Vol. 11, 2022, 41-48

DOI: 10.17512/bozpe.2022.11.05

Construction of optimized energy potential

Budownictwo o zoptymalizowanym potencjale energetycznym

ISSN 2299-8535 e-ISSN 2544-963X

Solving a stochastic time-cost-quality trade-off problem by meta-heuristic optimization algorithms

Mohammad Owais Mohammadi[1] (*orcid id: 0000-0003-4147-4147*)
Tayfun Dede[1] (*orcid id: 0000-0001-9672-2232*)
Maksym Grzywiński[2*] (*orcid id: 0000-0003-4345-3897*)
[1] Karadeniz Technical University, Turkey
[2] Czestochowa University of Technology, Poland

Abstract: Actual time, cost, and quality of execution options for various activities within a considered project cannot be certainly determined prior to construction, there could be three different values of time and cost for each execution option, namely, optimistic value, most likely or normal value, and pessimistic value; and the quality could be described in linguistic terms. The objective of this research is to optimize time, cost, and quality of construction projects under uncertainty utilizing the program evaluation and review technique. In this study, multi-objective functions are used to decrease total project time and total project cost while maximizing overall project quality. For satisfying time-cost-quality trade-off optimization, a multi-objective optimization strategy is required. The non-dominating sorting-II concept and the crowding distance computation mechanism are combined with the teaching learning-based optimization algorithm to optimize time-cost-quality optimization problems. Non-dominating sorting-II teaching learning-based optimization algorithm is coded in MATLAB to optimize the trade-off between time, cost, and quality optimization problems. In the proposed model, the non-dominating sorting-II approach and crowding distance computation mechanism are responsible for handling objectives effectively and efficiently. Teaching learning-based optimization algorithm's teacher and learner phases ensure that the searched solution space is explored and exploited. The proposed algorithm is applied to a 13-activity example problem, and the results show that it provides satisfactory results.

Keywords: stochastic time-cost-quality trade-off (TCQT), non-dominating sorting-II (NDS-II), teaching learning-based optimization (TLBO)

Please, quote this article as follows:

Mohammadi M.O., Dede T., Grzywiński M., Solving a stochastic time-cost-quality trade-off problem by meta-heuristic optimization algorithm, Construction of Optimized Energy Potential (CoOEP), Vol. 11, 2022, 41-48, DOI: 10.17512/bozpe.2022.11.05

* Corresponding author: maksym.grzywinski@pcz.pl

Introduction

The construction labor, materials, equipment, and construction method used in each resource allocation decision affect the time, cost, and quality of an activity, resulting in a variety of options for carrying out an activity. Low-quality execution of an activity and disregard for quality control procedures can save time and money, but rework, repairs, extra materials, and penalty costs will take more time and cost due to poor quality management. Quality control procedures, such as tests and inspections, may lengthen an activity's operational time, but ignoring quality control does not equal time saving because more time is required to address defects.

Multi-objective optimization in construction projects has gotten a lot of attention. Initially, studies focused on time-cost trade-offs, but more recent efforts include more objectives in traditional time-cost trade-offs, such as safety, quality, resource, environment, and sustainability, among others (Vishnu et al., 2018).

The trade-off between the three most important parameters of a project, completion time, available budget, and required level of quality, is the focus of this paper.

Construction cost could be estimated during the initial phase of the project, but only once the project is completed is the actual cost of construction known (Patre & Ugale, 2020). The objective of this model is to optimize time, cost, and quality of construction projects under uncertainty utilizing the program evaluation and review technique (PERT) approach. PERT is utilized for planning and scheduling complex, uncertain, or innovative projects, when details and durations of all activities are not defined precisely. It is commonly used in conjunction with CPM by assigning three time estimates for each activity within a project: the optimistic time estimate (To); the most likely or normal time estimate (Tm); and the pessimistic time estimate (Tp).

