

**A ROBUST TIME-COST-QUALITY-ENERGY-ENVIRONMENT
TRADE-OFF WITH RESOURCE-CONSTRAINED IN PROJECT
MANAGEMENT: A CASE STUDY FOR A BRIDGE
CONSTRUCTION PROJECT**

REZA LOTFI*

Department of Industrial Engineering, Yazd University
Yazd, Iran

ZAHRA YADEGARI

Department of Industrial Engineering, Islamic Azad University
Science and Research Branch, Tehran, Iran

SEYED HOSSEIN HOSSEINI

Department of Project and Construction Management, Tehran University
Tehran, Iran

AMIR HOSSEIN KHAMENEH

Department of Project Management & Construction, Tarbiat Modarres University
Tehran, Iran
MAPNA Group, Oil & Gas Division, Tehran, Iran

ERFAN BABAEE TIRKOLAEI

Department of Industrial Engineering, Mazandaran University of Science and Technology
Babol, Iran
Department of Industrial and Systems Engineering, Istinye University, Istanbul, Turkey

GERHARD-WILHELM WEBER

Poznan University of Technology, Faculty of Engineering, Management, Poznan, Poland
Institute of Applied Mathematics, Middle East Technical University
Ankara, Turkey

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* Corresponding author: Reza Lotfi (Reza.lotfi.ieng@gmail.com, Rezalotfi@stu.yazd.ac.ir).

ABSTRACT. Sustainable development requires scheduling and implementation of projects by considering cost, environment, energy, and quality factors. Using a robust approach, this study investigates the time-cost-quality-energy-environment problem in executing projects and practically indicates its implementation capability in the form of a case study of a bridge construction project in Tehran, Iran. This study aims to take into account the sustainability pillars in scheduling projects and uncertainties in modeling them. To model the study problem, robust nonlinear programming (NLP) involving the objectives of cost, quality, energy, and pollution level is applied with resource-constrained. According to the results, as time diminished, the cost, energy, and pollution initially decreased and then increased, with a reduction in quality. To make the model close to the real world by considering uncertainties, the cost and quality tangibly improved, and pollution and energy consumption declined. We applied the augmented ε -constraint method to solve the proposed model. According to the result of the research, with regard to the time-cost, time-quality, time-energy, and time-pollution charts, as uncertainty increases, the cost and quality will improve, and pollution and energy will decrease.

The proposed model can be employed for all industrial projects, including roads, construction, and manufacturing.

1. Introduction. An important problem in projects considered by beneficiaries is to execute activities accurately at the scheduled time. However, the determination of cost, quality, energy, and environmental effects such that the project will be beneficial to executors in terms of cost, to customers in terms of quality, and to other people in terms of energy consumption and pollution is a key question for researchers and this study. Many researchers spent efforts in this regard, which is provided in the literature under the names of Scheduling Projects by Time-Cost Trade-off [50]. In some cases, it is required to complete the project sooner than the schedule. This date is usually determined by the employer of high-level management based on objective and time restrictions. Indeed, to complete sooner than scheduled, the time has to be diminished for a number of the activities. This time reduction can be made by one of the two approaches of compression and rapid follow-up. Both of them would affect the key performance factors, including work resources, cost, quality, energy, and environmental pollution. Since a project competition date in each stage results from the total activities that are in the path or the critical path, the objective of trade-off between the given key factors is to achieve a more suitable completion time by selecting a set of activities for compression such that cost, energy, and pollution are minimized, and the quality in executing the activities are maximized.

Green Project Management and the consideration of environmental issues are discussed in the book of Green Management Project by Maltzman and Shirley [35]. They emphasized the environment, nature, and energy consumption, considering the environmental pollution. Moreover, climate changes, population increase, development of nations and income reduction, environmental collapse, species diversity reduction, governmental requirements, Kyoto Protocol, and other treaties mentioned in different governments are the reasons for the importance of environmental issues. Hwang and Tan [20] studied green construction project management and mentioned the obstacles that may be imposed on its execution. The obstacles increasing the costs are unfair interest distribution, shortage of information in executing green project management, legislation complications, and unawareness. In another study, Hwang and Ng [21] investigated the challenges of the project managers in executing

green construction projects. Other studies also discussed the importance of green project management and sustainable development [6, 22, 27, 61].

2. Background and motivation. Numerous studies have been conducted on project scheduling with a time-cost trade-off. For example, Prager [43] and Siemens [50] introduced heuristic algorithms for this problem. Moselhi [39] also presented a heuristic method to solve this problem and compared it to the method introduced by Ahuja et al. [3]. He showed that his proposed method was more efficient and very close to optimization. He also obtained the Pareto optimal border for cost and time.

In recent decades, different methods have been introduced to optimize the time and costs of the project activities, which can be generally classified into three groups: accurate, heuristic, and meta-heuristics ones. Many models have been implemented in mathematical planning for the optimal balance of the three project factors. Babu and Suresh [4] conducted a study to balance the three factors at the same time. In their work, they made a Crashing Hypothesis and assumed that as the time of activity decreases, cost increases linearly, and quality declines linearly. They considered three linear target functions in which the result analysis led to decision-making in balancing the mentioned factors. At the end of their paper, they proposed that neither the total quality of the project (whether weighted mean or arithmetic mean) nor the quality calculation as the product of the activities affects their work result procedure. Examples of the proposed mathematical methods are linear programming (LP) method of Hendrickson et al. [23], and Pagnoni [41] and integer programming method of Patterson and Huber [42] where the time-cost trade-off problem is accurately optimized by a mathematical planning model. Since a combination of different options can be selected to do activities at any possible time, there are compound optimization methods that are viewed as difficult optimization problems. With the problems becoming more complicated and dimensions increasing, they become less probable to be solved with common optimization methods or rapid computational methods. Thus, optimal solutions were very difficult to obtain in that situation. The comprehensive and successful development of meta-heuristic optimization algorithms to solve single-objective optimization problems made the researchers consider if these algorithms could be applied to solve multi-objective optimization problems. Various solutions to properly employ these algorithms, classify and apply them indeterministic classes of optimization problems, and their validations were among the problems and complications that would be faced by those who applied these algorithms. In this regard, Feng [12], Li and Love [28], Hegazy [24], and Zheng et al. [60] made efforts to introduce optimal solutions based on genetic algorithm (GA). However, in all these studies, uncertainties were not considered due to complications, and the studies were conducted in a deterministic space. But in real-world projects, factors such as cost and time of the projects are always affected by many changes due to the uncertainties. Therefore, to solve this problem, Feng et al. [13], Azaron et al. [1], Abbasnia et al. [2], and Zhang and Li [62] studied the bi-objective balance of time and cost in a real-world uncertain space.

Since the 1990s, researchers gradually found that it made no sense to execute a project at the right time with the lowest cost without taking into account the execution quality. As of then, the time-cost-quality balance was brought up, and the researchers started to attempt to find solutions for this problem.

