IJE TRANSACTIONS B: Applications Vol. 31, No. 5, (May 2018) 770-779

International Journal of Engineering

Journal Homepage: www.ije.ir

A New Multi-objective Model for Multi-mode Project Planning with Risk

H. R. Mollaei[a], R. Tavakkoli-Moghaddam*[b], A. Toloie-Eshlaghy[a]

[a] *Department of Industrial Management, Science and Research Branch, Islamic Azad University, Tehran, Iran*
[b] *School of Industrial Engineering, College of Engineering, University of Tehran, Tehran, Iran*

PAPER INFO

Paper history:
Received 24October2017
Received in revised form 02December2017
Accepted 04Januray2018

Keywords:
Project Scheduling
Risk based Project Planning
Discrete Time–Cost–Quality-risk Trade-off
Evolutionary Algorithm

ABSTRACT

The aim of this problem is to choose a set of project activities for crashing in such a way that the expected project time, cost and risk are minimized and the expected quality is maximized. In this problem, each project activity can be performed with a specific executive mode. Each executive mode is characterized with four measures, namely the expected time, cost, quality and risk. In this paper, linear relationships between time and cost, and between time and quality are omitted and the problem of the expected time-cost-quality trade-off is considered in a probabilistic and discrete state (DTCQRTP). Then, to make the problem more real, the combination of four measures are considered as uncertain for each executive mode. It means that the time, cost, quality or risk (or all of them) of each activity in each executive mode is considered as the expected numbers (probabilistic means). After modeling four-objective problems, a test problem with nine activities is presented and solved by the non-dominated sorting genetic algorithm (NSGA-II). In order to improve the results and speed of the proposed algorithm in accessing Pareto solutions, a new hybrid algorithm, called MEM-NSGA, is presented that gives better solutions than the original NSGA-II at the same conditions.

***doi**: 10.5829/ije.2018.31.05b.12*

1. INTRODUCTION

The main function of project management is to achieve the main goals of project implementation, including the earliest accomplishment date, the most acceptable quality and the least cost [1].

A time-cost trade-off problem has been focused on the reduction of project duration by crashing of the duration of each activity from the late of 1950s. The researcher of this field has used linear programming models [2, 3] and nonlinear programing models [4, 5] to solve time-cost trade-off problems. When the time-cost tradeoff is linear for each activity, this relationship can be demonstrated as a line on a graph that shows the relationship between time and cost of the activity [6]. The cost of the activity completion changes linearly between the normal and crashed time.

Crashing the time should be done cautiously if the quality of project completion is important, and sometimes it is necessary to improve the quality of the project by increasing the time [4]. In these cases, it is necessary to do preventive actions to avoid redundancy and corrections. The project will be successful if the project outcomes satisfy the expectations of the project owner. The durability of the project outcomes is important for the project owner and the results should be satisfying, so it is not enough to complete the project based on a deadline, a pre-determined budget, and the execution quality is very important.

Researchers believed that quality is an important factor in project planning, so they have developed linear programming models considered time, cost and quality simultaneously. Babo and Suresh [7] developed five limitations with a lower bound for quality in their studies. In two other studies, modeling and solving of the time-cost-quality trade-off problem was proposed [8, 9].

Table 1 provides a general overview of the time-cost- quality trade-off problem. In addition to time, cost and quality, another factor that affects on project performance and is important in project completion is

*Corresponding Author Email: *tavakoli@ut.ac.ir* (R. Tavakkoli-Moghaddam)

TABLE 1. A summary of the studies on the TCTP problem

Problem type	Meta heuristic/deterministic solution algorithm	References
TCTP	GA, MOGA	[10-15]
Non-nonlinear TCTP	Simulated annealing and MOGA	[16]
TCQTP	Pareto solution genetic algorithm ,GA	[17, 18]
DTCQTP	Particle swarm optimization algorithm	[19]
DTCTP	NSGA II, Ant colony optimization	[20, 21]
Quality loss cost in the time-cost trade-off problem	ε-constraint method and a dynamic self-adaptive multi-objective evolutionary algorithm	[22]
PERT environment	Hybrid scatter search	[23]
Renewable and nonrenewable resource	Ant colony optimization	[24]
Setup times after preemption	Genetic algorithm	[25]
Tardiness and earliness	Genetic algorithm	[26]
Time-cost-environment trade-off	Adaptive-hybrid genetic algorithm	[27]
Multi-mode resource constrained project scheduling problem (MM-RCPSP)	Branch-and-bound algorithm	[28]

an uncertainty condition, which is resulted from three factors of an external environment, changes in business objectives and unsuitable methods designed for execution.

Uncertainty is not just the result of insufficient knowledge and low experience of the project team, but can mostly be related to the complexity and newness of the project. An external environment includes factors, such as commercial and political forces, changes in values and norms, rules related to technical and financial goals of the project, and changes in stockholders requirements.

Changes in the basic information for decision making during the time will result in project uncertainties, which put the project at risk. One of the most important challenges in project control is management of project risks. Today, risk management is an important part of project management, which results in an efficient improvement, cost saving and profit increase [29]. Every business has some risks and most of the problems of the project management are the results of the risks [30]. Today, the number and severity of risks has increased and this has motivated the stockholders to control the risks in order to protect their projects against the negative financial and legal outcomes [31].

One of the methods to solve such problems is to use the probability theory. In order to act in conditions of uncertainty, this theory can provide mathematical formulation of concepts, variables and systems that are unclear and ambiguous. It provides grounds for reasoning, inferring, controlling, and decision making. Despite the important role of uncertainty and risk in the success of projects, a few studies have been carried out on mathematical modeling in project planning. In this study, another dimension is added to the cost-time-quality trade-off problem, which is called risk. On the other hand, this problem is an NP-hard one. It means that by increasing the problem size, the computational time will increase exponentially. Since this problem is a multi-objective optimization one, exact methods cannot be used to optimally solve large-sized problems. In most cases, meta-heuristic algorithms cannot be used alone. Thus, in this paper, the multi-objective model is solved by two different meta-heuristics as high-performance algorithms.