According to Hinze (2004) and Hegazy (2002) for each activity, the expected value or weighted mean of its duration, cost, and quality are computed using the following equations:

$$\mathrm{Te} = (\mathrm{To} + 4^*\mathrm{Tm} + \mathrm{Tp}) / 6 \tag{1}$$

$$\mathrm{Ce} = (\mathrm{Cop} + 4^*\mathrm{Cml} + \mathrm{Cpe}) / 6 \tag{2}$$

$$\mathrm{Qe} = (\mathrm{Qop} + 4^*\mathrm{Qml} + \mathrm{Qpe}) / 6 \tag{3}$$

where: Cop is the optimistic value of activity cost, Cml is its most likely cost value, Cpe is the pessimistic cost value, Qop is the optimistic quality value, Qml is its most likely quality value, and Qpe is the pessimistic quality value.

PERT techniques are now widely used in large projects such as software development, building construction and maintenance work (Chinneck, 2009).

The MATLAB program is used to combine the non-dominating sorting-II (NDS-II) concept and the teaching-learning-based optimization (TLBO) algorithm in this study. A stochastic time-cost-quality trade-off optimization problem is solved using the developed decision-making algorithm. The proposed algorithm was used to solve the 13-activity project.

1. General terms

1.1. Total project cost

Construction costs should be estimated during the initial phase of the project, but only once the project is completed can actual costs be known. Contractors bidding at the outset should have a thorough understanding of the direct, indirect, and penalty/incentive costs (Patre & Ugale, 2020).

The total project cost, including the project direct cost, the project indirect cost, and tardiness penalty/incentive cost can be calculated as shown in equation (4)

$$\begin{aligned} C = \sum_{i=1}^{N} dc_i^{(k)} + D \cdot ICR + \\ + \bar{u}(D - D_{deadline}) \cdot (D - D_{deadline}) \cdot C_{pen} - \bar{u}(D_{deadline} - D) \cdot (D_{deadline} - D) \cdot C_{in} \end{aligned} \tag{4}$$

where:

C – the total project cost,
$dc_i^{(k)}$ – the direct cost of the activity (i),
N – the number of activities,
D – the total duration of the project,
ICR – the indirect cost rate that is a constant number for each project,
$D_{deadline}$ – the deadline of the project,
C_{pen} – the penalty cost considered for the project,
C_{in} – the incentive cost considered for the project,
$\bar{u}(x)$ – 1 for positive value of x, or 0 for negative value of x.

1.2. Overall project quality

Quality can be measured using measurable quality indicators that are unique to each project activity. Quality indicators must be chosen so that the performance of each indicator can be measured objectively and realistically.

The following equation can be used to determine the quality of each individual project activity:

$$q_i = \sum_{i=1}^{N} wt_{i,k} \cdot q_{i,k}^{n} \tag{5}$$

where:

q_i – the quality of activity (i),
N – the number of activities,
$wt_{i,k}$ – indicates the relative importance of the quality indicator (k) in comparison to other indicators used to evaluate the quality of activity (i), and
$q_{i,k}^{n}$ – indicates the result or performance of the quality indicator (k) in activity (i) when resource utilization (n) is used.

The overall project quality can be calculated using the following equation once the quality of each activity has been determined (El-Rayes & Kandil, 2005):

$$Q = \sum_{i=1}^{N} wt_i \cdot q_i \tag{6}$$

where wt_i represents the weight of activity (i) in terms of its contribution to the project's overall quality.

1.3. Critical Path Method (CPM)

The Critical Path Method (CPM) is developed by Morgan R. Walker and James E. Kelley in the 1950s (Hinze, 2004). It's a crucial tool for coordinating the numerous tasks that make up a project. The critical path method calculates the longest path that includes all critical activities for the project's completion. The length of the critical path indicates the shortest time for the project to be completed.

To schedule the project activities and compute the entire project duration, among all the project scheduling techniques, this paper employs the critical path method (CPM) with the activity on node network diagram and the Finish to Start relationship between activities.