The first study was conducted by Babu and Suresh in 1996. They proposed three LP optimization models as an analytical time-cost-quality balance framework. In 1999, Khang and Myint [26] implemented this model in a real-world project of construction of a cement factory in Thailand. The successful experience of meta-heuristic optimization algorithms in solving the two-factor problem of time-cost balance made the researchers focus on solving the three-factor problem of time-cost-quality optimization. A number of researchers solved the time-cost-quality optimization problem, including El-Rayes and Kandil [10] by using GA, Zhang et al. [63] and Rahimi and Iranmanesh [47] by employing particle swarm algorithm (PSO), Tareghian and Taheri [53] by implementing electromagnetism meta-heuristic algorithm, Abbasnia et al. [2] by using ant colony optimization (ACO) algorithm, Iranmanesh et al. [25] by using a recently developed version of GA called FAST PGA, Wang and Feng [59] by applying hierarchical PSO, and El Razeq et al. [11] by employing GA called automatic execution resource multi-objective optimization system.

In the studies mentioned above, the researchers used the objectives of time, cost, and quality, which are usually considered known and deterministic.

Gap research and one of the initiatives in this study is the expression of the robust optimization for time-cost-quality-energy-environment trade-off in construction projects (see Table 1). The addition of the objectives of energy consumption and environmental pollution was done to consider sustainable development goals in the project activities. To consider sustainable development, in addition to the economic aspects of the projects, consideration of the project execution with the lowest social and environmental effects is an important strategic principle for the projects. However, no definite opinion can be made on time, cost, quality, energy, and pollution of the activities during the execution to make the mathematical models close to the real-world conditions as much as possible, and all these are obscure and uncertain. Hence, the robust optimization is applied to take into consideration these uncertainties during the problem-solving process. In this study, the factors time, cost, quality, energy, and CO_2 pollution have uncertainties, which is a new topic in the field of the multi-objective optimization problem of time-cost-quality-energy-environment trade-off with resource-constrained for the project executions. To solve the mentioned multi-objective model, the augmented ε -constraint method was employed. This method was rarely applied in previous studies.

In Section 2, we state the problem and define a mathematical model for this study. In Section 3, the proposed mathematical model is solved using the augmented ε -constraint method. Section 4 provides the case study, and finally, Section 5 is devoted to a conclusion and a prospect to future studies..

3. Problem statement. Moving toward sustainability was started in 1960 when pollution and increasing fuel cost coincided with the prohibition of oil imports and made many organizations review their energy consumption, ways to get energy, and the effects of their activities on earth [48]. Given the factors cost, environment, energy, and quality, the execution and scheduling of the projects are a requirement for the beneficiaries and sustainable development. In this regard, in addition to the economic aspects, it is required to consider the execution of the projects with the lowest negative environmental and social effects.

In this section, we provide a sustainable project management model using a cost-time-quality-energy-environment trade-off, which was rarely paid attention in the

TABLE 1. Survey on related works.

Reference	Problem	Objective	Algorithms	Case Study	Uncertainty
[43]	TCTP	One	Heuristic algorithm	NE	-
[50]	TCTP	One	Heuristic algorithm	NE	-
[39]	TCTP	One	Heuristic algorithm	NE	-
[4]	TCQTP	Multi	Unknown Solver	NE	-
[42]	RCTCTP	One	Min and Max Bound	NE	-
[12]	TCTP	One	GA	NE	-
[28]	TCTP	One	GA	Household biogas	-
[8]	RCDTCTP	One	Branch-and-bound	NE	-
[24]	TCTP	One	GA	Construction	-
[26]	TCQTP	Multi	LINDO	Cement factory	-
[60]	TCTP	Multi	GA	NE	-
[10]	RCDTCQTP	Multi	GA	Highway construction	-
[47]	TCQTP	Multi	PSO	NE	-
[53]	DTCQTP	Multi	Electromagnetism algorithm	NE	-
[2]	FTCTP	One	ACO	Construction	Fuzzy logic
[25]	MMTCTP	One	FAST PGA Pareto optimal front	NE	-
[59]	TCTP	One	Hierarchical PSO	NE	-
[11]	TCQTP	Multi	Simplified GA	Construction	-
[7]	RTCTP	One	GAMS	NE	Robust optimization
[15]	RMMDTCTP	One	Benders Decomposition and Tabu search	NE	Robust optimization
[9]	MMDTCTP	One	Branch and bound and heuristic algorithms	NE	-
[16]	FTCQTP	Multi	GAMS	NE	Interval-valued fuzzy
[54]	MMRCPSP	Multi	ϵ -constraint method NSGA-II MOSA	NE	-
[17]	MMRCTCTP	One	Cplex-Soler	NE	-
[56]	RCTCTP	One	Heuristic procedure	NE	-
[18]	CRCTCTP	One	LINGO	Highway	-
[19]	RCDTCTP	Multi	Microsoft Excel and project	NE	-
[52]	MMRCTCTP	One	Heuristic method	NE	-
[57]	RCDTCTP	One	Hybrid heuristic method	NE	-
[67]	MMRCTCTP	One	GA	NE	-
[29]	MMRCTCTP	Multi	ϵ -constraint method Nesting GA	NE	-
[30]	MMDTCTP	One	Discrete symbiotic organisms search	NE	-
This research	RRCTCQEPTP	Multi	GAMS Augmented ϵ -constraint	Bridge Construction	Robust optimization

- NE: Numerical Example.
- NSGA-II: Non-dominated Sorting Genetic Algorithm II. MOSA: Multi-Objective Simulated Annealing Algorithm
- TCTP: Time-cost Trade-off Problem
- FTCTP: Fuzzy Time-cost Trade-off Problem
- RTCTP: Robust Time-cost Trade-off Problem
- RMMDTCTP: Robust Multi-mode Discrete Time-cost Trade-off Problem
- MMTCTP: Multi-mode Time-cost Trade-off Problem
- MMDTCTP: Multi-mode Discrete Time-cost Trade-off Problem
- TCQTP: Time-Cost- Quality Trade-Off Problem
- FTCQTP: Fuzzy Time-Cost- Quality Trade-Off Problem
- RCTCTP: Resource Constraint Time-cost Trade-off Problem
- DTCQTP: Discrete Time-Cost- Quality Trade-Off Problem
- RCDTCTP: Resource Constraint Discrete Time-Cost- Quality Trade-Off Problem
- MMRCSP: Multi-mode Resource Constraint Scheduling Problem
- MMRCTCTP: Multi-mode Resource Constraint Time-cost Trade-off Problem
- CRCTCTP: Cooperation Resource Constraint Time-cost Trade-off Problem
- RRCTCQEPTP: Robust Resource Constraint Time-Cost- Quality-Energy-Pollution Trade-off Problem

previous studies. Thus, when doing an activity, it should be attempted to control the cost and time of the activity and do it in the shortest time with the lowest cost, energy consumption, and pollution while keeping a high level of quality.

