzy numbers into crisp values.

$$def = a + \varphi(h - g) \tag{24}$$

$$\mathrm{def}(VL) = \frac{1}{20}$$
$$\mathrm{def}(L) = \frac{1}{4}$$
$$\mathrm{def}(M) = \frac{1}{2}$$
$$\mathrm{def}(H) = \frac{3}{4}$$
$$\mathrm{def}(VH) = \frac{19}{20}$$

The results of implementing the proposed model in a construction project of oil storage tanks are presented in Table 6.

Table 6. Compressing time with the aim of optimizing cost, risk and quality

Code	**Activity Name**	**Optimal compression time corresponding with minimization of project cost**	**Optimal compression time corresponding with minimization of the impacts of negative risks on project goals**	**Impact rate and optimal weight corresponding with quality**
A1	Vendor Print Index & Schedule (VPIS)	5	3	0.12
A2	Process/Mechanical Data Sheet 1	5	4	0.13
A3	Process/Mechanical Data Sheet 2	4	5	0.2
A4	Deviation Confirmation	4	6	0.26
A5	General Arrangement and Detail Drawing	7	4	0.15
A6	General Arrangement and Detail Drawing	7	4	0.05
A7	Boot Attachments Fit-up & Welding	7	3	0.01
A8	Fitting & Welding of Legs	6	3	0.01
A9	Hydrostatic Test	3	2	0.03
A10	Sand Blast & Primer Coating	4	1	0.04

According to Table 6, the activities with negative floats can be compressed, so that the cost and risk of the project remain optimal. Crashing activity duration leads to quality reduction, which is shown in the last column of Table 6 for each activity. Figure 2 displays the optimal compression time to optimize cost and risk compared to the initial durations of activities.

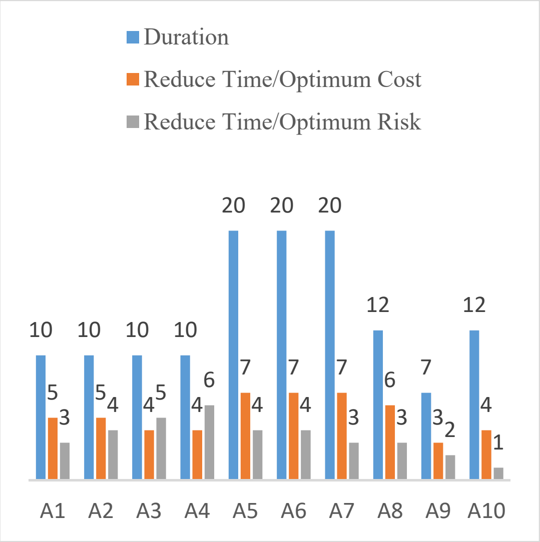

Figure (2): The initial activity durations *vs.* optimal compressed durations

The highest crashing cost per day is $ 120 for activity A9. The duration of this activity can be reduced by 3 and 2 days for optimizing cost and risk, respectively. The quality level of this activity has also been decreased by 3%.

Figure 3 shows the set of Pareto solutions and the algorithm convergence trend.

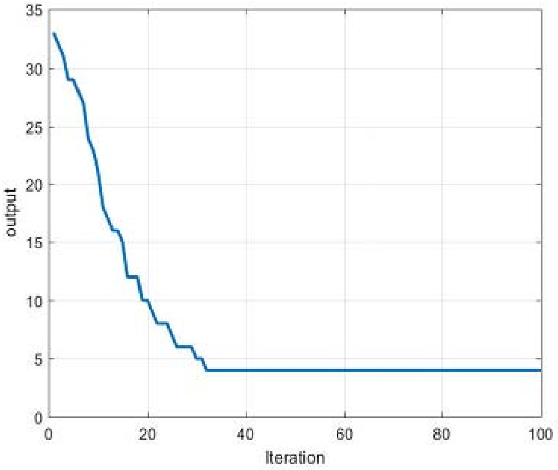

Figure (3): The output diagram of the MATLAB software and algorithm convergence trend

As can be seen, the values of all three objective functions are optimal.

DISCUSSION

Various project stakeholders demand for reducing the duration and total costs of the project, as well as increasing the project quality. Due to increasing competition between companies, the importance of quality, delivery time and costs of a project to succeed in tenders and earn profits and increase credit, has become higher. Therefore, companies are looking to consider these key factors in the best possible way in their decisions.

Project scheduling problem of time-cost-quality trade-off optimization seeks to help project practitioners and decision-makers by simultaneously finding the best possible combinations of time, cost and quality for project completion and delivery. The time-cost-quality trade-off optimization model presented in this research can be applied to all construction projects for timely delivery of projects considering cost and quality. Hence, the results of this study can assist project managers to make better decisions in order to complete the project with the least duration and cost along with the highest quality. These benefits will obviously increase the credibility of contractors and gain a competitive advantage for the organizations in the construction industry.

CONCLUSION

In this paper, a multi-objective optimization model was presented to solve the time-cost-risk-quality trade-off project scheduling problem. The proposed model was able to select the optimal compression time while maintaining the optimality of cost, quality and risk objective functions. Another contribution of this model is incorporating the penalty costs of delays into the cost objective function, which is the main concern of project managers. Entering the option of project due date in the PRIMAVERA P6 software provides the project manager with the amount of probable negative float at each stage of planning and implementation, which has not been used for the calculation of project delay so far. Also, each project activity is compressed to the extent that it has the least impact on diminishing the quality of the whole project. Also, a new defuzzification method was exploited to convert the fuzzy numbers into crisp values with the least deviations.

The model was also validated by solving small-size problems with the Goal Programming method and NSGA-II algorithm. In addition, the proposed model was implemented in a construction project of oil storage tanks. Due to the NP-Hard and large-sized problem, the model was solved by using the metaheuristic NSGA-II algorithm. The results showed that the NSGA-II algorithm achieved close to the optimal solution.

In fact, project managers can find the amount of compression time for timely project completion by calculating the negative floats in the project schedule using this algorithm. As it was seen, the solution obtained by the NSGA-II algorithm was approximately equal to the optimal compression time, which is a verification for the proposed algorithm. As some suggestions for future research, the model can be applied to any real-world project. Also, the uncertainty of other parameters can be taken into account using the fuzzy numbers, Moreover, other metaheuristic algorithms, such as MOPSO and MOGWO, should be employed and the findings be compared.

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