2. PROBLEM STATEMENT

Estimating the completion date of the project is based on the assumption that the project activities, especially critical path activities, are all practicable in a normal time. However, in most cases, it is necessary to accomplish the project on the net before the estimated date. In this condition, one of the possible solutions to shorten the project executive time is to accelerate the activities. In order to reduce the time of an activity, the level of the used resources should be increased or the technical methods of activity execution should be changed. In other words, to perform an activity in a shorter time than the normal time, it is necessary to increase the amount of resources (e.g., workforce, equipment and machinery) to use more advanced and expensive equipment, or to modify the technical methods. In this way, reducing the activity normal time to a shorter time is always costing. In contrast, reducing the completion time of a project has some revenues for stakeholders, including the flowing of involved capitals. Also, in new product development projects, especially in competition conditions between different producers, a faster presentation of a new product will possibly increase the market share of the company.

In most of time-cost trade-off models, the relationship between the reduction of the activity time and the growth of the activity cost is assumed as a linear function. In these models, the objective is to deliver the project product in the given due date with the minimum cost. There are so many alternative methods to solve these linear models [8, 32-34]. Although some other models are presented with convex and concave cost functions [35, 36], the discrete time-cost trade-off problem is more suitable for real applications. In contrast to the linear models, there is little research on a discrete time-cost trade-off problem (DTCTP). It may be because this model is very difficult to be solved [37]. There are at least two reasons for the problem discreteness. Firstly, resources and execution modes and the type of technology in real world projects are in form of discrete options, and secondly, it is easy to formulate every time-cost relationship in a discrete form in real projects.

In recent years, there have been requests from the project stakeholders for the cost and simultaneously time reduction and the increase of the project quality. This has led researchers to the development of models, which add the quality factor to the previous time-cost trade-off models. The quality of the whole project is influenced by the compression of the project net. So, the quality factor has added to the time-cost trade-off problem and has formed the discrete time-cost-quality trade-off problem (DTCQTP) [38, 39].

However, most of the today's projects are accomplish in a dynamic and complicated environment, in which uncertainty and risk are inherent feature of that environments. Most of the projects have not been successful in achieving the pre-determined goals because of the uncertainty and risk. These features have caused some problems, such as a lack of economic justification of the projects, reduction of the efficiency and dissatisfaction of key stockholders [40].

According to the PMBOK, risk is defined as an uncertain event, which will affect at least one of the project objectives if it is happened [1]. The goal of risk management is to increase the probability of the success of the project. It is achieved by systematic risk recognition and evaluation, presenting methods to avoid and reduce them using the opportunities [41]. According to the PMBOK, risk can decrease the quality and increase the time and cost of the project. Respect to the importance of the influence of the risk on the project performance, there is a serious need to develop methods for the project planning and evaluating; which are correspondent to the project risks. Despite the importance of the risk identification, qualitative and quantitative analysis of the risks, no comprehensive mathematic model has been represented for the intervention of risks in planning, evaluating and controlling the projects in multi-mode cases so far. In this study, it has been attempted to evaluate the risk impacts on project goals; simultaneously to present a method for calculating their effects on project objectives including the quality, time and cost. This study also attempts to formulate a four-objective model, including the expected cost, quality, time and overall risk.

3. PRESENTED MODEL

The goal of solving the risk and expected time, cost, and quality problem is to choose a set of project activities for time compression, as the overall risk and expected time and cost are minimized and the expected project quality is maximized. In this problem, each project activity can be executed with specific executive methods. Each executive method has three features of E(t), E(c), and E(q), which represent the expected time, cost and quality, respectively. So far, no research has been carried out on combinational optimization problems. To eliminate the linear relationship between cost and time, also between time and quality, this research investigates the risk-based time-cost-quality trade-off problem in a discrete state (RDTCQTP)[2]. To make the three-objective combinational optimization problem closer to the real situation, each executive method is assumed as uncertain. It means that in each executive method, the time, cost or quality (or all three factors) of each activity will be in the form of expected values (i.e., mean).

3. 1. Risk-based Project Performance Objectives

In this study, we examine time and cost overrun and quality reduction risks. The use of untrained human resources is a typical example of a case that ends up with more time, costs and less quality. Although these risks may not necessarily lead to project cancelation, they impair project's economic performances. They are called 'performance risks'[42].

Suppose that cost C is a stochastic value instead of a deterministic value, which depends on a probability density function $pc(C)$ and does not fall below a certain minimum cost C_{min}. We define metrics $r_{\propto}$ for the cost overrun risk of an activity with the expected value of cost $E\{C\}$.

$$E\{C\} = \frac{C_{min}}{1-r_{\propto}} \quad (1)$$

[2]- Risk-based Discrete Time-Cost-Quality Trade-off Problem

Additionally, suppose that time T is a stochastic value instead of a deterministic value. This time depends on a probability density function p (T) and does not fall below a certain minimum time T_{min}. We define metrics r_γ for the time overrun risk of an activity with the expected value of cost $E\{\mathrm{T}\}$.

$$E\{T\} = \frac{T_{min}}{1-r_\gamma} \tag{2}$$

Furthermore, suppose that quality Q is a stochastic value instead of a deterministic value, which depends on a probability density function $p_q(Q)$ and does not increase more than a certain maximum quality Q_{max}. We define metrics r_β for the quality reduction risk of an activity with the expected value of quality $E\{\mathrm{Q}\}$.