3.1. **Mathematical model.** First indices, parameters, and variables of decision-making are defined as follows:

Notation and definition:

Indices

- I Set of activities $i, j \in \{1, \dots, |I|\} \subset I$,
- I_1 Set of activities with a start to start the relationship $I_1 \subset I$,
- I_2 Set of activities with a start to finish the relationship $I_2 \subset I$,
- I_3 Set of activities with a finish to start the relationship $I_3 \subset I$,
- I_4 Set of activities with a finish to finish the relationship $I_4 \subset I$,
- R Set of required resources including renewable and non-renewable items $r \in R$.
- k Index of the objective function $k \in \{1, \dots, 4\} \subset K$.

Parameters

- t_i Normal duration time of activity i (Day),
- \bar{t}_i Nominal normal duration time of activity i (Day),
- t'_i Compacted duration time of activity i (Day),
- \bar{t}'_i Nominal compacted duration time of activity i (Day),
- c_i Normal cost of activity i (Dollar/Day),
- \bar{c}_i Nominal normal cost of activity i (Dollar/Day),
- c'_i Compacted cost of activity i (Dollar/Day),
- \bar{c}'_i Nominal compacted cost of activity i (Dollar/Day),
- q_i Normal quality of activity i (Percent/Day),
- \bar{q}_i Nominal normal quality of activity i (Percent/Day),
- q'_i Compacted quality of activity i (Percent/Day),
- \bar{q}'_i Nominal compacted quality of activity i (Percent/Day),
- e_i Normal energy consumption of activity i (Mega Joule /Day),
- \bar{e}_i Nominal normal energy consumption of activity i (Mega Joule /Day),
- e'_i Compacted energy consumption of activity i (Mega Joule /Day),
- \bar{e}'_i Nominal compacted energy consumption of activity i (Mega Joule /Day),
- p_i Normal pollution of activity i (Ton/Day),
- \bar{p}_i Nominal normal pollution of activity i (Ton/Day),
- p'_i Compacted pollution of activity i (Ton/Day),
- \bar{p}'_i Nominal compacted pollution of activity i (Ton/Day),
- T Total duration time of project (Day),
- \bar{T} Nominal total duration time of project (Day),
- d_{ir} Normal daily demand of activity i for resource r (Unit/Day),
- \bar{d}_{ir} Nominal daily demand of activity i for resource r (Unit/Day),
- Cap Available capacity for resource r (Unit),
- Cap Available capacity for resource r (Unit),
- SS_{ij} Start to start delay between activities i and j (Day),
- SF_{ij} Start to finish delay between activities i and j (Day),
- FS_{ij} Finish to start delay between activities i and j (Day),
- FF_{ij} Finish to finish delay between activities i and j (Day),
- y_1 Project duration-dependent indirect cost coefficient (Dollar),
- y_2 Project duration-dependent indirect quality coefficient (Percent),
- y_3 Project duration-dependent indirect energy coefficient (Mega Joules),
- y_4 Project duration-dependent indirect pollution coefficient (Ton),
- f_{ik} A alternative parameter for c_i, q_i, e_i, p_i in a simplified form of objective function k ,
- \bar{f}_{ik} Nominal value of f_{ik} ,
- ρ_f Standard deviation of \bar{f}_{ik} ,
- f^l_{ik} A alternative parameter for c'_i, q'_i, e'_i, p'_i in a simplified form of objective functions,
- \bar{f}^l_{ik} Nominal value of f^l_{ik} ,

- $\rho_{f'}$ Standard deviation of f'_{ik} ,
- ρ_i Time deviation coefficient of activity with respect to \bar{t}_i ,
- ρ_T Total time deviation coefficient of the project with respect to \bar{T} .

Decision Variables

- z_k Value of objective function k ,
- x_i Duration time of activity i (Day),
- st_i Starting time of activity i ,
- ft_i Finish time of activity i ,
- η_{ik} Permissible deviation for f_{ik} ,
- η'_{ik} Permissible deviation for f'_{ik} ,
- ψ_i Permissible deviation for t_i ,
- ψ'_i Permissible deviation for t'_i ,
- τ Permissible deviation for T ,
- λ_{ir} Permissible deviation for d_{ir} ,
- θ_r Permissible deviation for Cap_r .

To describe the mathematical model, consider a project based on an Activity on Node (AON) network. This network has $i \in \{1, \dots, |I|\} \subset I$ nodes that show the activities. The activity I have a normal time, cost, quality, energy and pollution of t_i, c_i, q_i, e_i and p_i , while the compacted time, cost, quality, energy, and pollution are denoted as t'_i, c'_i, q'_i, e'_i and p'_i .

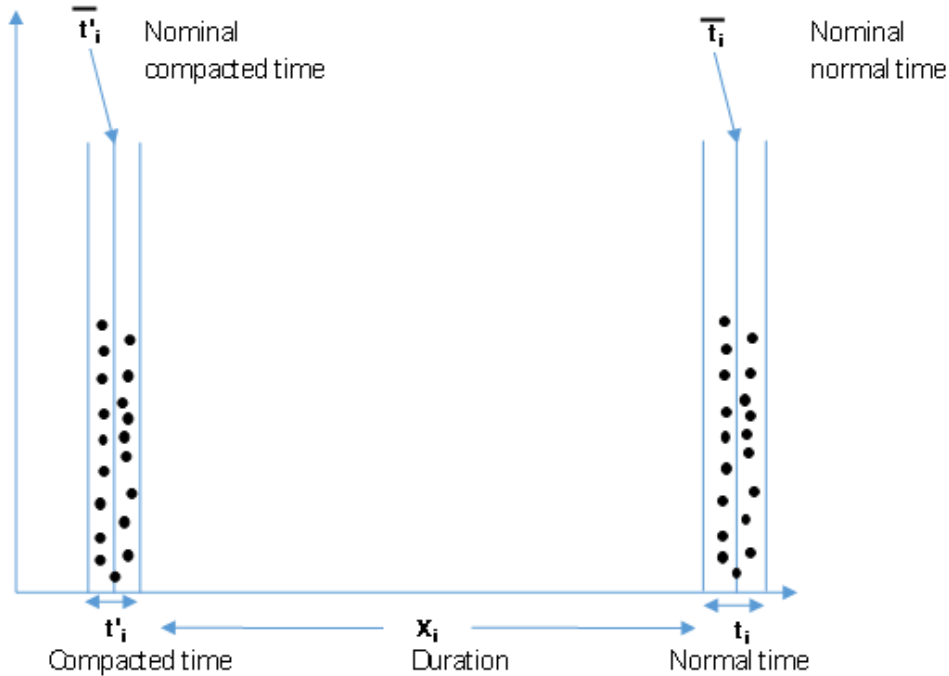


FIGURE 1. Schematic of time parameters.