2. The proposed model

For several years, optimization techniques have been used for single-objective optimization; however, in recent research studies, the unification of multiple objectives in the fitness function has become increasingly common. The term "multi-objective function" refers to the fitness function's unification of multiple objectives. This study uses multi-objective functions to reduce project time and total cost while improving overall project quality. For satisfying time-cost-quality trade-off optimization, a multi-objective optimization strategy is required. To optimize time--cost-quality optimization problems, the non-dominating sorting (NDS-II) concept and the crowding distance mechanism computation are combined with the teaching--learning-based optimization (TLBO) algorithm. The NDS-II approach and crowding distance computation mechanism are in charge of achieving goals effectively and efficiently in the NDS-TLBO-II model. The teacher and learner phases of TLBO also make sure that the solution space is explored and exploited. Rao et al. (2011; 2012) introduced the first teaching-learning-based optimization (TLBO) method motivated by the philosophy of teaching and learning.

The initial population, which includes a predetermined P number of students, is organized using the non-dominance concept. When using the NDS-II approach, each solution is assigned a rank value. According to the non-dominance concept, a higher rank indicates a higher level of superiority. However, there is nothing that can be said about dominance among solutions in the same rank. The crowding distance is a metric for making a comparison of solutions in the same rank. All solutions are saved in an external archive at the end of the day, and the student with the highest rank and crowding distance value is chosen as the class's teacher. The procedure continues in accordance with the TLBO algorithm's teacher phase after the teacher has been chosen.

3. Numerical example

The bridge construction project is used to validate the stochastic time-cost-quality model and demonstrate its capabilities in generating time-cost-quality trade-offs. The example was initially introduced by Zhang and Xing (2010) and recently used by El Bassuony (2016). It is located in southwest China and includes thirteen activities: preliminary work, three foundation excavations, three foundation piling, three piers concreting, two beam construction, and deck pavement. Figure 1 depicts the precedence relationship between activities.

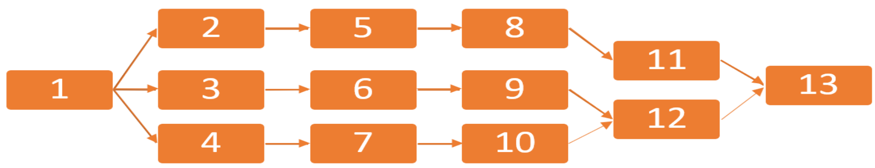

Fig 1. The CPM network of the 13-activity example (Zhang & Xing, 2010)

Figure 2 depicts the time, cost, and quality of various execution options, where the duration, cost, and quality are measured by fuzzy numbers, and the quality of each execution option is described in linguistic terms. The expected values of each objective function are calculated and tabulated in Table 1. We now have one and the expected value of time, cost, and quality of each execution option using equations (1), (2) and (3) for time, cost and quality respectively.

The optimization settings that have been adopted are: the population number (100), iteration number (1000), and the Pareto front population fraction (0.2), which specifies the percentage of the population size that should be taken into account.

The example was evaluated in MATLAB using the data in Table 1. Figure 3 shows the graphic representation of the Pareto front solutions obtained using the NDS-TLBO-II approach. In this MATLAB analysis, the critical path method is used to calculate total project time, equation (4) is used to calculate the project cost, and equation (6) is used to calculate overall project quality.

The results of NDS-TLBO-II (Table 2) and other metaheuristic techniques applied to the 13-activity example problem in the literature indicate that NDS-TLBO-II is successful and generates acceptable outcomes.