$$E\{Q\} = Q_{max} \times (1 - r_\beta) \tag{3}$$

3. 2. Quality Measurement of Project In this study, the method presented by Babu and Suresh [7] is used to evaluate the quality of the project. To evaluate the value of the quality of each activity in each qualitative feature (q_{ijl}), we can ask from technical experts by asking this question: "how much the technical feature l related to the activity (link between i and j) is considered if the activity is performed by k executive mode?" the experts' reply to this question will be q_{ijlk}. Obviously, the qualitative features of the activities are different. If $\acute{w}_{ijl}$ is the qualitative weight of each l feature in each activity, which is determined by experts, then the quality of each activity will be as follows:

$$q_{ijk} = \sum_{l=1}^{L} \acute{w}_{ijl} * q_{ijlk} \ , \ \sum_{l=1}^{L} \acute{w}_{ijl} = 1 \tag{4}$$

The value of the quality impact of each activity on the project quality can be calculated by the use of the technical experts' group decision-making. Then, the project quality can be calculated by:

$$Q = \sum_{ij \in E} \sum_{k \in M_{ij}} w_{ij} \times q_{ijk} \times y_{ijk} \tag{5}$$

3. 3. Problem Formulation A project is represented by a direct acyclic graph G=(V, E) consisting of m nodes and n arcs, in which V={1, 2, ..., m} is the set of nodes and E={(i, j), …, (l, m)} is the set of direct arcs. Arcs and nodes represent activities and events, respectively. Each project activity, called (i, j)∈E, can be executed by a set of modes, M_{ij}. Each $k \in M_{ij}$ needs an expected execution time of t_{ijk}, cost of c_{ijk} and quality of q_{ijk}. Let k and r be two modes for activity (i, j) and $k<r$; then, it is assumed that $t_{ijk}>t_{ijr}$, $c_{ijk}<c_{ijr}$ and $q_{ijk} \neq q_{ijr}$. Although in the literature, it is assumed that any activity time decreasing leads to activity quality decreasing. It is noteworthy that this is not always the case in real world projects. For instance, a new technology can be employed to reduce the required time, while this reduction can be accompanied by an increase in the cost and quality.

The aim of this paper is to obtain the optimal combination (t_{ijk}, $c_{ijk}$and q_{ijk}) of each activity for crashing the project network in the situation of existence of performance risk, including the risk of time and cost overrun and the risk of quality reduction, such that the risk-based cost and time of the project is minimized while the risk based project quality is maximized. Notations used for the problem formulation are as follows:

Parameters:

- M_{ij} Set of available execution modes for activities i and j, where (i, j)∈E
- C_{ijk} Direct cost of activities i and j performed by execution mode k
- t_{ijk} Duration of activities i and j performed by execution mode k
- q_{ijk} Quality of activities i and j performed by execution mode k
- ω_{ij} Quality weight of activities i and j in the project, $\sum_{ij \in E} \omega_{ij} = 1$
- $\acute{\omega}_{ijl}$ Weight of quality level L in activities i and j
- $r_{\propto ijk}$ Probability of the cost overrun risk of the project activity execution in execution mode k
- $r_{\beta ijk}$ Probability of the quality reduction risk of the project activity execution in execution mode k
- $r_{\gamma ijk}$ Probability of the time overruns risk of the project activity execution in execution mode k
- $r_{\theta ijk}$ Failure probability of the project through the implementation of the executive mode k of activities i and j.Consequently, re-execution of the activity.

Decision Variables:

$$y_{ijk} \begin{cases} 1 & \text{if mode } k \text{ is assigned to activities } i \text{ and } j \\ 0 & \text{otherwise} \end{cases}$$

- x_i Earliest time of event i (i={1, 2, ..., m})

Objective Functions:

- *E (C)* Total expected project cost
- *E (T)* Total expected project duration
- *E (Q)* Total expected project quality
- OR Overall project risk

The problem of the RDTCQTP is formulated by:

$$\text{Min } E(C) = \sum_{ij \in E} \sum_{k \in M_{ij}} \left(\frac{\min(c_{ijk})}{1 - r_{\propto ijk}} \right) \times y_{ijk} \tag{6}$$

$$\text{Min } E(T) = x_n - x_1 \tag{7}$$

$$\text{Max } E(Q) = \sum_{ij \in E} \sum_{l \in L} \sum_{k \in M_{ij}} \times w_{ij} \times (1 - r_{\beta ijk}) \times \text{Max}(q_{ijk}) \times y_{ijk} \tag{8}$$

$$Min\ (OR) = \prod_{ij\in E}[1 - \sum_{k\in M_{ij}}(1 - r_{\propto ijk}) * (1 - r_{\beta ijk}) * (1 - r_{\gamma ijk}) * (1 - r_{\theta ijk}) * y_{ijk}] \quad (9)$$

s.t.

$$x_j - x_i \geq \sum_{k\in M_{ij}} \left(\frac{min(t_{ijk})}{1 - r_{\gamma ijk}}\right) \times y_{ijk}\ ; ij \in E;\ i,j \in V \quad (10)$$

$$\sum_{k\in M_{ij}} y_{ijk} = 1\ ;\ ij \in E \quad (11)$$

$$x_i \geq 0\ ; i \in V \quad (12)$$

$$y_{ijk} \in \{0,1\}\ ;\ i,j \in E\ ;\ k\ \in M_{ij} \quad (13)$$

Equations (6) and (7) minimize the total project cost and duration. Equation (8) maximizes the total project quality. Equation (9) minimizes the overall project risk. Equation (10) preserves the precedence relations between project activities. In Equation (11), one and only one execution mode is assigned to each activity.

4. SOLUTION PROCEDURE

In the RDTCQTP, there are a number of execution modes to select for each activity. If the number of project activities is *n* and there are *k* execution modes for each activity to choose from, then there are k^n solutions, which results in a very large search space.Therefore, it is necessary to develop an efficient evolutionary algorithm.