The main assumptions of the proposed model are as follows:

1. No activity is done before providing the prerequisites.
2. Time, cost, quality, energy, and consumption are uncertain for every activity.
3. It should be noted that $t_i \geq t'_i$, $c_i \geq c'_i$, $q_i \geq q'_i$, $e_i \leq e'_i$ and $p_i \geq p'_i$.
4. Cost and energy consumption increase as time diminishes.
5. It should be noted that the energy consumption of each activity is estimated based on the consumption amount of energy-based resources.
6. Activities have a daily demand for their required resources.
7. Multiple renewable and non-renewable resources are defined. The supply capacity of these resources is restricted and is known at the beginning of the project.
8. Quality and pollution increase as time reduces.

In the following, the mathematical model of the time-cost-quality-energy-environment trade-off is introduced.

In Figure 1, we show that duration (x_i) is between normal time (t_i) and compacted time (t'_i). Because of uncertainty in t_i and t'_i , both of them have nominal amount. Nominal normal time is (\bar{t}_i) and nominal compacted time is (\bar{t}'_i). All uncertainty parameters applied in this research use this form.

Model 1 Cost-Time-Quality-Energy-Environment Trade-off with Resource-Constrained:

$$\text{minimize } z_1 = \sum_{i \in I} \left\{ c'_i + \left(\frac{c_i - c'_i}{t_i - t'_i} \right) (x_i - t'_i) \right\} + y_1 f i_{|I|} \tag{1}$$

$$\text{maximize } z_2 = \sum_{i \in I} \frac{\left\{ q'_i + \left(\frac{q_i - q'_i}{t_i - t'_i} \right) (x_i - t'_i) \right\}}{|I|} + y_2 f i_{|I|} \tag{2}$$

$$\text{minimize } z_3 = \sum_{i \in I} \left\{ e'_i + \left(\frac{e_i - e'_i}{t_i - t'_i} \right) (x_i - t'_i) \right\} + y_3 f i_{|I|} \tag{3}$$

$$\text{minimize } z_4 = \sum_{i \in I} \left\{ p'_i + \left(\frac{p_i - p'_i}{t_i - t'_i} \right) (x_i - t'_i) \right\} + y_4 f i_{|I|} \tag{4}$$

subject to

$$st_1 = 0, \tag{5}$$

$$f i_{|I|} = T, \tag{6}$$

$$t'_i \leq x_i \leq t_i, \quad \forall i \in I, \tag{7}$$

$$\sum_{i \in I} d_{ir} x_i \leq Cap_r, \quad \forall r \in R, \tag{8}$$

$$st_i + x_i \leq f i_i, \quad \forall i, j \in I, \tag{9}$$

$$st_i + SS_{ij} \leq st_j, \quad \forall i, j \in I_1; I_1 \subset I, \tag{10}$$

$$st_i + SF_{ij} \leq f i_i, \quad \forall i, j \in I_2; I_2 \subset I, \tag{11}$$

$$f i_i + FS_{ij} \leq st_j, \quad \forall i, j \in I_3; I_3 \subset I, \tag{12}$$

$$f i_i + FF_{ij} \leq f i_i, \quad \forall i, j \in I_4; I_4 \subset I, \tag{13}$$

$$st_i, f i_i, x_i \geq 0, \quad \forall i \in I. \tag{14}$$

The objective function (1) is the direct and indirect minimization of the total costs for the activities. The objective function (2) is the direct and indirect maximization of the mean quality for the activities. The objective function (3) is the direct and indirect minimization of the project energy consumption. The objective function (4) is the direct and indirect minimization of the total CO₂ pollution for the project. Constraint (5) is the start time for an activity (1) at time 0. Constraint (6) is the finish time for the last activity equal to the mandatory time (T). Constraint (7) is the time of each activity between the compacted time t'_i and the normal time t_i . Constraint (8) represents the capacity limitation of the resources. Constraint (9) denotes that the start time of activity (i) plus the time of activity (i) equals to the finish time of activity (i). Constraints (10)-(13) represent the dependency degree and the prerequisite between activities (i) and (j). Constraint (14) represents decision variables, involving a time of each activity as well as the start and finish time of it.

3.2. Robust optimization of the model. Since a long time ago, it has been an important subject of how to deal with uncertainties in mathematical planning problems, or in other words, system optimizations. Different approaches have been developed to deal with uncertainties in mathematical planning problems, including fuzzy and robust planning (in ambiguity cases) and random planning (in case of historical data). The robust planning approach is one of the latest methods to deal with uncertainties. It is a popular method due to its significant capabilities. As a prerequisite in dealing with uncertainties, Soyster [49] developed a pessimistic planning method for inaccurate NLP models. A few decades later, in 2000, Ben-Tal and Nemirovski [5] developed Soysters method for uncertain NLP models with different convex uncertainty sets and took a significant step forward in developing a robust planning theory.

According to them, an uncertain robust optimization problem involving a set of linear optimization problems is defined.

Assume the following certain linear optimization model with Objective Function (15) and Constraint (16).

Model 2 Deterministic form of the LP Model:

$$\text{minimize } z = cx + d \tag{15}$$

subject to

$$Ax \leq b, \tag{16}$$

where b , A , d , and c change in the given uncertainties set, converting into Eqs. (17)-(19).

Model 3 Uncertain form of the LP Model:

$$\text{minimize } z = cx + d \tag{17}$$

subject to

$$Ax \leq b, \tag{18}$$

$$(c, d, A, b) \in U. \tag{19}$$

A vector x is a robust solution for Model (3) if it satisfies all the constraints obtained from uncertainties set U . Ben-Tal and Nemirovski [5] defined the robust counterpart problem as Model (4).

Model 4 Robust Problem of the LP Model:

$$\text{minimize } \hat{c}(x) = \sup_{(c,d) \in U} [cx + d] \tag{20}$$

subject to

$$Ax \leq b, \quad \forall (c, d, A, b) \in U.$$

An optimal solution for Model (4) is a robust optimal solution for Model (3). Such a solution satisfies all the constraints for all the uncertain data and ensures that the value of the optimal objective function $\hat{c}(x^*)$ is not worse than any value [31, 44, 64]. It means that Model (4) solves the model in the worst case. Model (4) is a semi-finite linear optimization problem and seems to be computationally strong. However, it seems that for a wide range of convex uncertainties sets, a convex mathematical problem can be solved (in the form of a solvable polynomial) - it is usually a linear optimization or a conic quadratic problem.

For ease of solution, the compact form of Model (1) can be expressed as Model (5).

Model 5 Compact form of Model (1):

$$\text{minimize } z_k = \sum_{i \in I} \left\{ f'_{ik} + \left(\frac{f_{ik} - f'_{ik}}{t_i - t'_i} \right) (x_i - t'_i) \right\} + y_k f_{i|I} \quad \forall k \in K \tag{21}$$

subject to

$$\text{Constraints (5) - (14),}$$

where f_{ik} has replaced normal parameters and f'_{ik} has replaced normal parameters (t_i, c_i, q_i, e_i and p_i) and f'_{ik} has replaced compact parameters (t'_i, c'_i, q'_i, e'_i and p'_i) for objective function k .

