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ORIGINAL PAPER

Optimization of environmental impacts of construction projects: a time–cost–quality trade-off approach

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Abstract

The construction industry and the implementation of civil projects are considered to be one of the causes of environmental pollution. Given the impacts and pollution created by the implementation of projects, it is necessary to identify the environmental impacts in order to reduce their effects. The purpose of this paper is to present a discrete time–cost–quality–environmental impacts trade-off problem for the construction industry with multiple execution modes for project activities in order to reduce the environmental impacts of the project implementation. A multi-objective planning model was developed in this problem to address the four objectives of minimizing time, cost, and environmental impacts and maximizing quality of the project implementation. Then, the problem was modeled as a single-objective programming model by converting the objective function to a constraint. The Leopold matrix method was used to evaluate environmental impacts. Finally, part of a rural water supply project was used as a practical example to demonstrate the applicability and efficiency of the model. The results of this study showed that the proposed method to optimize the aforementioned objectives is highly efficient, and planning and decision making in the early stages of a project to choose the method of doing the project activities will result in reducing costs, time, environmental impacts, and enhancing the quality of the project. By calculating the environmental impacts of project activities in each execution mode, project managers and stakeholders can take into account the environment around them, along with pursuing the economic, time, and quality objectives of the project, and minimize the project overall negative environmental impacts as a measurable amount. This research can help project managers choose the most appropriate method to execute their activities so that the project will ultimately be delivered with the least amount of time, cost, and environmental impact, and with the highest quality.

Keywords Time–cost–quality–environmental impacts trade-off' · Construction projects · Environmental impacts assessment · Leopold matrix · Multi-objective planning

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Introduction

Construction projects are among the main sources of environmental pollution. Zhaojian and Yi (2006) state that construction projects are responsible for about 45.5% of total energy consumption in the world. In other words, the construction industry is a major producer of carbon dioxide (Wu et al. 2012). According to Zolfagharian et al. (2012), the extent to which ecosystem, natural resources, and public resources are affected by construction activities in Malaysia is 67.5%, 21%, and 11.5%, respectively. The substantial environmental impacts of construction projects have led governments around the world to adopt and enforce a variety of financial regulations and incentives to mitigate these impacts (Dirckinck-Holmfeld 2015). Researchers have reported that the construction industry, particularly road projects, cause many environmental, health, and social disruptions (Celauro et al. 2017; Molenaar 2013; Ossa et al. 2016; Rooshdi et al. 2014). These studies focus on developing new construction methods which include methods and techniques for waste reduction and material transportation in order to minimize pollution emission and energy consumption, and to reduce environmental impacts of the construction projects on social and economic activities around them.

The duration of construction projects and their costs are two important factors in the success of projects and the performance of companies which have been the focus of researchers for many years. The discrete time–cost trade-off problem (DTCTP) was introduced by Harvey and Patterson (1979) and Hindelang and Muth (1979). This is an important issue in project scheduling theory and its applications. Each activity has a duration and cost, and manipulating the duration and input resources of each activity yields certain combinations of these two factors in the project implementation (Ahn and Erenguc 1998). In addition to time and cost, quality as a third factor has also been investigated by researchers (Zhang and Xing 2010).

However, the environmental impacts of the implementation of projects have been largely neglected. Past studies have examined the negative consequences of environmental impacts of the activities in the construction industry (Liu et al. 2013), and the construction industry has been accused of causing environmental problems such as overconsumption of global resources and production of environmental pollutants (Ding 2008). Therefore, effective techniques for managing environmental impacts are necessary to mitigate these effects in construction projects (Marzouk et al. 2008).

Today, construction projects are growing rapidly in various quantities and scales throughout the world. Project managers often face challenges in adapting and coordinating the conflicting aspects of a project (Liang 2010). These conflicting aspects include the time, cost, quality, and environmental impacts of the project implementation. Reducing project duration may be associated with increased costs, lower quality, and increased environmental impacts due to increased use of machinery, fossil fuel, and similar factors (Xu et al. 2012). Environmental impact assessment (EIA) is a very efficient way to conserve natural resources and protect the environment. Therefore, most countries have introduced and approved the environmental impact assessment in their laws, especially for construction projects (EPA 2007).

According to the above, it can be concluded that environmental impact assessment is a tool to ensure proper implementation of a project that can be used to determine, predict, and interpret the environmental impacts of the project, or to develop a proposal involving the whole set of the environment, public health, and the health of ecosystems on which human life and sustainability depend. The most important objectives of assessing environmental impacts of industrial projects can be summarized in the following areas:

1. Raising the level of environmental awareness of officials and decision makers.
2. Understanding the environmental problems arising from the implementation of development plans.
3. Predict the emergence of important and sustainable environmental impacts of development plans.
4. Incorporating environmental criteria into development planning.
5. Maintaining the quality of renewable resources for maximum operational efficiency along with properly maintaining the life cycles (Khatami 2008).

A review of the literature on environmental impact assessment shows that these studies can be divided into two categories. In the first category, only the environmental impacts of the construction industry and construction projects have been examined. Švajlenka and Kozlovská (2020) investigated the efficiency and sustainability of wood-based buildings Cianciarullo (2019) expressed the concept of green construction by considering transmission networks in various modes (gas, oil, and other products) Najjar et al. (2019) proposed a framework for building sustainability by optimizing materials selection and environmental impact assessment through modeling of building information and Life Cycle Assessment (LCA). Švajlenka et al. (2018) used the LCA method to analyze the sustainability of materials (concrete, steel, and wood) in the construction industry, and examined the sustainability parameters related to environmental impacts Hashemkhani Zolfani et al. (2018) applied MCDM to rank 5-star hotels based on sustainability and environmental indicators Moretti et al. (2018) implemented LCA to evaluate the Trench and Embankment section in Italy and examined the impact of transportation and machinery conditions Sandanayake et al. (2017) studied greenhouse gas emissions directly and indirectly during the construction phases, and reported that between 12.7% and 13.4% of greenhouse gas emissions occur during the machinery transport phase.

Dong and Ng (2015) examined the environmental impacts of construction projects as demand for construction of buildings in Hong Kong is on the increase. In this study, they presented a LCA model called the Environmental Construction Model to help decision-makers evaluate the environmental performance of construction projects in Hong Kong from start to finish. This model provided a comprehensive analysis of 18 categories of environmental impacts at the middle and bottom levels. The results showed that materials have the greatest effect on the environmental impacts of the upstream stages of public housing construction.