4. 1. Non-dominated Sorting Genetic Algorithm (NSGA-II) Initialization of a random parent population P_O sorted based on non-domination. First, the offspring Q_0 of size *N* will be created using the usual binary tournament selection, recombination and mutation operators. Algorithm 1 describes the procedure for the *t*-th generation. First, we combine the parents and the offspring ($R_t = P_t \cup Q_t$), which has the size 2*N*. Then, we sort the population R_t according to their non-domination.

Elitism is ensured that the current and previous members are included in R_t. The new population (P_{t+1}) will be filled with the best fronts (first F_1, then F_2, etc.), until the size of the next front (F_l) is bigger than the number of open spots in P_{t+1}. To have exactly *N* members in the new population and the diversity preservation (i.e., that a good spread of solutions is maintained in the obtained solution set), the front F_l will be ordered based on the crowding-distance and the first $N - \mid P_{t+1}\mid$ (i.e., the number of open spots) solutions will be added to end up with exactly *N* solutions in P_{t+1}. Then, we start again to make an offspring (Q_{t+1}) of P_{t+1} and we repeat this algorithm until the stopping criterion is met [43].

Algorithm 1: NSGA-II (main-loop for the *t*-th generation).
$R_t = P_t \cup Q_t$
F = fast- non-dominated-sort (R_t)
$Pt+1 = \emptyset$ and $i = 1$
while $\mid P_{t+1}\mid + \mid F_i\mid \leq N$ **do**
crowding-distance-assignment (F_i)
$P_{t+1} = P_{t+1} \cup F_i$
$i = i + 1$
end while
Sort ($F_i \gg n$)
$P_{t+1} = P_{t+1} \cup F_i[1 : (N - 1 \mid P_{t+1}\mid)]$
Q_{t+1} = make-new-pop (P_{t+1})
$t = t + 1$

4. 2. Memetic Algorithms (MA) A classical genetic algorithm acts well in finding the response regions, but spend a lot of time in obtaining the answer with the desired accuracy. This defect can be partially improved by utilizing existing knowledge of the problem or adding a local search phase to the evolutionary cycle [44].

Memetic algorithms during the implementation, due to the effective local improvement and correction made on the genes, provide a small step-by-step search capability, but they may miss the great search capacity, such as the convergence of the population to an optimal it should be avoided in dynamic environments. Therefore, this can be an interesting research idea in an efficient environment for examining the effectiveness of the algorithms that have been improved with a variety of appropriate methods. Therefore, local search (MEM) is related to the problem. So, how to find optimal operators and prevent us from using inappropriate local search methods is one of the most important issues. A consistent algorithm combines local initiative search with genetic algorithm to achieve better results in less time. In the following, we discuss the concepts and their differences with other algorithms and their application in dynamic environments.

Therefore, due to the structure of the memetic algorithm concept used in this paper, a structural change occurs, so that after the mutation in the NSGA-II algorithm, all mutant chromosomes are mutually mutated. In this case, a two-point mutation is used. Then, the mutant chromosome and the mutated chromosome from this pairwise chromosome are compared, while each of these chromosomes in the better position is selected as the mutated chromosome Otherwise, the distance between the chromosomes is calculated and the superior chromosome is selected and transferred to the population. The structure of this structure is depicted in Figures 1 and 2. The formulated model has more than 32 binary variables, which includes only 2^{32} modes for selection.

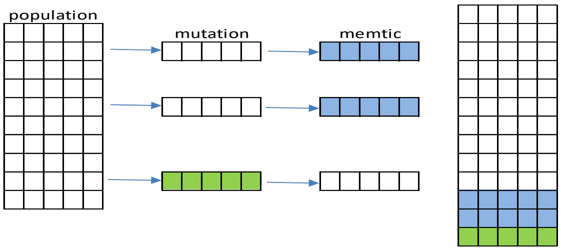

Figure 1. New memetic mutations

TABLE 2. Network matrix

	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9
1	1	1	0	0	0	0	0	0	0
2	-1	0	0	1	1	0	0	0	0
3	0	-1	1	0	0	0	0	0	0
4	0	0	-1	-1	0	1	1	0	0
5	0	0	0	0	-1	-1	0	1	0
6	0	0	0	0	0	0	-1	-1	1
7	0	0	0	0	0	0	0	0	-1

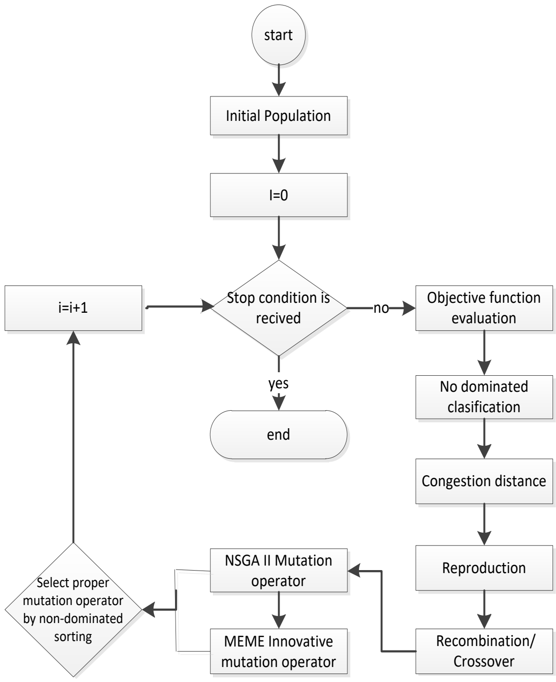

Figure 2. MEM-NSGAII algorithm [10]

5. ILLUSTRATIVE EXAMPLE

As an example, a project consisting of nine activities is presented in this section as depicted in Table 2. Different execution modes of each activity associated with its time, cost, quality and risk are presented in Table 5.