To develop the above robust counterpart model, all the parameters are treated as having uncertainties. Each of the uncertainty parameters is assumed to change in a box range [49]:

$$u_{box} = \{ \xi \in \mathbb{R}^n : |\xi_t - \bar{\xi}_t| \leq \rho G_t, t = 1, \dots, n, \}$$

where $\bar{\xi}_t$ is the nominal value of vector ξ_t (of n dimensions). A positive value of G_t represents uncertainty scale, and $\rho > 0$ represents uncertainty level. The most widely applied case is $G_t = \bar{\xi}_t$ which belongs to a simple case, that is, a box containing ξ_t whose maximum relative deviation from the nominal data is ρ .

According to the above statements, the robust counterpart model can be expressed as:

Model 6 Robust optimization of Cost-Time-Quality-Energy-Pollution Trade-off Model:

$$\text{minimize } z_k \quad \forall k \in K \tag{22}$$

subject to

$$\sum_{i \in I} \left\{ f'_{ik} + \left(\frac{f_{ik} - f'_{ik}}{t_i - t'_i} \right) (x_i - t'_i) \right\} + y_k f i_{|I|} \leq z_k \quad \forall f \in u_{box}^f, f' \in u_{box}^{f'},$$

$$t \in u_{box}^t, t' \in u_{box}^{t'}, \tag{23}$$

$$t'_i \leq x_i \leq t_i, \quad \forall i, j \in I, t_i \in u_{box}^t, t'_i \in u_{box}^{t'}, \tag{24}$$

$$f i_{|I|} = T, \quad T \in u_{box}^T, \tag{25}$$

$$\sum_{i \in I} d_{ir} x_i \leq Cap_r \quad \forall r \in R, d_{ir} \in u_{box}^d, Cap_r \in u_{box}^{Cap}, \tag{26}$$

Constraints (5), (9) – (14).

Ben-Tal and Nemirovski [5] indicated that for this case (i.e., close box), the robust counterpart problem could be solved as an equivalent problem such that u_{box} is replaced by a finite set u_{ext} and u_{ext} involves the radical points of u_{box} . To demonstrate the solvable form of compacted robust Model (5), Eq. (20) addressed in the following robust solvable form:

$$\sum_{i \in I} \left\{ f'_{ik} + \left(\frac{f_{ik} - f'_{ik}}{t_i - t'_i} \right) (x_i - t'_i) \right\} + y_k f i_{|I|} \leq z_k \tag{27}$$

$$\forall f \in u_{box}^f, f' \in u_{box}^{f'}, t \in u_{box}^t, t' \in u_{box}^{t'}; \tag{28}$$

$$u_{box} = \{ \xi \in \mathbb{R}^n : |\xi_t - \bar{\xi}_t| \leq \rho \bar{\xi}_t, t = 1, \dots, n \}.$$

The left side of (28) contains uncertainty parameters. Thus, the solvable form of the semi-finite inequality of the above objective function can be rewritten as:

Model 7 Robust optimization of Cost-Time-Quality-Energy-Pollution Trade-off with Resource-Constrained

$$\text{minimize } obj_1 = z_1 \tag{29}$$

$$\text{minimize } obj_2 = -z_2 \tag{30}$$

$$\text{minimize } obj_3 = z_3 \tag{31}$$

$$\text{minimize } obj_4 = z_4 \tag{32}$$

subject to

$$\sum_{i \in I} \left\{ \bar{c}'_i + \eta'_{i1} + \left(\frac{\bar{c}_i + \eta_{i1} - \bar{c}'_i - \eta'_{i1}}{\bar{t}_i + \psi_i - \bar{t}'_i - \psi'_i} \right) (x_i - \bar{t}'_i) \right\} + y_1 f_{i|I} \leq z_1, \tag{33}$$

$$\sum_{i \in I} \frac{1}{|I|} \left\{ \bar{q}'_i + \eta'_{i2} + \left(\frac{\bar{q}_i + \eta_{i2} - \bar{q}'_i - \eta'_{i2}}{\bar{t}_i + \psi_i - \bar{t}'_i - \psi'_i} \right) (x_i - \bar{t}'_i) \right\} + y_2 f_{i|I} \leq z_2, \tag{34}$$

$$\sum_{i \in I} \left\{ \bar{e}'_i + \eta'_{i3} + \left(\frac{\bar{e}_i + \eta_{i3} - \bar{e}'_i - \eta'_{i3}}{\bar{t}_i + \psi_i - \bar{t}'_i - \psi'_i} \right) (x_i - \bar{t}'_i) \right\} + y_3 f_{i|I} \leq z_3, \tag{35}$$

$$\sum_{i \in I} \left\{ \bar{p}'_i + \eta'_{i4} + \left(\frac{\bar{p}_i + \eta_{i4} - \bar{p}'_i - \eta'_{i4}}{\bar{t}_i + \psi_i - \bar{t}'_i - \psi'_i} \right) (x_i - \bar{t}'_i) \right\} + y_4 f_{i|I} \leq z_4, \tag{36}$$

$$-\rho \bar{c}_i \leq \eta_{i1} \leq \rho \bar{c}_i, \quad \forall i \in I, \tag{37}$$

$$-\rho \bar{c}'_i \leq \eta'_{i1} \leq \rho \bar{c}'_i, \quad \forall i \in I, \tag{38}$$

$$-\rho \bar{q}_i \leq \eta_{i2} \leq \rho \bar{q}_i, \quad \forall i \in I, \tag{39}$$

$$-\rho \bar{q}'_i \leq \eta'_{i2} \leq \rho \bar{q}'_i, \quad \forall i \in I, \tag{40}$$

$$-\rho \bar{e}_i \leq \eta_{i3} \leq \rho \bar{e}_i, \quad \forall i \in I, \tag{41}$$

$$-\rho \bar{e}'_i \leq \eta'_{i3} \leq \rho \bar{e}'_i, \quad \forall i \in I, \tag{42}$$

$$-\rho \bar{p}_i \leq \eta_{i4} \leq \rho \bar{p}_i, \quad \forall i \in I, \tag{43}$$

$$-\rho \bar{p}'_i \leq \eta'_{i4} \leq \rho \bar{p}'_i, \quad \forall i \in I, \tag{44}$$

$$-\rho \bar{t}_i \leq \psi_{i3} \leq \rho \bar{t}_i, \quad \forall i \in I, \tag{45}$$

$$-\rho \bar{t}'_i \leq \psi'_{i3} \leq \rho \bar{t}'_i, \quad \forall i \in I, \tag{46}$$

$$\bar{t}'_i + \psi'_i \leq x_i \leq \bar{t}'_i + \psi_i, \quad \forall i \in I, \tag{47}$$

$$f_{i|I} = \bar{T} + \tau, \tag{48}$$

$$-\rho \bar{T} \leq \tau \leq \rho \bar{T}, \tag{49}$$

$$\sum_{i \in I} (\bar{d}_{ir} + \lambda ir) x_i \leq C \bar{a} p_r + \theta_r, \quad \forall r \in R, \tag{50}$$

$$-\rho \bar{d}_{ir} \leq \lambda ir \leq \rho \bar{d}_{ir}, \quad \forall i \in I, r \in R, \tag{51}$$

$$-\rho C \bar{a} p_r \leq \theta_r \leq \rho C \bar{a} p_r, \quad \forall r \in R, \tag{52}$$

Constraints (5), (8) – (14).