The second category of studies have investigated the environmental impacts of the projects, along with considering other variables affecting project optimization.

Marzouk et al. (2008) conducted the first study on time–cost–environmental impacts trade-off. They developed a multi-objective optimization model for project scheduling using genetic algorithm, which, in addition to minimizing time and cost, decreases pollutants produced in the construction project. Three types of pollutants were considered in this study: dust, harmful gases, and noise pollution. To calculate the total pollution at the project level, the values of the pollutants at the activity level were normalized, and these dimensionless values were aggregated. Also in order to validate the proposed model, this model was evaluated in a real-world project. Ozcan-Deniz et al. (2012) proposed a framework based on the concept of optimal control of construction executive operations. In their study, they aimed at minimizing the three factors of project time, cost, and environmental impacts. To assess the environmental impacts with regard to global warming, LCA was used, and the multi-objective genetic algorithm with non-dominated sorting was selected to obtain the optimal response. Xu et al. (2012) examined the discrete time–cost–environmental impacts trade-off. To investigate the environmental impacts of the project, the researchers divided the project environment into two categories: indoor and outdoor. The following Fig. 1 shows the classification of the project environment as well as the area under study.

Liu et al. (2013) examined the main factors of greenhouse gases emissions from industrial projects. They applied the multi-objective particle swarm optimization (MOPSO) model to determine the optimal solution for cost and CO_2 pollutants trade-off in construction projects.

Ozcan-Deniz and Zhu (2017) embarked on multi-objective optimization of the greenhouse gases emissions in highway construction projects. They added greenhouse gases emissions to the project's time and cost trade-off objectives. Their purpose was to investigate the relationship between the three variables of time, cost, and environmental impacts of projects. To this end, they studied the data related to time, cost, and environmental impacts (greenhouse gases) of two projects which included 20 optimal solutions. They also used Pearson's correlation coefficient and coefficient of determination to examine the relationship between the three project objectives (time, cost, environmental impacts). The results showed a positive relationship between project cost and project duration. The use of new technologies not only reduces the time and cost of the project, but also can reduce greenhouse gases emissions. The emission of these gases also accounts for about one-third of the changes in project's cost. Furthermore, a very small percentage of variation in project's greenhouse gas emissions is associated with project duration. Table 1 provides a summary of the research literature.

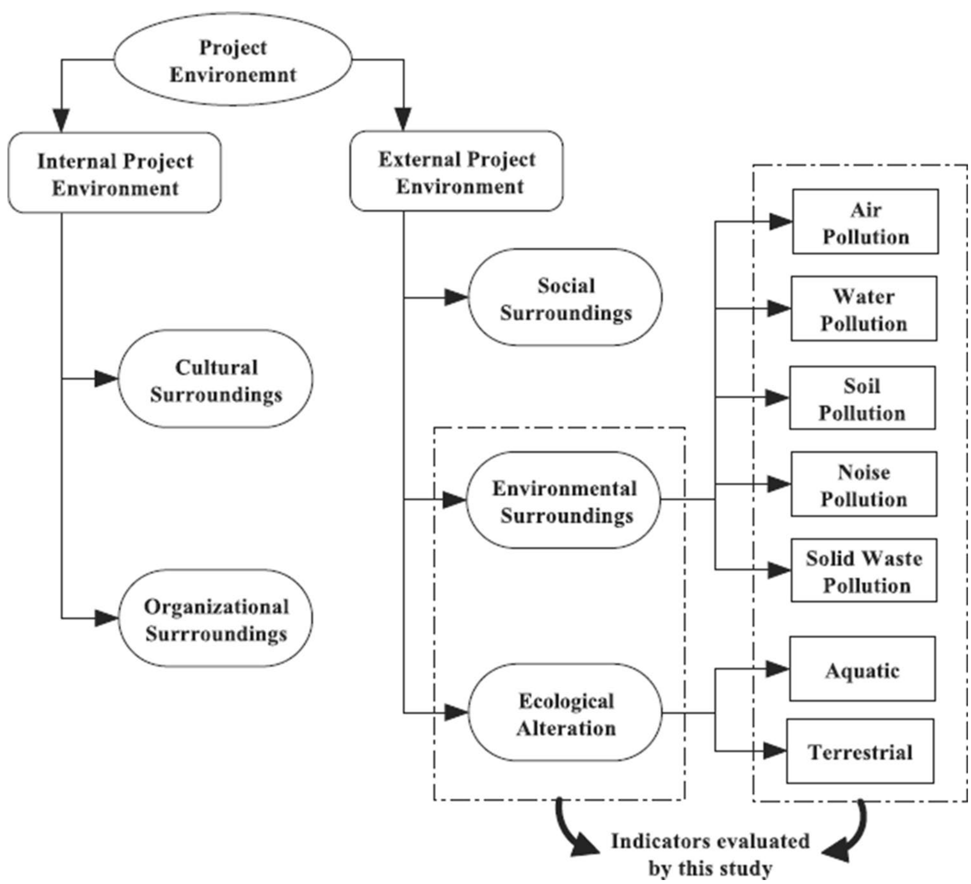


Fig. 1 The environmental parameters examined in the study by Xu et al. (2012)

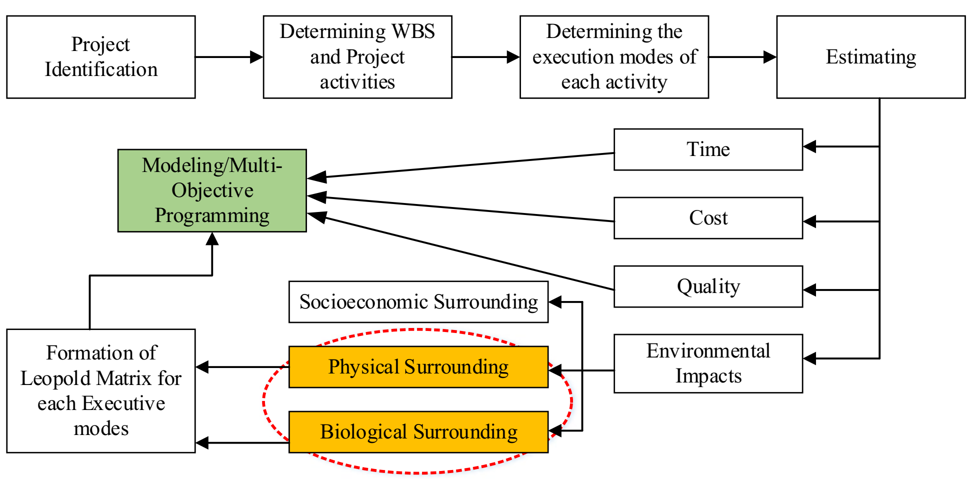
Table 1 Research on trade-off problems in project management