On the other hand, due to the nonlinearity of the objective function of the overall risk, it is possible to solve this nonlinear model with standard methods and available software that is impossible to achieve Pareto's solutions.

First, the NSGA-II is coded in MATLAB software, and then improvements are made by improving the algorithm using the MEMTIC algorithm. In this section, the results of solving the designed model with the above-mentioned algorithms are discussed. Solving the formulated problem, a set of chromosomes that shows the combinational activities execution modes and its corresponding time, cost and quality are obtained as the output. Some parts of the results are shown in Tables 6 and 7. The project manager may then obtain executive solutions that best fit with project conditions. The values of Pareto solutions presented in these tables are obtained based on different execution modes with two meta-heuristic algorithms. For example, in Table 6 first row solution, execution modes of 5, 5, 5, 5, 6, 5, 2, 5 and 4 are respectively selected for the first to the ninth project activities. Based on this solution, the values of the expected time cost and quality and overall risk objective functions are respectively obtained as 28, 2032.579, 822.3523 and 0.000226.

6. EXPERIMENTAL EVALUATION

To validate the algorithm and the formulated model, the results of the MEM-NSGAII and NHGA [41] algorithms are compared under equal conditions. The results of this statistical comparison are presented in Tables 3 and 4.

The results of solving the three-objective model by using NHGA and MEM-NSGAII are compared. Description of the presented model results based on the central statistic features and dispersion is presented in Tables 3 and 4. The results of the ANOVA test show that the time and cost of the project plan in the NHGA is more than the MEM-NSGAII and its quality is less.

TABLE 3. NHGA and MEM-NSGAII description

	method	N	Mean	Std. Deviation
Time	MEM-NSGAII	499	35.00	1.73
	NHGA	499	37.4444	2.404
Cost	MEM-NSGAII	499	1536.66	35
	NHGA	499	2143.33	32.016
Quality	MEM-NSGAII	499	815.860	.423
	NHGA	499	812.176	1.876

TABLE 4. Results of the analysis of variance (ANOVA) test

		F	Sig.	t	Sig. (2-tailed)	Mean Difference
Time	Equal variances	2.248	0.153	-2.47	0.025	-2.44
	Unequal variance			-2.47	0.026	-2.44
Cost	Equal variances	.278	0.605	-38.4	0.000	-606.67
	Unequal variances			-38.4	0.000	-606.67
Quality	Equal variances	0.883	.061	-.492	.0429	-.315
	Unequal variances			-.492	0.0435	-.3155

TABLE 5. Activities executions modes

mode	*measure*	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	mode	*measure*	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9
	T	7	8	8	10	14	8	11	11	11		*T*	4	5	5	7	11	5	8	8	8
	C	160	140	110	100	160	130	150	140	150		*C*	200	180	150	150	200	170	200	170	200
	Q	90	85	90	88	92	85	87	91	90		*Q*	70	75	80	75	70	85	90	75	90
1	R_1	600	550	500	350	450	300	250	200	600	4	R_1	98	70	65	57	40	86	38	46	54
	$r_{\propto ijk}$	0.12	0.137	0.137	0.171	0.240	0.137	0.189	0.189	0.189		$r_{\propto ijk}$	0.08	0.100	0.100	0.140	0.220	0.100	0.160	0.160	0.160
	$r_{\beta ijk}$	0.1	0.088	0.069	0.063	0.100	0.081	0.094	0.088	0.094		$r_{\beta ijk}$	0.15	0.135	0.113	0.113	0.150	0.128	0.150	0.128	0.150
	$r_{\gamma ijk}$	0.1	0.094	0.100	0.098	0.102	0.094	0.097	0.101	0.100		$r_{\gamma ijk}$	0.175	0.188	0.200	0.188	0.175	0.213	0.225	0.188	0.225
	$r_{\theta ijk}$	0.02	0.023	0.023	0.029	0.040	0.023	0.031	0.031	0.031		$r_{\theta ijk}$	0.04	0.050	0.050	0.070	0.110	0.050	0.080	0.080	0.080
	T	6	7	7	9	13	7	10	10	10		*T*	3	4	4	6	10	4		7	
	C	180	150	120	130	170	140	180	150	170		*C*	230	200	170	165	220	190		265	
	Q	85	82	85	90	90	82	90	88	88		*Q*	85	80	90	80	80	90		85	
2	R_1	300	250	250	450	450	250	400	350	350	5	R_1	520	490	470	240	160	350		236	
	$r_{\propto ijk}$	0.1	0.117	0.117	0.150	0.217	0.117	0.167	0.167	0.167		$r_{\propto ijk}$	0.05	0.067	0.067	0.100	0.167	0.067		0.117	
	$r_{\beta ijk}$	0.1125	0.094	0.075	0.081	0.106	0.088	0.113	0.094	0.106		$r_{\beta ijk}$	0.112	0.097	0.083	0.080	0.107	0.093		0.129	
	$r_{\gamma ijk}$	0.125	0.121	0.125	0.132	0.132	0.121	0.132	0.129	0.129		$r_{\gamma ijk}$	0.2	0.188	0.212	0.188	0.188	0.212		0.200	
	$r_{\theta ijk}$	0.03	0.035	0.035	0.045	0.065	0.035	0.050	0.050	0.050		$r_{\theta ijk}$	0.05	0.067	0.067	0.100	0.167	0.067		0.117	
	T	5	6	6	8	12	6	9	9	9		*T*					9				
	C	190	170	140	140	180	150	190	160	180		*C*					240				
	Q	80	80	84	85	86	80	85	85	85		*Q*					90				
3	R_1	720	700	610	550	420	650	510	505	510	6	R_1					300				
	$r_{\propto ijk}$	0.09	0.108	0.108	0.144	0.216	0.108	0.162	0.162	0.162		$r_{\propto ijk}$					0.05				
	$r_{\beta ijk}$	0.125	0.112	0.092	0.092	0.118	0.099	0.125	0.105	0.118		$r_{\beta ijk}$					0.112				
	$r_{\gamma ijk}$	0.15	0.150	0.158	0.159	0.161	0.150	0.159	0.159	0.159		$r_{\gamma ijk}$					0.2				
	$r_{\theta ijk}$	0.025	0.030	0.030	0.040	0.060	0.030	0.045	0.045	0.045		$r_{\theta ijk}$					0.05				