4. Solution technique. Given that the presented model is nonlinear and multi-objective, the augmented ε -constraint method is utilized to calculate the objectives of the above model. In the following, the ε -constraint method is first defined and, then, the augmented ε -constraint method is described.

The main limitations of the study are the scale of the problem. When the scale of the problem is large, the time of solving is exponential growth and NP-hard. Metaheuristic algorithms are the best choice to show the best possible solutions for these large-scaled models within a reasonable computational time. However, the proposed approach of this research considers an exact solution algorithm.

4.1. ε -constraint method. This method is based on transforming the multi-objective problem into a single-objective optimization problem. In this method,

one of the objectives is optimized as the main objective [36, 14]. The advantages of this method are

- By changing ε value, different solutions can be obtained.
- Unlike the weighting method, differences in the scales of the objectives do not make any problem. This method can obtain a more diverse set of Pareto optimal solutions.

On the other hand, the disadvantages of this method are

- The solutions obtained considerably depend on the values selected for ε . These values have to be selected such that they fall between the maximum and minimum values of each fixed objective function.
- As the number of objectives increase, more information has to be given by the user.

Assume that it is decided to minimize Objective Function (53) subject to Constraints (54) and (55).

$$\text{minimize } F(x) = \{f_1(x), \dots, f_n(x)\} \tag{53}$$

subject to

$$k(x) \leq 0, \tag{54}$$

$$s(x) = 0. \tag{55}$$

According to the method, one of the objective functions is selected as the main objective function, according to Eq. (56). Other objective functions are treated as Constraint (57), and the problem is solved with respect to one of the objective functions each time, calculating the optimal and peer value for each objective function. The range between the two optimal and peer values is divided into a predefined number, and t values table is determined for ε_j . Ultimately, Pareto solutions are obtained [58].

$$\text{minimize } F(x) = f_i(x) \tag{56}$$

subject to

$$f_j(x) \leq \varepsilon_j, \quad \forall j \neq i, \tag{57}$$

$$f_j^{\min}(x) \leq \varepsilon_j \leq f_j^{\max}(x), \tag{58}$$

However, despite its advantages of ε -constraint over the weighting method, it has three points that need attention in its implementation: (a) the calculation of the domain of the objective functions over the efficient set, (b) the guarantee of efficiency of the acquired solution and (c) the increased solution time for problems with several (more than two) objective functions. We try to address these three issues with a novel version of the ε -constraint method that is presented in the next section [37].

The ε -constraint method graph is drawn in Figure 2.

4.2. Augmented ε -constraint method (AUGMECON). Here, the augmented ε -constraint method (AUGMECON) Method is employed for multi-objective optimizations. It produces efficient optimal Pareto solutions and avoids inefficient solutions. In this method, one of the objective functions is optimized as the main

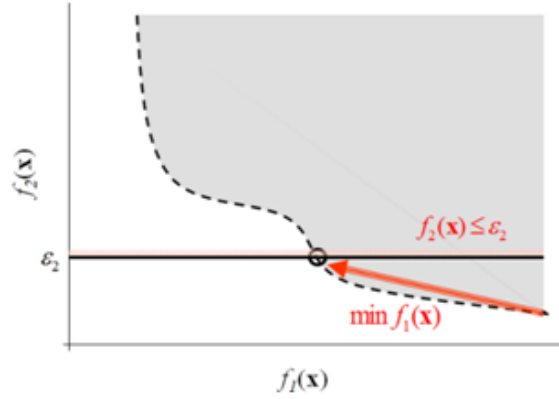


FIGURE 2. Schematic performance of the ε -constraint algorithm [38].

objective function, while other objective functions appear as constraints [37]. An innovative addition to the algorithm is the early exit from the nested loop when the problem becomes infeasible, and this significantly accelerates the algorithm in the case of several (more than three) objective functions.

AUGMECON is defined in Objective Function (59):

$$\text{maximize } \left\{ f_i(x) + \delta \left(\frac{s_2}{r_2} + \frac{s_3}{r_3} + \dots + \frac{s_n}{r_n} \right) \right\} \tag{59}$$

subject to

$$f_j(x) - s_j = \varepsilon_j, \quad \forall j \neq i, s_j \in \mathbb{R}^+. \tag{60}$$

The optimal solutions of the model are added by changes in the right side of ε_j (Constraint (60)). Optimal Pareto solutions are obtained where r is the changing scope of objective function i , δ is a very small value between 0.000001 and 0.001, and s_i is a non-negative surplus variable. The minimum and maximum values of objective function j are calculated as NIS_j and PIS_j , respectively. Then, the changing scope r_j of objective function j is calculated as Eq according to (61):

$$r_j = PIS_j - NIS_j. \tag{61}$$

Then, r_j is divided into an equal number l_j . Then, $l_j + 1$ network points are calculated by Eq. (62) based on the value of ε_j :

$$\varepsilon_j^n = NIS_j + \frac{r_j}{l_j} \cdot n, \tag{62}$$

where n is the number of network divisions. The augmented ε -constraint model has to be solved for each vector ε . Thus, $\prod_{j=2}^n (l_j + 1)$ optimization sub-problems should be solved.

To solve the mentioned multi-objective robust resource-constrained time-cost-quality-energy-environment trade-off (RRCTCQEPTP) model, the augmented ε -constraint method is used. In the following, the importance of simultaneous consideration of all the objectives is highlighted by presenting a bridge construction project.

5. Case study and sensitivity analysis. Here, the proposed methodology of the research is validated using a real case study. The case study of this research is an underpass bridge construction project in downtown Tehran, Iran. For this project, it is required to consider time, cost, quality, energy, and environment specifically since the consideration of time, cost, and quality enhances the employers satisfaction and consideration of energy consumption, and the environment is a legislation requirement. The underpass bridge project has an abutment, west and east ramps, and a column at the deck (cf. Figure 3).



FIGURE 3. the underpass bridge in Tehran.

Table 3 gives a list of activities and prerequisites along with time, cost, quality, energy, and pollution of each activity at normal and compact conditions for the underpass bridge project. Figure 4 represents the network graph based on the AON of the case study. Every Box represents activity i and has id-code, duration (cf. Table 3), early start and finish, late start and finish in nominal normal. Every activity has a dependency on other activity that was shown with an arrow. Activities 1 to 24 have been shown in Figure 4. The model was solved by GAMS software on a computer with 1.7GHz and 6GB of CPU and RAM, which is implemented by BONMIN solver of GAMS software. Table 4 shows the computation results obtained using the augmented ε -constraint method.