No	Author	Year	Trade-off problem				Objective function	Solution method
			Time	Cost	Quality	Environment impacts		
1.	Khang and Myint	1999	*	*	*		Multi objective	Exact
2.	Chiang and Lai	2002				*	Single objective	Exact
3.	Wang et al.	2003				*	Single objective	Exact
4.	Vanhoucke	2005	*	*			Single objective	Exact
5.	Tareghian and Taheri	2006	*	*	*		Multi objective	Exact
6.	Marzouk et al	2008	*	*		*	Multi-objective	Non-exact
7.	Ozcan-Deniz et al.	2012	*	*		*	Multi-objective	Non-exact
8.	Xu et al	2012	*	*		*	Multi-objective	Non-exact
9.	Liu et al.	2013		*		*	Multi-objective	Non-exact
10.	Ke and Ma	2014	*	*			Single objective	Non-exact
11.	Tavana et al.	2014	*	*	*		Multi-objective	Exact
12.	Agrawal et al.	2014				*	Single objective	Exact
13.	Ozcan-Deniz and Zhu	2017	*	*		*	Multi-objective	Exact
14.	Sandanayake et al.	2019				*	Single objective	Exact
15.	Wu et al.	2019				*	Single objective	Exact
16.	Toğan and Eirgash	2019	*	*			Multi-objective	Non-exact
17.	Tavakoli and Barkdol	2020		*		*	Single objective	Exact
18.	Liu et al.	2020	*	*			Multi-objective	Non-exact
This Research			*	*	*	*	Multi-objective	Exact

Given the above, and since human activities on the path to development inevitably affect the environment in various ways, attention to the extent and outcome of the impacts is important. Also, a review of the past industrial and development plans and projects in the country reveals that environmental considerations have not been taken into account in their planning, and many of the projects were constructed and operationalized without attending to those considerations. Therefore, considering the destructive impacts, and irreparable and costly reduction of many development plans, it is necessary to evaluate the environmental impacts of projects.

The review of research literature on environmental impact assessment in construction projects shows that in many of these studies, environmental impact assessment was only limited to the physical environment and the air and gas pollution issues. In addition to the environmental impacts, in this study, time and cost factors of the project were also taken into account. Thus, the four factors of time, cost, quality, and environmental impacts

Fig. 2 Different stages of the research



of the project implementation are simultaneously examined in this study. Therefore, the purpose of this paper is a trade-off between the four factors of time, cost, quality, and environmental impacts of project activities in a way that the project can be implemented with minimal environmental impacts. This will lead to a discrete time–cost–quality–environmental impacts trade-off problem (DTCQEITP).

The contribution of this paper is threefold: First contribution is how to assess the environmental impact of projects. For this purpose, the Leopold Matrix method has been used to incorporate more complete aspects of environmental impacts. These aspects include the physicochemical and biological environment of the project. Second contribution is taking the different execution modes into account for each project activity. To address this issue, different execution modes consisting of different combinations of resources are considered for each activity, and each execution mode will have different time, cost, quality, and environmental impacts. Third contribution is considering four important factors in project management and control, namely the time, cost, quality, and environmental impacts of the project activities are considered throughout the project. In other words, in addition to reducing the environmental impacts of the entire project, the time and cost of the entire project are minimized, and the quality will be maximized. Therefore, different execution modes of project activities are examined in the project, and finally, the best mode to reduce the environmental impacts is proposed with respect to the three factors of time, cost, and quality.

Based on the purpose of the article, the main research question is concerned with choosing the best mode for doing the project activities after determining different execution modes of each activity in order to minimize time, cost, and environmental impacts of the whole project, and to maximize the overall quality. In other words, the trade-off between the four goals in the project must be met.

This article begins with an introduction and a review of research literature in section "Introduction". Section "Materials and methods" presents the environmental impact assessment of projects. Also introduces the problem and the mathematical model of the research along with the objectives and variables of the study. Finally, the model is examined with a real example in section "Numerical Example".

Materials and methods

The process of environmental impact assessment includes identification of the impacts, data evaluation, and conclusion. The steps taken in this research are presented in Fig. 2.

There are various methods for assessing the environmental impacts, and the choice of method is influenced by various factors such as the time required for evaluation, the cost, the available and required information, the type of project under evaluation, and so forth (Barzehkar et al. 2016). Some of these methods include checklists, matrices, system analysis, and overlay mapping methods. The matrix method has been used in this research due to the quantification of results and its wider application. The Leopold evaluation matrix method was first proposed by Leopold et al. (1971). The main advantage of the Leopold matrix is providing a checklist of factors needed to perform an environmental impact assessment. Matrices, in fact, express the causal relationship between an activity and its effect on important environmental components. In addition, by aggregating all project-related factors on the one hand, and environmental-related parameters on the other, a relatively simple, concise, and comprehensible picture of the effects of the activities on the environmental components is drawn (Ashofteh and Bozorg-Haddad 2019). In this study, the environmental effects of each activity depend not only on the nature and type of the activity, but also on other factors such as the resources used in each activity and the duration of that activity and are examined in different execution modes of each activity. In Leopold matrix method, the columns of the matrix consist of project activities, and rows of environmental factors. This matrix holds two numbers for each cell. One number relates to the scope and intensity of the effect, and the other to the significance or magnitude of the effect. Numbers 1, 2, and 3 respectively represent the immediate range of the project, the directly affected range, and the range of indirect effects. Range and intensity of effects on each environmental parameter in Iranian Leopold matrix method were from -1 to -5 for negative effects (low destruction to very high destruction), and from +1 to + for positive effects (low usefulness to very high usefulness). In summing up the effects, the means of positive and negative effects were calculated for each activity and for each environmental factor. Finally, for each environmental component and for each construction and operation stage, different numerical options were calculated. At this stage, the mean of positive impacts indicates the environmental acceptability of the project; however, if the average rating is between -3.1 and -5, the project will not be considered acceptable in environmental studies.