TABLE 6. Part of the Pareto solution setof the given problem with the NSGA-II

Pareto solution	Activities execution mode									Objective			
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Expected time**	**Expected cost**	**Expected quality**	**Overall risk**
1	5	5	5	5	6	5	2	5	4	28	2032.579	822.3523	0.000226
2	1	1	1	1	1	2	1	1	2	45	1522.874	819.6351	5.44E-05

TABLE 7. Part of the Pareto solution setof the given problem with the MEM- NSGAII

Pareto solution	Activities execution mode									Objective			
	1	2	3	4	5	6	7	8	9	**Expected time**	**Expected cost**	**Expected quality**	**Overall risk**
1	1	1	1	2	6	2	1	2	1	44	1585.614	820.115	5.18E-05
2	1	1	1	2	1	2	1	2	2	43	1562.634	819.9988	6.33E-05

In this paper, the NSGAII and MEM-NSGAII are coded and run in order to solve the four-objective time-cost-quality-risk trade-of problem and some of the results are presented in Tables 4 and 5.

In this section, the mean ideal distance (MID) measure is used to compare the results of the NSGA-II and MEM-NSGA. It is used for measuring the closeness between Pareto solution and an ideal point.

According to the objective functions, we consider (0, 0) as an ideal point. This metric is formulated as it is clear that a less value of the MID is of interest. In this equation, *n* denotes the number of non-dominated set and f1i and f2i denote the first and second objective value of the *i*-th non-dominated solution, respectively.

$$MID = \frac{\sum_{i=1}^{n}\sqrt{f_{1i}+f_{2i}}}{n} \quad (14)$$

The ideal point for the model solution results using the NSGA-II and MEM-NSGA-II is shown in Tables 8 and 9, which is based on the answers of the first front (a set of 100 of Pareto solutions). It means that the minimum value is used for the objectives of time, cost, and risk and the maximum value is in the quality objective.

To calculate the MID index, the answer matrix is normalized with the Euclidean method, and then the closeness index to the ideal normalized answer for the NSGA-II is 0.007226.

The closeness index to the ideal normalized answer for the MEM-NSGAII is 0.006526703. Based on the average distance to the ideal solution considered as the accepted criterion for scholars in this field, the new improved MEM-NSGA-II algorithm has better results than the NSGA-II algorithm in the analyzed solutions.

TABLE 8. Ideal solution for the final model solving by the NSGA-II

Minimum time	Minimum cost	Maximum quality	Minimum overall risk
28	1513.360	825.350	0.0000531

TABLE 9. Ideal solution for the final model solving by the MEM-NSGAII

Minimum time	Minimum cost	Maximum quality	Minimum overall risk
28	1547.176	826.5145	0.0000552

7. CONCLUSION

Over the past three decades, scheduling issues have been one of the most important issues for project managers. The literature review has shown that there is a deep gap in the discussion of risk issues in project control issues. In this regard, in order to better match this issue with real world applications and fill the gap, this paper has addressed the issue of the risk, project costs, project execution time and quality improvement. The model presented in this paper has addressed real world projects. To be as realistic as possible, the problem was considered in an uncertain condition. In this condition, a risk-based discrete time-cost-quality trade-off problem (RDTCQTP) was also considered, in which each project activity could be executed by one of several modes. Associated with each execution mode of any activity, there are specific resources, execution methods, technology and risk. For each mode of an activity, there is a triple combination of the expected risk-based time, cost and quality (*t*, *c*, *q*). These risk probability numbers have represented the effect of performance risk on project objectives in such a way that the time and cost has increased and the quality has decreased.

To solve the given problem, a multi-objective evolutionary algorithm, called non-dominated sorting genetic algorithm (NSGA-II) was also used and developed. The high speed of the proposed algorithm and its quick convergence have made it desirable for large projects with a large number of activities. Furthermore, we have used the ANOVA test to compare the performance of the NSGA-II in the conditions of the lack and existence of project performance risks. The results have shown that in the condition of existence of the performance risks, project objectives including time and cost minimizing and quality maximizing have affected by uncertainties such that the time and cost of a project have increased and the quality has decreased. Considering critical risk factors, this model can be extended to more realistic cases. Also, after modeling the problem with four objectives, an applied scheduling problem with nine activities presented, solved and coded with the NSGA-II. In order to improve the results and the speed of the proposed algorithm in accessing the Pareto solutions, a new hybrid algorithm, called MEM-NSGA-II, is presented that gives better solutions than the NSGA-II at the same conditions.

8. REFERENCES

1. Guide, P., "A guide to the project management body of knowledge", in Project Management Institute. Vol. 3, (2004).
2. Perera, S., "Linear programming solution to network compression", ***Journal of the Construction Division***, Vol. 106, No. 3, (1980), 315-326.
3. Phillips Jr, S. and Dessouky, M.I., "Solving the project time/cost tradeoff problem using the minimal cut concept", ***Management Science***, Vol. 24, No. 4, (1977), 393-400.
4. Deckro, R., Hebert, J. and Verdini, W., "Non-linear multiple criteria time/cost tradeoff", ***Proceedings of the 1987 Annual Western DSI, Palm Springs, CA***, (1987), 134-137.