Figures 5(a)-(d) demonstrate augmented ε -constraint method results and the time-cost, time-quality, time-energy, and time-pollution charts. In this figure, uncertainty is equal to zero ($\rho = 0$), and as time decreases, cost, energy, and pollution first decline and then increase, while quality reduces as time reduces. On the one hand, this shows the correction of the modeling, and on the other hand, for decision-makers, it shows what would happen to quality, cost, pollution, and energy as time decreases. As it is seen, at the time about 305, the cost is at the minimum level, and quality, energy, and pollution are acceptable.

Figures 6(a)-(d) indicate time-cost, time-quality, time-energy, and time-pollution charts with increased uncertainty $\rho = 2\%$, and $\rho = 3\%$. Costs are lowered, and quality is improved. Moreover, energy and pollution are reduced.

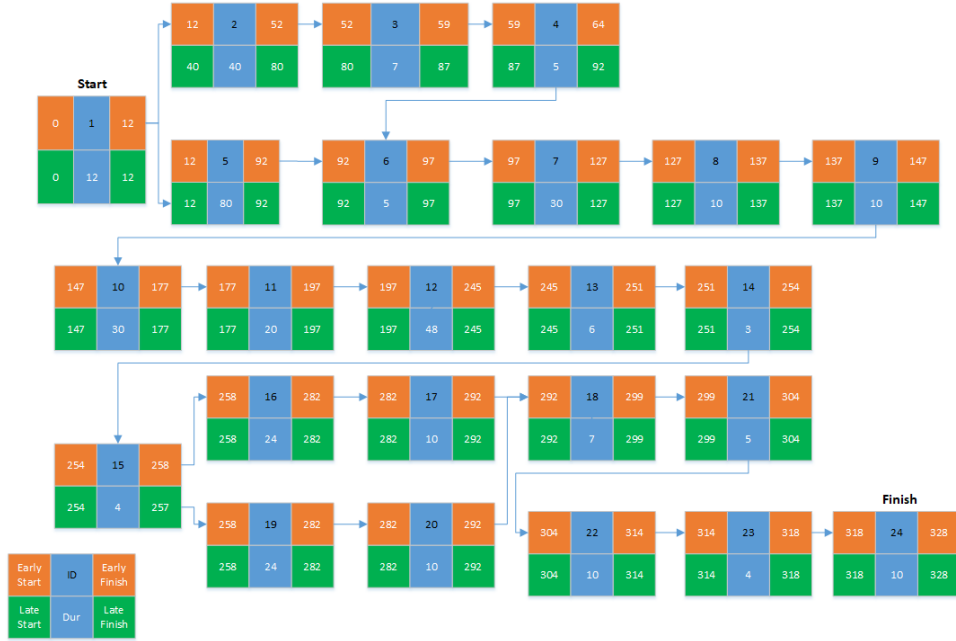


FIGURE 4. Network Graph of the bridge construction project.

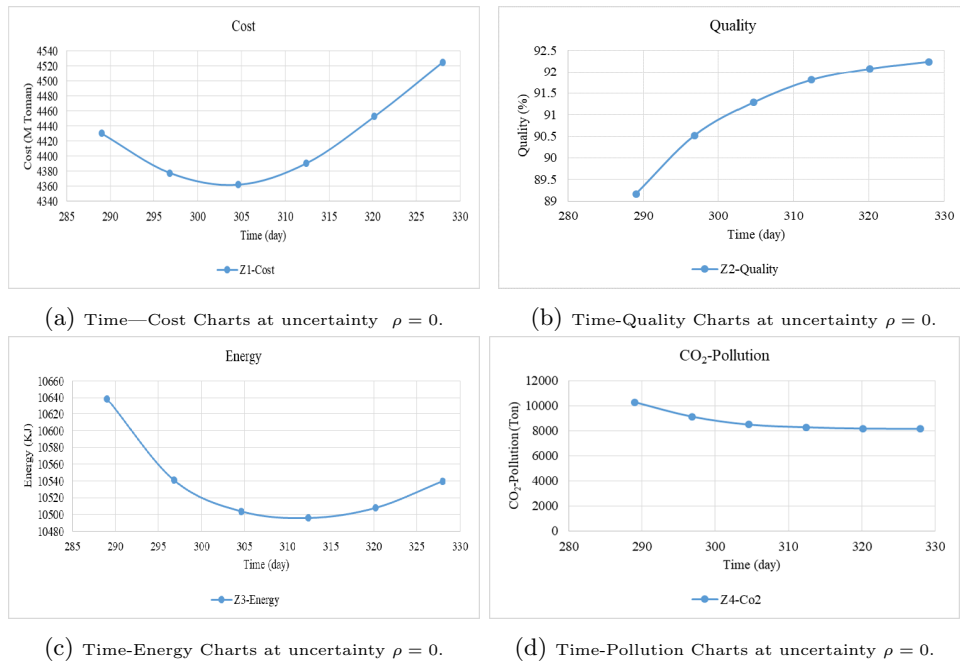


FIGURE 5. Time-cost, Time-quality, Time-Energy and Time-Pollution Charts.

TABLE 3. Cost, Quality, Energy, and Pollution Information for the bridge.

ID-Code	Activity	Predecessor	Nominal Normal					Nominal Compacted					Resource	
			Time (day)	Cost (Million Toman)	Quality (%)	Energy (KJ)	CO ₂ Pollution (Ton)	Time (day)	Cost (Million Toman)	Quality (%)	Energy (KJ)	CO ₂ Pollution (Ton)	Men (Person/day)	Machine (per day)
			\bar{t}_i	\bar{c}_i	\bar{q}_i	\bar{e}_i	\bar{p}_i	\bar{t}_i'	\bar{c}_i'	\bar{q}_i'	\bar{e}_i'	\bar{p}_i'	\bar{d}_i1'	\bar{d}_i2'
1	Workplace equipment		12	100	100	900	300	10	110	96	932	370	7	10
2	Foundation pile	1FS	40	40	100	400	400	37	60	98	406	572	8	12
3	Foundation	2FS	7	40	100	500	100	5	48	96	535	162	5	7
4	Column	3FS	5	40	100	600	300	3	44	97	608	438	6	5
5	Girder construction	1FS	80	200	100	400	200	73	300	98	413	329	7	9
6	Bearings installation	4.5FS	5	5	100	200	400	2	6	98	213	677	10	7
7	Girder installation	6FS	30	20	100	300	500	28	22	100	312	820	11	8
8	Bolting	7FS	10	5	100	450	600	8	7.5	100	450	962	15	5
9	Welding	8FS	10	40	100	300	400	8	48	97	300	614	20	6
10	Slab form working	9FS	30	50	100	200	200	28	55	99	215	220	10	7
11	Cantilever form working	10FS	20	40	100	300	300	18	60	98	322	450	14	10
12	Reinforcement	11FS	48	60	100	700	450	46	72	99	740	750	7	11
13	Concreting	12FS	6	45	100	300	300	4	49.5	99	310	355	8	7
14	Cantilever coffrage	13FS	3	20	100	100	200	2	30	99	108	289	9	8
15	Bituminizing	14FS	4	60	100	200	300	3	72	100	210	506	10	9
16	East all	15FS	24	50	100	300	700	22	55	96	320	868	5	6
17	East ramp	16FS	10	40	100	600	300	7	60	98	639	348	6	7
18	Ramp and deck guard rail installation	17.2 FS	7	100	100	300	60	6	150	99	307	76	8	8
19	West wall	15FS	24	50	100	400	60	23	60	97	434	100	7	9
20	West ramp	19FS	10	40	100	200	100	7	66	97	218	150	8	10
21	Ramp and desk curb installation	18FS	5	60	100	450	40	4	72	95	458	51	9	5
22	Ramp and deck side walk implementation	21FS	10	40	100	300	60	6	44	99	323	77	5	6
23	Ramp and deck (asphalt) Take workshop down	22FS	4	60	100	200	40	3	90	99	217	59	2	8
24	Resource need in all project	23FS	10	40	100	300	200	9	48	95	313	251	1	1
												3387	3532	