Conclusions from the Leopold matrix with respect to the result of the mean ratings of the effects created are as follows:

1. The project is approved when none of the rows or columns means is less than −3.1.
2. The project is rejected when more than half of the rows or columns means are smaller than −3.1.

3. The project is verified by a corrective option when less than half of the columns ratings means are less than −3.1, and none of the means in the matrix rows is less than −3.1.
4. The project is verified by presenting improvement plans when none of the ratings means in the columns is less than −3.1, and less than half of the ratings means in the rows is smaller than −3/1.
5. The project is verified by corrective option and improvement plans when in both columns and rows, less than half of the ratings means are smaller than −3.1 (Golchubi-Diva and Salehi 2019).

Problem definition and modeling

In recent years, numerous scientific meetings have been held to emphasize the importance of the sustainable development (Zahedi 2013). Therefore, effort was made to develop a new model for the time–cost–quality trade-off problem in the project, taking into account the environmental impacts of the project. According to the definition of project, which refers to providing a unique product or service within a specific time period, the project completion time is the first goal in this mathematical model. Cost is another objective of the mathematical model that changes with changes in project time. Also the overall quality of the project is defined as the third objective, which changes with changes in the resources, duration, and cost of the project. The fourth objective is concerned with the detrimental and negative impacts of project activities on the environment that may increase if the project is accelerated. In this study, given the importance of the environment and the significant impacts of the projects on their surrounding environment, attempt was made to develop a new mathematical model taking into account the environmental pollution left over from the project.

Problem description

The project activities network is defined as an AON node network with $G=(N, A)$. In this graph, N is the number of activities in this network, and the arcs (E) represent the predecessor relationships of project activities $A \subset N * N$. Each activity i in the network G has a set of execution modes M_i, so that each activity can be executed in one way or mode. This means that if activity i is performed in execution mode m, it will continue uninterrupted until it is completed. For each execution, mode, certain time, cost, quality, and environmental impacts were defined.

The Leopold matrix method was used to evaluate the environmental impacts of each activity execution mode, and only negative effects were considered. These negative effects were expressed as a percentage, and the objective of the mathematical model was to reduce the environmental impacts of the whole project in a way that the project is accomplished with minimum time and cost, and with maximum quality.

Mathematical model assumptions

The assumptions based on which the mathematical model of the problem was presented and solved are as follows:

1. The environmental impacts of each activity are considered, and the model will be a trade-off between the four objectives of time, cost, quality, and environmental impacts.
2. Project activities are multi-mode in nature, meaning that several execution modes are specified for each activity.
3. The number of activities is specified and definite.
4. Time, cost, quality, and environmental impacts are considered definite.
5. Project activities during the execution are uninterruptible.
6. The type of predecessor relationships for the execution of the activities is finish-to-start with zero lag.
7. Modeling is discrete, multi-objective, and definitive.
8. The mathematical model of the problem is solved by transforming the multi-objective planning problem into a single objective one by converting the objective function to a constraint.

Symbols and variables of model

The symbols used in the mathematical model of the research are as follows:

Number of activities $i=1, 2, \ldots, n$

Number of modes for activity i $m_i=1, 2, \ldots, M_i$.

The decision variable of the research mathematical model is defined as follows. This variable determines the optimal execution mode for each project activity.

x_{imi} If the activity i is performed in Mode m_i, it is 1; otherwise, it is 0.

The mathematical model parameters are as follows:

c_{imi}: Cost of performing the Activity i in Execution mode m_i.

q_{imi}: Quality of performing the Activity i in Execution mode m_i.

e_{imi}: Environmental impacts of Activity i in Execution mode m_i.

w_i: Weight factor of activity i.

$T_{\max}$: Maximum completion time of the project.

$C_{\max}$: Maximum cost of the entire project (budget).

$Q_{\min}$: Minimum value of the expected project quality.

$E_{\max}$: Maximum value of the expected environmental impacts of the project.

E_{fs}: The set of arcs in which the activity (i, j) is a predecessor finish-to-start relationship with the delay value of fs_{ij}. It means that the jth activity starts once the ith activity finishes.

Objective functions

The objective functions of the problem consists of four objectives. The first objective is to minimize the project implementation time. Project completion time is one of the most important goals that are considered in all project scheduling issues such as RCPSP and TCTP. Since the mathematical model is written according to the network of project activities, to minimize the project duration, we consider the sum of activities that are on the critical path. Therefore, the objective function of time is written as follows:

$$\text{Min } f_1 = \sum_i d_{im_i}.x_{im_i} \quad i \in CP \tag{1}$$

The second goal is to minimize the cost of implementation of the project. The execution of each activity and its execution mode require a certain cost. Given the execution mode selected for each activity, the sum of costs of the selected activities is equal to the total cost of completing the project.

$$\text{Min } f_2 = \sum_{i=1}^{n} \sum_{m_i=1}^{M_i} c_{im_i}.x_{im_i} \tag{2}$$

The third goal is to maximize the quality of the whole project. The overall quality of the project is derived from the average quality of all project activities. Given the importance weight of each activity, the overall quality of the project will be a weighted average of the quality of project activities in the selected execution mode.

$$\text{Max } f_3 = \sum_{i=1}^{n} w_i \sum_{m_i=1}^{M_i} q_{im_i}.x_{im_i} \tag{3}$$

The fourth goal is to minimize the environmental impacts of the project. Since each project can have multiple environmental consequences depending on the nature and environment of its implementation, these effects are examined in both physicochemical and biological environments. Considering the importance weight of each activity, the overall environmental impacts of the project will be a weighted average of the environmental impacts of the project activities in the selected execution mode.

$$\text{Min } f_4 = \sum_{i=1}^{n} w_i \sum_{m_i=1}^{M_i} e_{im_i}.x_{im_i} \tag{4}$$

Mathematical model

After explaining the generalities of the research problem and examining its basics, the mathematical model of the research is presented. Each project contains a set of different activities which must be appropriately conducted, with the least cost, time, and environmental impacts, and with the highest possible quality, so that the project can be completed. To achieve these goals, the best way to do the activities must be identified. In fact, the trade-off (exchange) problem seeks to find this optimal method. In the multi-objective planning model, the environmental objective was considered as the first priority, and other objectives (time, cost, quality) as the second to fourth priorities. Therefore, we used the method of converting the objective function to a constraint, and incorporated the objectives of minimizing time and cost, and maximizing quality as constraints into the model. The problem became a single-objective planning problem.