No	Name	Activity Weight	Method	Time			Cost (10^3)			Quality			
1	Preliminary work	0.01	1	26	28	30	16	18	20	0.9	1	1	Highest
			2	23	25	27	19	20	22	0.7	0.9	1	V. High
			3	17	19	21	20	22	24	0.6	0.8	0.9	High
2	Foundation excavation 1	0.08	1	40	42	46	160	170	180	0.9	1	1	Highest
			2	35	37	39	180	190	200	0.6	0.8	0.9	High
			3	30	33	36	210	220	230	0.2	0.4	0.6	Low
3	Foundation excavation 2	0.09	1	40	45	50	165	175	185	0.9	1	1	Highest
			2	38	40	43	190	200	210	0.4	0.6	0.7	Medium
			3	32	35	38	215	225	235	0.2	0.4	0.6	Low
4	Foundation excavation 3	0.08	1	39	44	49	160	170	180	0.9	1	1	Highest
			2	36	38	42	190	200	210	0.4	0.6	0.7	Medium
			3	30	33	36	210	220	230	0.2	0.4	0.6	Low
5	Foundation piling 1	0.11	1	36	38	40	124	134	144	0.9	1	1	Highest
			2	32	34	36	154	164	174	0.6	0.8	0.9	High
			3	28	30	32	210	220	230	0.2	0.4	0.6	Low
6	Foundation piling 2	0.11	1	46	50	54	180	190	200	0.9	1	1	Highest
			2	40	42	44	220	230	240	0.4	0.6	0.7	Medium
			3	33	36	39	260	270	280	0.2	0.4	0.6	Low
7	Foundation piling 3	0.11	1	38	40	42	130	140	150	0.9	1	1	Highest
			2	33	35	37	160	170	180	0.7	0.9	1	V. High
			3	28	30	32	175	180	185	0.6	0.8	0.9	High
8	Pier concreting 1	0.08	1	83	85	87	210	220	230	0.7	0.9	1	V. High
			2	80	82	84	240	250	250	0.6	0.8	0.9	High
			3	73	75	77	260	275	290	0.4	0.6	0.7	Medium
9	Pier concreting 2	0.08	1	87	90	93	230	240	250	0.7	0.9	1	V. High
			2	82	84	86	250	260	270	0.6	0.8	0.9	High
			3	76	78	80	280	300	320	0.4	0.6	0.7	Medium
10	Pier concreting 3	0.08	1	83	85	87	220	230	240	0.7	0.9	1	V. High
			2	78	80	82	240	250	260	0.6	0.8	0.9	High
			3	74	76	78	270	280	290	0.4	0.6	0.7	Medium
11	Beam construction 1	0.06	1	18	20	22	110	120	130	0.9	1	1	Highest
			2	16	18	20	135	145	155	0.4	0.6	0.7	Medium
			3	14	16	18	150	160	170	0.2	0.4	0.6	Low
12	Beam construction 2	0.06	1	20	22	24	120	130	140	0.9	1	1	Highest
			2	14	17	20	130	140	150	0.4	0.6	0.7	Medium
			3	12	14	16	155	165	175	0.2	0.4	0.6	Low
13	Deck pavement	0.05	1	22	25	28	59	65	71	0.9	1	1	Highest
			2	20	22	24	70	75	80	0.7	0.9	1	V. High
			3	13	15	17	75	80	85	0.6	0.8	0.9	High

Fig. 2. The original data of a 13-activity example problem (Zhang & Xing, 2010)

Table 1. Expected values of time cost and quality for 13-activity example (*own research*)

Activity	Preactivity	Activity weight [%]	Option 1			Option 2			Option 3		
			D	C	Q	D	C	Q	D	C	Q
1		1	28	18	0.98	25	20.17	0.88	19	22	0.78
2	1	8	42.33	170	0.98	37	190	0.78	33	220	0.40
3	1	9	45	175	0.98	40.17	200	0.58	35	225	0.40
4	1	8	44	170	0.98	38.33	200	0.58	33	220	0.40
5	2	11	38	134	0.98	34	164	0.78	30	220	0.40
6	3	11	50	190	0.98	42	230	0.58	36	270	0.40
7	4	11	40	140	0.98	35	170	0.88	30	180	0.78
8	5	8	85	220	0.88	82	248.3	0.78	75	275	0.58
9	6	8	90	240	0.88	84	260	0.78	78	300	0.58
10	7	8	85	230	0.88	80	250	0.78	76	280	0.58
11	8.9	6	20	120	0.98	18	145	0.58	16	160	0.40
12	9.10	6	22	130	0.98	17	140	0.58	14	165	0.40
13	11.12	5	25	65	0.98	22	75	0.88	15	80	0.78