Figures 5,6 show that as uncertainty increases and becomes closer to real-world situations, sustainability can be improved in every aspect of project execution. As can be seen, with respect to the consideration of sustainable development, in addition to the time and cost of project execution, environment and pollution are considered. This study makes project managers pay attention to sustainable development in executing projects. All the beneficiaries of the projects are required to manage the project execution in a way that it is executed in a sensible period and cost, energy, and pollution are minimized. So, considering these items provides a sustainable development to the project.

TABLE 4. Augmented ε -constraint method results for RRCTCQEPTP.

Time (day)	Cost (Million Toman)	Quality (%)	Energy (KJ)	CO2 Pollution (Ton)	Time (day)	Cost (Million Toman)	Quality (%)	Energy (KJ)	CO2 Pollution (Ton)
328	4525	92	10540	8150	305	4362	90	10596	9828
328	4525	92	10540	8150	305	4461	91	10554	9445
328	4533	92	10540	8590	305	4464	91	10504	9427
328	4525	92	10540	8150	305	4556	91	10610	8488
328	4802	89	10816	10249	305	4610	89	10745	10474
320	4453	92	10542	8653	297	4378	89	10626	10378
320	4557	92	10522	8405	297	4483	91	10608	10016
320	4512	92	10508	8757	297	4454	90	10541	9927
320	4508	92	10553	8172	297	4518	90	10622	9124
320	4741	89	10794	10344	297	4554	89	10730	10596
312	4390	91	10535	9187	289	4430	89	10679	10535
312	4488	92	10527	8892	289	4472	89	10645	10359
312	4484	91	10496	9098	289	4464	89	10639	10495
312	4558	91	10538	8276	289	4473	89	10679	10277
312	4672	89	10768	10397	289	450	88	10718	10734

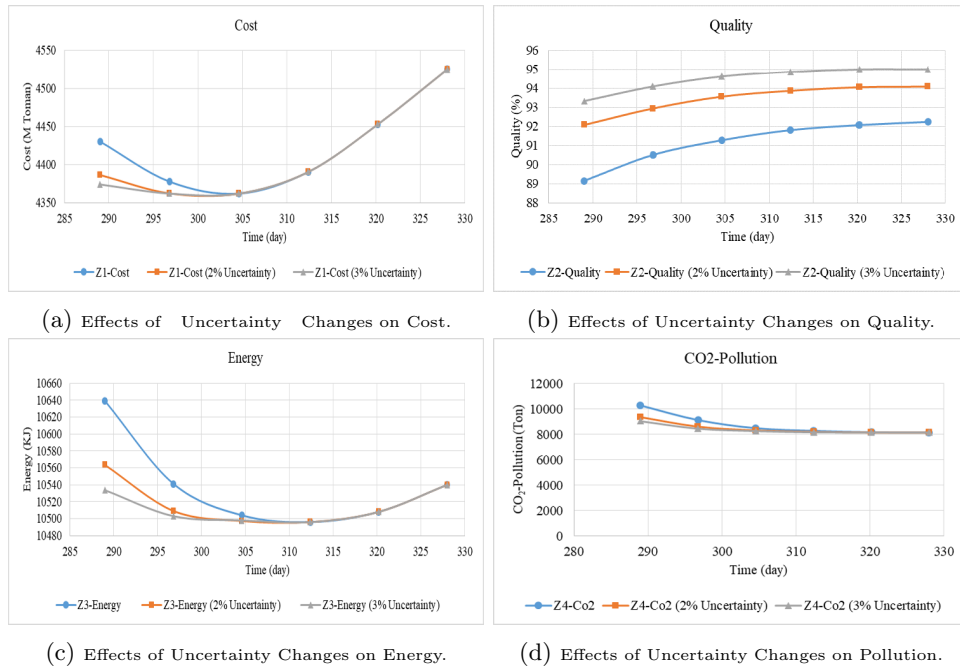


FIGURE 6. Effects of uncertainty changes on Cost, Quality, Energy and Pollution.

6. Conclusion and outlook. This study investigated the robust problem of cost-time-quality-energy-environment trade-off with resource-constrained and provided a case study of a bridge construction project in Tehran. The goal of this study was to consider sustainable development in scheduling projects and simultaneously taking into account all sustainability factors, including cost, environment, energy, and quality in executing projects. Nonlinear programming (NLP) model with four objectives (i.e., cost, quality, energy, and pollution) was applied for formulating the problem, which was solved by BONMIN solver of GAMS software. Time affected all the objectives, both directly and indirectly. It usually first declines and then increases cost, energy, and pollution, while it only reduces quality. The robust

optimization technique proposed by Ben-Tal and Nemirovski [5, 40] was utilized to include uncertainties in the model efficiently. As it is obvious in the results section, uncertainty is very low (almost zero). When uncertainty is equal to zero, and as time decreases, cost, energy, and pollution first decline and then increase, while quality reduces as time reduces. Moreover, in time-cost, time-quality, time-energy, and time-pollution charts, as uncertainty increases, cost and quality improvement and pollution and energy reduction. This model can be employed for all industrial projects, including roads, construction, manufacturing, etc. The main limitations of the study are the scale of the problem. When the scale of the problem is large, the time of solving is exponential growth and NP-hard.

Future works can investigate resource constraints and inventory [32, 33] into the model, using fuzzy uncertainty and robust stochastic programming [34]. Moreover, given the type problem (i.e., nonlinearity of the model and NP-hardness of the problem), heuristics [45, 46] and meta-heuristic algorithms [51, 55, 65, 66] can be developed to solve large-sized problems in project management.

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E-mail address: Reza.lotfi.ieng@gmail.com

E-mail address: rezalotfi@stu.yazd.ac.ir

E-mail address: zahra.yadegari@gmail.com

E-mail address: shoseinhoseini@ut.ac.ir

E-mail address: amirhossein.khameneh@gmail.com

E-mail address: e.babaee@ustmb.ac.ir

E-mail address: gerhard.weber@put.poznan.pl