$$\text{Min } f_4 \tag{5}$$

Subject to:

$$\sum_{m_i=1}^{M_i} x_{im_i} = 1 \quad , \; i = 1, \dots, n \tag{6}$$

$$\sum_{m_i=1}^{M_i} d_{im_i} x_{im_i} t \le \sum_{m_j=1}^{M_j} x_{jm_j} \quad , \; (i,j) \in E_{fs} \tag{7}$$

$$\sum_i d_{im_i} x_{im_i} \le T_{\max} \tag{8}$$

$$\sum_{i=1}^{n} \sum_{m_i=1}^{M_i} c_{im_i}.x_{im_i} \le C_{\max} \tag{9}$$

$$\sum_{i=1}^{n} w_i \sum_{m_i=1}^{M_i} q_{im_i}.x_{im_i} \ge Q_{\min} \tag{10}$$

$$x_{im_i} \in \{0, 1\} \quad , \quad \begin{matrix} i = 1, \dots, n \\ m_i = 1, \dots, M_i \end{matrix} \tag{11}$$

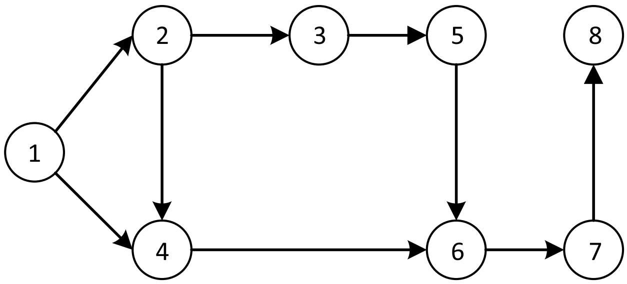


Fig. 3 Network of the project under study

In the proposed planning model, Eq. 6 states that each activity can be performed by only one of the execution modes. This limitation is written as many times as the number of project activities. Equation 7 expresses the predecessor relationships between project activities, and all relationships are of the finish-to-start type, meaning that upon completion of activity *i*, activity *j* can begin. Equations 8–10 are also the boundaries set for the three objectives of time, cost, and quality of the entire project, which are defined by the project's R&D team according to the project's policies and stakeholders. Finally, Eq. 11 states that the decision variable is a 0–1 variable. This decision variable determines the optimal execution mode for each activity. If Activity *i* is conducted through Execution mode m_i, its value is 1, otherwise it will be 0.

Numerical example

To investigate the proposed mathematical model, a part of a rural water supply project was considered. The project was related to rural water supply in a village in Birjand with a 3-km-long pipeline. Although this project was aimed at repairing the village's old pipelines, the environmental impacts have only been investigated in the construction phase of the project. The pipe-laying operation and the other stages of project implementation were carried out alongside the old pipeline.

The corresponding node network is shown in Fig. 1. Each activity consists of seven execution modes, each of which has its own duration, cost, quality, and environmental impacts. These seven execution modes were developed based on the following points for each activity, and the variables of time, cost, quality, and environmental impacts were measured and predicted:

1. Minimum resources utilization: In this execution mode, all project activities are performed with minimum amount of resources (machinery, manpower, consumables). Doing this for each activity will increase the duration of the activity.
2. The most likely execution mode: This mode provides a more normal prediction of the activity with different combinations of resources and duration of the activity.

3, 4. Changing resources to reduce time: In these two execution modes, the combination of resources used in each activity changes in a way that reduces the duration of the activity.

5, 6, 7 In these three execution modes, the resource consumption in modes 2, 3, and 4 is kept constant and the execution time increases (Fig. 3).

In order to assess the environmental impacts of the project under consideration, from among the physicochemical, biological, and sociocultural and economic environments in the two phases of construction and operation of the project, eventually the two physicochemical and biological environments in the project construction phase were chosen according to the nature of the project and the implementation area. Also, given the project implementation area, the range of environmental impacts of the project was considered within the immediate area of the project. This includes the proposed scope of the water supply project implementation, in which all execution operations and major changes were carried out in its physical and biological environment. Since there is more than one implementation option in the project, the two modes of implementing or not implementing the project are not the case. Seven factors have been considered to evaluate the environmental impacts of the project activities. These factors include soil texture and contamination, erosion and deposition, surface and groundwater contamination, dust and air pollution, noise pollution in the physico-chemical environment, factors related to plant, wildlife, habitat, and protected areas in the biological environment.

The Leopold matrix method was used to evaluate the environmental impacts of the project. For this purpose, seven matrices were developed for impact assessment, each of which was related to one execution mode. The amount of environmental impacts of each execution mode was eventually expressed as a percentage. For example, the extent of the environmental impacts of each execution mode in the third project activity (excavation and route construction diggings) is shown in Fig. 4.

The data obtained in the project are summarized in Table 2. These data include the time, cost, quality, and environmental impacts of each of the execution modes of the project activities. The duration of each activity has been determined by the amount of resources of each activity. The cost of each activity was calculated based on the price and cost of each resource and the number of its uses in the activity. The quality of each activity was also estimated by experts according to the two factors of time and resources of each activity. Environmental impacts were calculated by

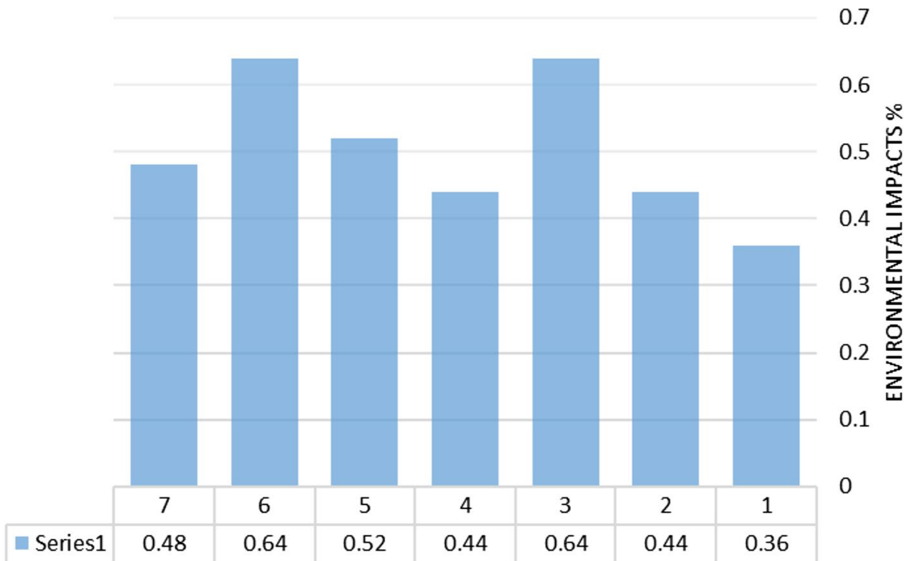


Fig. 4 Environmental impacts of execution modes of Activity 3 (excavation and route construction diggings)

Leopold Matrix (Hu and He 2014), based on seven execution modes and environmental impact factors (soil texture and contamination, erosion and deposition, surface and groundwater pollution, air and dust pollution, noise pollution in the physico-chemical environment, and factors of plant species, wildlife and habitats and protected areas in biological environment).