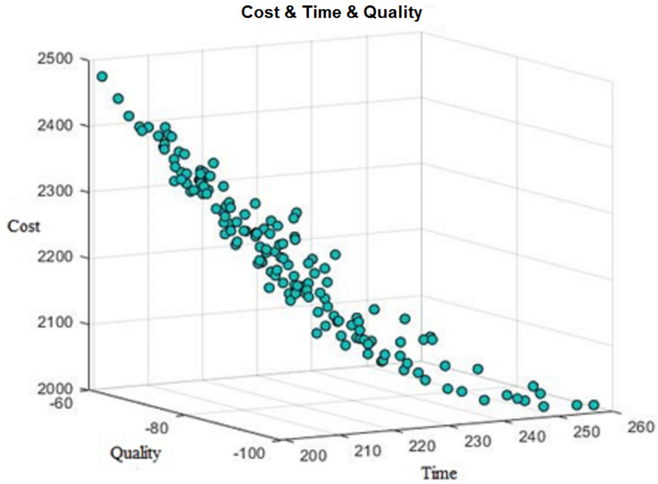

Fig. 3. The Pareto front solutions (scatter) for a 13-activity example problem (*own research*)

Table 2. Comparison of the results obtained by different methods (*own research*)

Authors	Project Duration	Project Cost	Project Quality	Pareto Number
El Bassuony (2016)	199	2481	60.40	–
	238	2077	92.53	–
This Paper	199	2481	62.86	2
	235	2041	93.93	6

Conclusion

A new multi-objective optimization method, incorporating the NDS and TLBO, was utilized to solve TCQTPs. The superiority of the utilized method and its ability to produce better results compared to the methods in the literature have been proven. When the results of this study are compared to those of previous studies, it becomes clear how effective the proposed algorithm is, as shown in Table 2. In the 13-activity example problem, on the Pareto front created by El Bassuony (2016), there is a solution with a 238 days completion time, 2 077 000 Chinese Yuan cost and 92.53% quality, while our proposed model offers a solution with a 235 days completion time, 2 041 000 Chinese Yuan cost and 93.93% quality for the same example problem. This means that all three targets are better than the literature method.

In this study, a flexible time-cost-quality model is developed in the MATLAB program that facilitates the use of TLBO in time-cost-quality optimization for the first time.

Bibliography

Chinneck, J.W. (2009) *Operations research and cyber-infrastructure. Tailoring classifier hyperplanes to general metrics*. Springer, 365-387.

El Bassuony, M. (2016) *Time-cost-quality trade-off analysis for construction projects*. Master thesis. School of Sciences and Engineering, American University in Cairo.

El-Rayes, K. & Kandil, A. (2005) Time-cost-quality trade-off analysis for highway construction. *Journal of Construction Engineering and Management*, 131(4), 477-486.

Hegazy, T. (2002) *Computer-Based Construction Project Management*. Ontario, Prentice Hall.

Hinze, J. (2004) *Construction planning and scheduling*, New York, Pearson/Prentice Hall.

Patre, A.D. & Ugale, A.B. (2020) Indirect cost in construction project. *Aegaeum Journal*, 8(5), 925-928.

Rao, R.V., Savsani, V.J. & Vakharia, D.P. (2011) Teaching-learning-based optimization: a novel method for constrained mechanical design optimization problems. *Computer-Aided Design*, 43(3), 303-315.

Rao, R.V., Savsani, V.J. & Vakharia, D.P. (2012) Teaching-learning-based optimization: an optimization method for continuous non-linear large scale problems. *Information Sciences*, 183(1), 1-15.

Vishnu, V., Achu, V., Riyana, M.S. & Jayakrishnan, R. (2018) Time-cost-risk optimization in construction work by using ant colony algorithm. *International Research Journal of Engineering and Technology*, 5(4), 2298-23.

Zhang, H. & Xing, F. (2010) Fuzzy-multi-objective particle swarm optimization for time-cost-quality tradeoff in construction. *Automation in Construction*, 19, 1067-1075.