5. Patterson, J.H. and Huber, W.D., "A horizon-varying, zero-one approach to project scheduling", ***Management Science***, Vol. 20, No. 6, (1974), 990-998.
6. Wiest, J.D. and Levy, F.K., "Management guide to pert/cpm", Englewood Cliffs. Prentice-Hall, Inc, New Jersey, (1997).
7. Babu, A. and Suresh, N., "Project management with time, cost, and quality considerations", ***European Journal of Operational Research***, Vol. 88, No. 2, (1996), 320-327.
8. Tareghian, H.R. and Taheri, S.H., "On the discrete time, cost and quality trade-off problem", ***Applied Mathematics and Computation***, Vol. 181, No. 2, (2006), 1305-1312.
9. Tareghian, H.R. and Taheri, S.H., "A solution procedure for the discrete time, cost and quality tradeoff problem using electromagnetic scatter search", ***Applied Mathematics and Computation***, Vol. 190, No. 2, (2007), 1136-1145.
10. Li, H. and Love, P., "Using improved genetic algorithms to facilitate time-cost optimization", ***Journal of Construction Engineering and Management***, Vol. 123, No. 3, (1997), 233-237.
11. Azaron, A. and Tavakkoli-Moghaddam, R., "Multi-objective time–cost trade-off in dynamic pert networks using an interactive approach", ***European Journal of Operational Research***, Vol. 180, No. 3, (2007), 1186-1200.
12. Elazouni, A.M. and Metwally, F.G., "Expanding finance-based scheduling to devise overall-optimized project schedules", ***Journal of Construction Engineering and Management***, Vol. 133, No. 1, (2007), 86-90.
13. Pathak, B.K. and Srivastava, S., "Moga-based time-cost tradeoffs: Responsiveness for project uncertainties", in Evolutionary Computation, 2007. CEC 2007. IEEE Congress on, IEEE., (2007), 3085-3092.
14. Hooshyar, B., Tahmani, A. and Shenasa, M., "A genetic algorithm to time-cost trade off in project scheduling", in Evolutionary Computation, 2008. CEC 2008.(IEEE World Congress on Computational Intelligence). IEEE Congress on, IEEE., (2008), 3081-3086.
15. Mohammadi, G., "Using genetic algorithms to solve industrial time-cost trade-off problems", ***Indian Journal of Science and Technology***, Vol. 4, No. 10, (2011), 1273-1278.
16. B.K., P., Srivastava, S. and Srivastava, K., "Neural network embedded with multi-objective genetic algorithm to solve nonlinear time cost trade-off problem of project scheduling", ***Journal of Scientific and Industrial Research***, Vol. 67, (2008), 124-131.
17. Iranmanesh, H., Skandari, M. and Allahverdiloo, M., "Finding pareto optimal front for the multi-mode time, cost quality trade-off in project scheduling", ***World Academy of Science, Engineering and Technology***, Vol. 40, (2008), 346-350.
18. El Razek, R.H.A., Diab, A.M., Hafez, S.M. and Aziz, R.F., "Time-cost-quality trade-off software by using simplified genetic algorithm for typical-repetitive construction projects", ***World Academy of Science, Engineering and Technology***, Vol. 37, (2010), 312-320.
19. Rahimi, M. and Iranmanesh, H., "Multi objective particle swarm optimization for a discrete time, cost and quality trade-off problem", ***World Applied Sciences Journal***, Vol. 4, No. 2, (2008), 270-276.
20. Shahsavari-Pour, N., Modarres, M., Tavakoli-Moghadam, R. and Najafi, E., "Optimizing a multi-objectives time-cost-quality trade-off problem by a new hybrid genetic algorithm", ***World Applied Science Journal***, Vol. 10, No. 3, (2010), 355-363.
21. Mokhtari, H., Kazemzadeh, R.B. and Salmasnia, A., "Time-cost tradeoff analysis in project management: An ant system approach", ***IEEE Transactions on engineering management***, Vol. 58, No. 1, (2011), 36-43.
22. Kim, J., Kang, C. and Hwang, I., "A practical approach to project scheduling: Considering the potential quality loss cost in the time–cost tradeoff problem", ***International Journal of Project Management***, Vol. 30, No. 2, (2012), 264-272.
23. Baradaran, S., Ghomi, S.F., Ranjbar, M. and Hashemin, S., "Multi-mode renewable resource-constrained allocation in pert networks", ***Applied Soft Computing***, Vol. 12, No. 1, (2012), 82-90.
24. Li, H. and Zhang, H., "Ant colony optimization-based multi-mode scheduling under renewable and nonrenewable resource constraints", ***Automation in Construction***, Vol. 35, (2013), 431-438.
25. Afshar-Nadjafi, B. and Majlesi, M., "Resource constrained project scheduling problem with setup times after preemptive processes", ***Computers & Chemical Engineering***, Vol. 69, (2014), 16-25.
26. Bagherinejad, J. and Majd, Z.R., "Solving the mrcpsp/max with the objective of minimizing tardiness/earliness cost of activities with double genetic algorithms", ***The International Journal of Advanced Manufacturing Technology***, Vol. 70, No. 1-4, (2014), 573-582.
27. Zheng, H., "Multi-mode discrete time-cost-environment trade-off problem of construction systems for large-scale hydroelectric projects", in Proceedings of the ninth international conference on management science and engineering management, Springer., (2015), 337-346.
28. Chakrabortty, R.K., Sarker, R.A. and Essam, D.L., "Multi-mode resource constrained project scheduling under resource disruptions", ***Computers & Chemical Engineering***, Vol. 88, (2016), 13-29.
29. Zou, P.X., Zhang, G. and Wang, J., "Understanding the key risks in construction projects in china", ***International Journal of Project Management***, Vol. 25, No. 6, (2007), 601-614.
30. Subramanyan, H., Sawant, P.H. and Bhatt, V., "Construction project risk assessment: Development of model based on investigation of opinion of construction project experts from india", ***Journal of Construction Engineering and Management***, Vol. 138, No. 3, (2012), 409-421.
31. Fang, C. and Marle, F., "A simulation-based risk network model for decision support in project risk management", ***Decision Support Systems***, Vol. 52, No. 3, (2012), 635-644.
32. Fulkerson, D.R., "A network flow computation for project cost curves", ***Management Science***, Vol. 7, No. 2, (1961), 167-178.
33. Siemens, N., "A simple cpm time-cost tradeoff algorithm", ***Management Science***, Vol. 17, No. 6, (1971), B-354-B-363.
34. Adel, S.M. and Elmaghraby, S.E., "Optimal linear approximation in project compression", ***IIE Transactions***, Vol. 16, No. 4, (1984), 339-347.
35. Falk, J.E. and Horowitz, J.L., "Critical path problems with concave cost-time curves", ***Management Science***, Vol. 19, No. 4-part-1, (1972), 446-455.
36. Kapur, K.C., "An algorithm for project cost-duration analysis problem with quadratic and convex cost functions", ***AIIE Transactions***, Vol. 5, No. 4, (1973), 314-322.
37. De, P., Dunne, E.J., Ghosh, J.B. and Wells, C.E., "The discrete time-cost tradeoff problem revisited", ***European Journal of Operational Research***, Vol. 81, No. 2, (1995), 225-238.
38. Pour, N.S., Modarres, M., Aryanejad, M.B. and Moghadam, R.T., "Calculating the project network critical path in uncertainty conditions", ***International Journal of Engineering and Technology***, Vol. 2, No. 2, (2010), 136-140.
39. Tavana, M., Abtahi, A.-R. and Khalili-Damghani, K., "A new multi-objective multi-mode model for solving preemptive time–cost–quality trade-off project scheduling problems", ***Expert Systems with Applications***, Vol. 41, No. 4, (2014), 1830-1846.