Given the different nature of project activities and stages, as well as project owners' attitudes and concerns about prioritizing activities, it is inevitable to compare the weights of activities. The activities can be weighted based on the criteria of time, cost, resources, and risk. In this study, a weighting method based on expert opinion (employer, consultant, contractor) was applied. Therefore, all the criteria of duration of each activity, cost of each activity, amount of resources consumed by each activity, etc. contributed to determining the weight of each activity.

Since the project consists of eight activities, and each activity can be implemented in seven modes, the total number of possible ways to implement this project is 7^8 or 5764801.

Results and discussion

Results

Given the total number of possible solutions for doing project activities, for example, if all project activities use the first execution mode, that is the minimum resource consumption mode, the total environmental impacts of the project would be 0.342. For other modes where project activities use the second, third, etc., execution modes, the calculations will be as indicated in Table 3 and Fig. 5.

These seven solutions are among all possible solutions to this problem which represent different combinations of the four variables of time, cost, quality, and environmental impacts.

Figures 6, 7 and 8 illustrate the status of time, cost, and quality variables against the environmental impacts variable in the seven scenarios above. Among these three variables, only the time factor and environmental impacts have a significant relationship. In other words, the environmental impacts increase by reducing the total project duration. The correlation between these two factors is -0.952 which is significant at the alpha level of 0.01.

However, this situation in Figs. 6, 7 and 8 is only specific to the seven scenarios considered in Table 3. Therefore, in order to determine which execution mode of each activity should be performed to reduce the environmental impacts of the whole project, the problem was modeled using the GAMS software. To begin solving the problem, it is necessary to determine the maximum duration of the project, the maximum cost, and the minimum quality of the whole project. Following the project team reviews, these values were determined as presented in Table 4.

The purpose of solving the problem is to determine the optimal execution modes for each activity so as to minimize the environmental impacts of the whole project implementation. Also certain boundaries were specified for the time, cost, and quality of the entire project. After modeling the problem and solving it using GAMS software, the optimal

Table 2 Project obtained data

Id	Activity	W_i	Execution modes	Duration (day)	Cost ($)	Quality (%)	Environmental impacts (%)
1	Canal construction	0.172	1	19	$1,216	0.82	0.30
			2	15	$1,200	0.80	0.35
			3	6	$684	0.74	0.50
			4	5	$650	0.76	0.50
			5	16	$1,280	0.81	0.30
			6	7	$798	0.75	0.44
			7	6	$780	0.77	0.44
2	Leveling and regulating the floor of the tank	0.070	1	7	$392	0.84	0.27
			2	6	$588	0.80	0.55
			3	3	$240	0.85	0.33
			4	3	$516	0.87	0.65
			5	7	$686	0.83	0.60
			6	4	$320	0.88	0.33
			7	4	$688	0.90	0.64
3	Drilling and excavating the track	0.103	1	13	$1,170	0.78	0.36
			2	9	$1,098	0.80	0.44
			3	8	$1,376	0.85	0.64
			4	7	$1,022	0.83	0.44
			5	10	$1,220	0.82	0.52
			6	9	$1,548	0.87	0.64
			7	8	$1,168	0.85	0.48
4	Drilling and tracing of tank location	0.070	1	8	$192	0.82	0.20
			2	6	$192	0.80	0.40
			3	4	$160	0.78	0.33
			4	2	$96	0.76	0.47
			5	7	$224	0.83	0.33
			6	5	$200	0.81	0.40
			7	3	$144	0.79	0.47
5	Concrete	0.024	1	4	$80	0.88	0.35
			2	2	$59	0.80	0.45
			3	2	$60	0.80	0.45
			4	1	$38	0.80	0.45
			5	3	$89	0.90	0.45
			6	3	$90	0.90	0.45
			7	2	$76	0.89	0.45
6	Preparation and execution of reinforcement and molding and floor concrete	0.229	1	22	$2,288	0.79	0.33
			2	20	$2,400	0.80	0.33
			3	20	$2,400	0.89	0.40
			4	17	$2,856	0.94	0.40
			5	22	$2,640	0.82	0.33
			6	22	$2,640	0.91	0.40
			7	19	$3,192	0.96	0.40
7	Reinforcement and molding of walls and ceilings	0.275	1	26	$3,536	0.76	0.40
			2	24	$3,648	0.80	0.40
			3	23	$3,496	0.78	0.47
			4	22	$3,872	0.87	0.40
			5	25	$3,800	0.81	0.40
			6	24	$3,648	0.79	0.40
			7	23	$4,048	0.88	0.40

Table 2 (continued)

Id	Activity	W_i	Execution modes	Duration (day)	Cost ($)	Quality (%)	Environmental impacts (%)
8	Concrete ceiling and wall	0.057	1	6	$341	0.81	0.47
			2	5	$308	0.80	0.53
			3	3	$234	0.81	0.53
			4	2	$162	0.79	0.53
			5	6	$370	0.84	0.53
			6	4	$312	0.85	0.53
			7	3	$242	0.83	0.47

Table 3 Different implementation scenarios of project activities

Scenario	Time	Cost	Quality	Environmental impacts
Scenario 1	97	9215	0.79	0.342
Scenario 2	81	9493	0.8	0.399
Scenario 3	65	8650	0.81	0.460
Scenario 4	57	9212	0.84	0.452
Scenario 5	89	10,309	0.82	0.397
Scenario 6	73	9556	0.83	0.435
Scenario 7	65	10,338	0.86	0.442

execution modes for each activity were determined according to Table 5.

Implementation of each project activity according to the optimal execution mode minimized the environmental impacts as well as the time and cost of the project. It also maximized the overall quality of the project, as shown in Table 6.

Therefore, the project cost $9434 and was completed in 78 days. The overall quality of the project was 82.5%, and the environmental impacts of the overall project was 34.8%.

Discussion

This study aimed to make a trade-off between the three goals of time, cost, and quality in construction projects with an environmental impact approach. The results of the mathematical model have identified optimal execution modes in the activities so that the project is completed with minimal environmental impacts, and the three objectives of project duration, cost, and quality have their desired amount. The project under study has eight activities, and each activity has seven execution modes. According to the project activities execution modes, the total number of solutions for the project is 5764801, out of which seven are listed in Table 3. Data on time, cost, quality, and environmental impacts of the project are shown in Table 2. To evaluate the environmental impacts, according to the seven execution modes described above, seven Leopold matrices were formed with the factors applicable to the project implementation environment

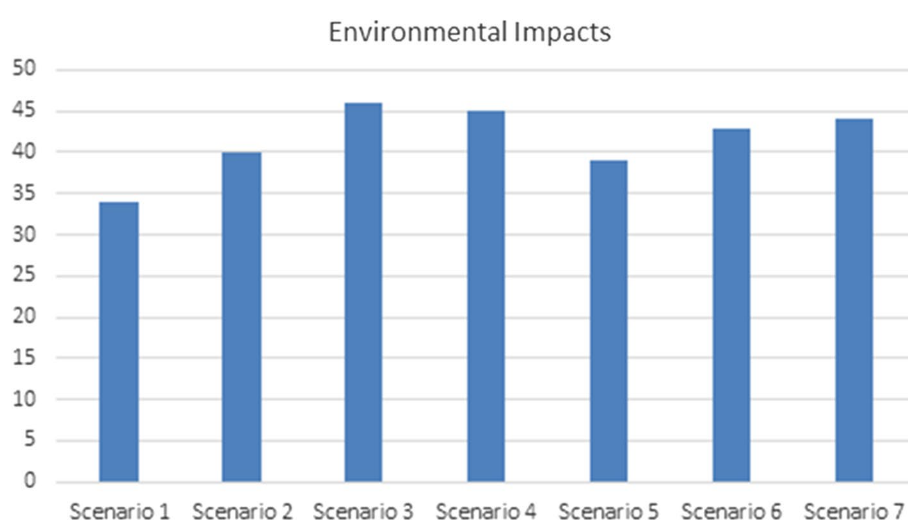


Fig. 5 Environmental impacts of the whole project in the first execution mode for all project activities

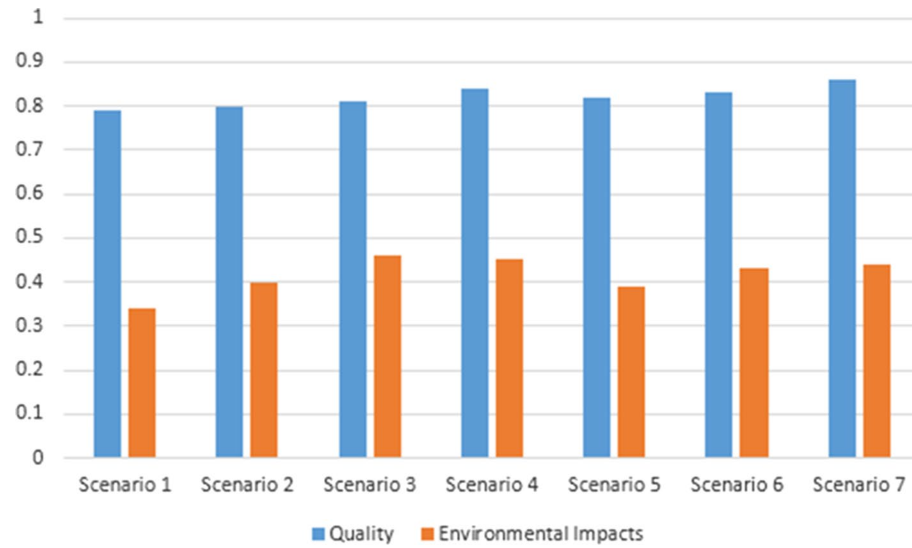


Fig. 6 Environmental impacts and quality factor of the whole project

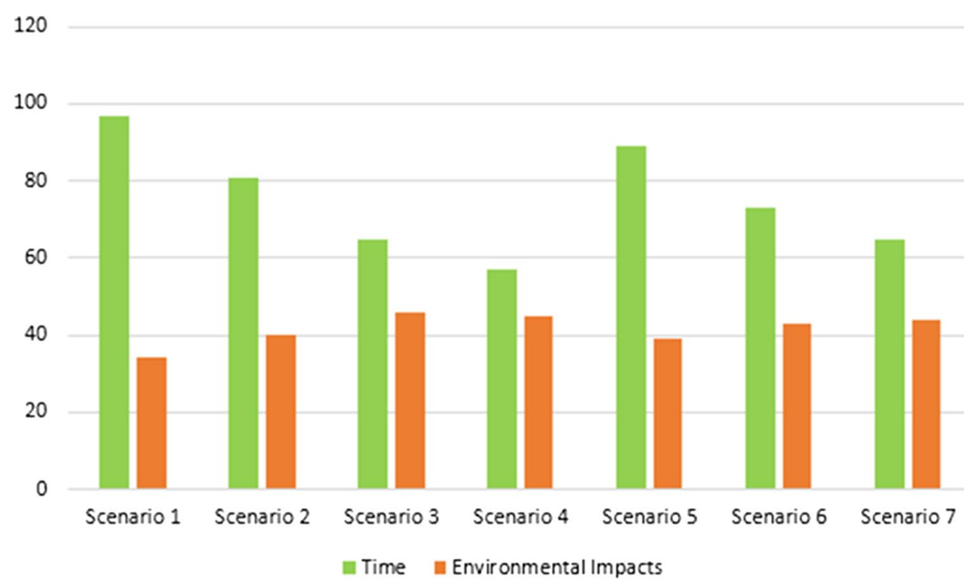


Fig. 7 Environmental impacts and total project duration

in the physicochemical and biological environment, and the amount of environmental impacts was determined. If we choose the execution modes through which the activities are completed with the least amount of time, and the execution modes through which the activities are completed with the most amount of time, the minimum project duration is 57 days, and the maximum project duration is 97 days. The total cost of the project would be between $7,992 and $11,440, the total project quality would be between 0.771 and 0.884, and the environmental impact of the project would be between 0.342 and 0.492 accordingly. Therefore, the project management team has set boundaries for the three factors of time, cost, and quality of the entire project as shown in Table 4. These boundaries were set according to the policy of the project managers and stakeholders. The mathematical model of the research is to select the execution modes for each activity so that the total weight of the environmental impacts is minimized throughout the project.