40. S.H., Z., E., R., Nazari, A. and Honarichbar, F., "Evaluating and selecting risk response strategies using multiple objective optimization model and fuzzy prioritizing approach in abadan power plant", ***Technology Research and Development Journal***, Vol. 5, No. 4, (2012), 393-400.
41. Chapman, C. and Ward, S., "Project risk management: Processes, techniques, and insights", 2nd Ed., Chichester, John Wiley & Sons (2003).
42. Sato, T. and Hirao, M., "Optimum budget allocation method for projects with critical risks", ***International Journal of Project Management***, Vol. 31, No. 1, (2013), 126-135.
43. van der Plas, C., Tervonen, T. and Dekker, I.R., "Evolutionary multi-objective optimization and preference modeling in green logistics", Economie & Informatica, Retrieved from http://hdl.handle.net/2105/11492, (2012).
44. Neri, F., Cotta, C. and Moscato, P., "Handbook of memetic algorithms, Springer, Vol. 379, (2012).

A New Multi-objective Model for Multi-mode Project Planning with Risk

H. R. Mollaei[a], R. Tavakkoli-Moghaddam[b], A. Toloie-Eshlaghy[a]

[a]*Department of Industrial Management, Science and Research Branch, Islamic Azad University, Tehran, Iran*
[b]*School of Industrial Engineering, College of Engineering, University of Tehran, Tehran, Iran*

PAPER INFO

Paper history:
Received 24October 2017
Received in revised form 02December 2017
Accepted 04Januray 2018

Keywords:
Project Scheduling
Risk based Project Planning
Discrete Time–Cost–Quality-risk Trade-off
Evolutionary Algorithm

چکیده

هدف از این مسئله، انتخاب مجموعه‌ای از فعالیت‌های پروژه برای فشرده‌سازی است، بطوریکه هزینه مورد انتظار، مدت‌زمان اتمام مورد انتظار، ریسک پروژه کمینه و کیفیت کل مورد انتظار پروژه بیشینه شود. در این مسئله هر فعالیت پروژه می‌تواند با روشهای اجرایی مشخص اجرا شود. هر روش اجرا با چهار مشخصه $E(t)$، $E(c)$، $E(q)$ و R بیان می‌شود، که به ترتیب بیانگر زمان، هزینه، کیفیت مورد انتظار و ریسک کلی مربوط به هر مد اجرائی آن فعالیت است. در این مقاله، با حذف رابطه خطی بین زمان–هزینه و زمان–کیفیت و مسئله موازنه هزینه–زمان–کیفیت–ریسک را در حالت گسسته (DTCQRTP) و احتمالی بررسی می‌کندو سپس برای واقعی‌تر کردن مسئله، ترکیب چهارتاییمشخصه های (t, c, q, r) را برای هر روش اجرایی به صورت غیرقطعی مطرح می‌کند. یعنی اینکه زمان یا هزینه یا کیفیت یا ریسک (یا هر چهار معیار) هر فعالیت در هر روش اجرایی، به صورت اعداد انتظاری (میانگین احتمالی) خواهد بود. پس از مدل‌سازی مسئله چهار هدفه، یک مسئله کاربردی با نه فعالیت، ارائه شده و با الگوریتم NSGA-II کد نویسی و حل شده است. برای افزایش سرعت دسترسی به جوابهای پارتو و بهبود جوابها، الگوریتم تلفیقی MEM-NSGA بصورت ابتکاری ارائه شده است که در شرایط یکسان جواب‌های بهتری را نسبت به الگوریتم NSGA-II ارائه نموده است.

doi*: 10.5829/ije.2018.31.05b.12*