As can be seen in Table 3, if all project activities are carried out with the first execution mode, the total environmental impact of the project will be 0.342, which is the lowest environmental impact of the project. In this mode, cost constraint was met, but time and quality constraints were not met. Therefore, the research mathematical model, which is a multi-objective optimization model, seeks to optimize the environmental impacts of the project so that the time, cost, and quality constraints of the project intended by the execution team are met. The results of solving the model show that the difference between the desired and minimum environmental impact of the whole project is only 4% which

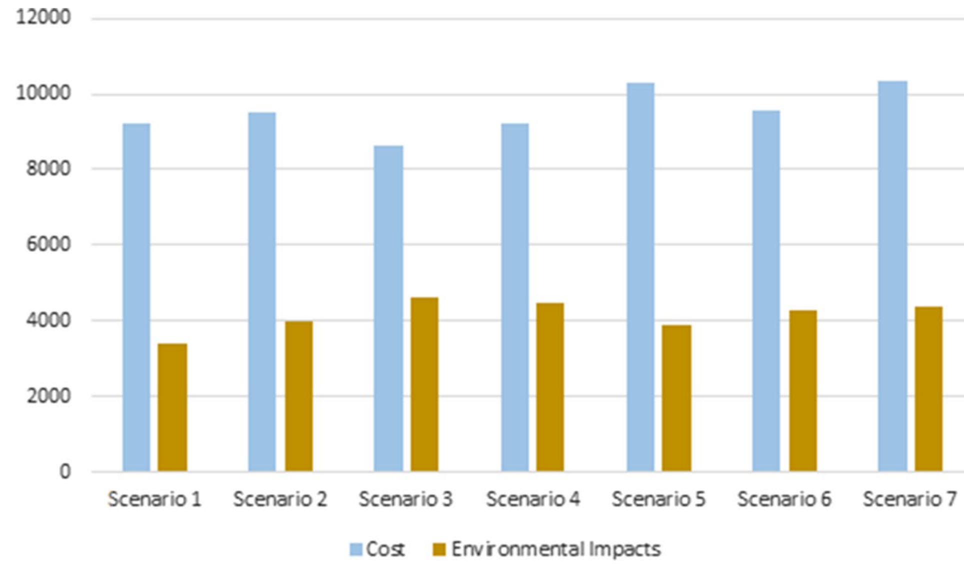


Fig. 8 Environmental impacts and total project cost

Table 4 Values determined for the time, cost, and quality of the entire project

	Maximum duration (day)	Maximum cost ($)	Minimum quality
Project total	85	10,000	0.80

Table 6 Final results of time–cost–quality–environmental impacts trade-off in the project

	Environmental impacts	Quality	Cost ($)	Duration (day)
Project total	0.348	0.825	9434	78

is considered a very favorite result. Furthermore, the other goals met the boundaries set by the project team, and were within 50% distance from their minimum and maximum values. If project managers change the determined values of time, cost, and the overall quality of the project, a different outcome will be achieved depending on the project team's policy.

Conclusion

Conducting any civil and industrial project has various positive and negative effects. Some of these effects are inevitable, and what matters most is that the project has the least negative impacts. Therefore, measures should be taken to avoid irreparable damage to the environment.

In this study, several execution modes were developed for each activity to evaluate the negative impacts and reduce them in the rural water supply project in Birjand. Finally, to evaluate the environmental impacts of the project, instead of considering two states of implementing and not implementing a project, a performance evaluation matrix was compiled and analyzed for each project execution mode. Then, for each of the project activities, the very execution

Table 5 Optimal execution modes in the project

Activity number	W_i	Execution modes	Duration (day)	Cost ($)	Quality	Environmental impacts
1	0.172	5	16	1280	0.81	0.30
2	0.070	3	3	240	0.85	0.33
3	0.103	1	13	1170	0.78	0.36
4	0.070	1	8	192	0.82	0.20
5	0.024	4	1	38	0.80	0.45
6	0.229	2	20	2400	0.80	0.33
7	0.275	4	22	3872	0.87	0.40
8	0.057	7	3	242	0.83	0.47

mode was selected that had the least environmental impacts and helped the project achieve the highest level of quality with the least time and cost. This is a multi-objective problem of time–cost–quality–environmental impacts trade-off. The goal is to reduce the time and cost of the project, and enhance its quality, with the minimum environmental impacts. This method helps project managers to choose the best execution mode of project activities. After measuring the environmental impacts of each of the execution modes through the Leopold matrix, the problem was modeled. The results showed that executing the project using the selected execution modes obtained from the GAMS software output, simultaneously optimizes the four objectives of time, cost, quality, and environmental impacts of the whole project.

Considering the fact that minimizing the time, cost, and environmental impacts of construction projects, and maximizing the quality of their implementation is one of the major challenges for project managers and practitioners, a multi-objective planning model was used in this study to select the optimal execution modes of the activities. Therefore, this research can help project managers and project planners to choose the most appropriate execution mode for the activities in order to complete the project with the minimum time, cost, and environmental impacts along with the maximum quality. This can be stated as one of the most important practical and managerial aspects of this research.

Lack of research resources and difficulties in calculating and estimating the four factors of time, cost, quality, and environmental impacts in each execution mode of project activities are among the limitations of the present study. Based on the results of this study, several aspects can be considered for future research. First, the problem data can be treated like fuzzy or gray data and be investigated using uncertainties. The second issue is how to solve the problem under study. In this study, the problem was solved by converting the objective function to a constraint in multi-objective optimization problems. Other methods can also be examined. According to the multi-objective mathematical model, meta-heuristic methods such as genetic algorithm and particle optimization algorithm can be applied, and the results can be compared with the method presented in this study. The third aspect is the method of calculating and evaluating the environmental impacts of the activities. In this study, the Leopold matrix method was used; however, other methods such as LCA can also be applied.

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