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Investigating the Environmental Impacts of Construction Projects in Time-Cost Trade-Off Project Scheduling Problems with CoCoSo Multi-Criteria Decision-Making Method

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Abstract: Currently, construction projects have a significant share in environmental pollution. Usually, the employers and managers of construction projects pay attention to the project implementation with the shortest duration and the lowest cost, whereas less attention is paid to the environmental effects of the implementation of projects. Sustainable development requires the planning and implementation of construction projects, taking environmental impacts, along with other factors, into account. Few studies have investigated the balancing time, cost, and environmental effects. Although the selection of an execution method for the project activity requires the use of decision-making methods, these methods have not been used in the project scheduling problems. This study seeks to simultaneously minimize the project time, cost, and environmental impacts. The purpose of this study is to evaluate the environmental impact of project activities in three physical, biological, and social aspects throughout the construction projects, and to attempt to minimize them as measurable values. In this paper, the environmental effects of an urban water supply construction project as a real case study are assessed in different activity execution modes by the Leopold matrix and the best execution mode of each project activity is selected using the CoCoSo (combined compromise solution) multi-criteria decision-making method, considering the time–cost-environmental impact trade-off. The CoCoSo method is employed because of its high flexibility compared to other multi-criteria decision-making methods. The results of this study will direct managers and stakeholders of construction projects to pay more attention to the environmental effects of construction project activities, together with the other conventional project goals and objectives, such as the time and cost.

Keywords: construction projects; environmental impact assessment; time–cost trade-off; CoCoSo multi-criteria decision-making method; case study

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1. Introduction

With the change in the development term from classic to modern, sustainable development, including environmental aspects, has become the main pillar of development. Meanwhile, the growing trend of world-wide public awareness of the importance of environmental issues in the form of sustainable development is of great importance. In general, construction projects are performed to meet a set of needs, and the aim of project managers is to direct and control projects to achieve predetermined project goals and objectives. Different goals and objectives are considered in projects. The most important goals of project scheduling are to complete the project with the shortest duration and the lowest cost [1]. The problem of balancing the main criteria of projects was first introduced in 1961 with regard to the two criteria of time and cost. The time–cost trade-off problem was raised in the field of construction projects so that project managers could implement projects within the predetermined time and cost, taking several execution modes for each project activity into account [2]. Eshtehardian et al. [3] proposed a method that combines fuzzy set theory and a genetic algorithm (GA) to solve the time–cost trade-off project scheduling problem, and the results showed that the method can provide Pareto solutions that consider different risk acceptance levels for contractors. Zhang and Ng [4] applied the ant colony optimization (ACO) to solve the time–cost trade-off project scheduling problem.

Increasing the number of construction projects and their financial turnover, together with developing technologies on the one hand and environmental concerns under the concept of "sustainable development" on the other hand, has resulted in paying more attention to the problem of the time–cost–environmental impacts trade-off [5–7]. The World Commission on Environment and Development provided a comprehensive definition of sustainable development in 1987 that has been widely accepted by the community [8]: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [9]. According to this definition, sustainable development must consider economic, social, and environmental goals in order to maximize the current human well-being.

Moldan and Dahl [10] stated that the set of indicators proposed in terms of sustainability are not equally precise and measurable, and that there are many ambiguities and contradictions in the definition of indicators. Stanitsas et al. [11] reviewed the sustainability indicators of construction project management in the literature. These indicators have been classified into three categories, including economic, social, and environmental aspects. Surveys in the world's environment over the past two decades show that destructive human effects on the environment have dramatically increased. Therefore, it is important to pay attention to environmental issues in the construction industry, which is accused of being one of the most important environmental pollutants [12]. Assessing the environmental impacts of implementing construction projects is a reasonable way for project decision makers, managers, and planners to achieve the goals of sustainable development. The environmental impact assessment (EIA) was first introduced in the United States. The environmental impact assessment is a way to identify the effects of the activities and the outcomes of construction projects on the environment, economy, and society [13]. In other words, the environmental impact assessment helps project managers to choose the best implementation methods of projects. As Morrison-Saunders [14] states, "Think before act". In recent years, the issue of environmental impacts has also become an interesting research topic in the construction industry. These environmental effects can be investigated during and after the implementation of projects [15].

Marzouk et al. [16] conducted the first study on the time, cost, and environmental impact trade-off. They developed a multi-objective optimization model for project scheduling using the genetic algorithm (GA), which minimizes the time, cost, and the pollutants of the construction projects. In this study, three types of pollutants, including dust, harmful gases, and noise pollution, have been considered. Ozcan-Deniz et al. [17] proposed a framework based on the concept of the optimal control of construction operations. They minimized the three objectives of the project time, cost, and environmental impact. To evaluate the environmental impacts in terms of the global warming potential (GWP), the life cycle assessment (LCA) together with the non-dominated sorting genetic algorithm (NSGAII) was used to solve the problem. Xu et al. [5] studied the discrete time–cost–environmental effect problem. They considered the environmental and ecological aspects of the project, including water and groundwater pollution, air pollution, soil pollution, noise pollution, and solid waste pollution. Liu et al. [18] investigated the main factors of greenhouse gas emissions of industrial projects. They used a multi-objective particle swarm optimization (MOPSO) algorithm to find solutions for the problem of balancing costs and CO2 pollutants in construction projects. Cheng and Tran [19] applied the metaheuristic algorithm to tackle the time–cost–environmental impact trade-off problem. They considered the three factors of dust, gases, and noise pollution to investigate the environmental effects in the case study project. Ozcan-Deniz and Zhu [20] studied the time–cost trade-off problem together with emissions of greenhouse gases in highway construction projects. Lotfi et al. [21] examined the time–cost–quality–environmental pollution trade-off problem. The results of their research showed that the cost, energy, and pollution initially decrease with a decrease in the durations of the project activities, but increase afterwards. Yu et al. [22] developed a multi-objective optimization model to deal with the cost–quality–environmental impact trade-off in the asphalt pavement project. The findings showed that the environmental impacts and costs decreased by 96.5% and 97.3%, respectively, and the quality level increased by 125.1% compared to the basic method. Other researchers, such as Santos et al. [23] and Vega et al. [24], also addressed the issue of the environmental impact assessment in hot asphalt and concrete pavement projects.

Stanujkic et al. [25] ranked the countries based on 17 goals and indicators for sustainable development using CoCoSo and Shannon entropy. Raj Mishra et al. [26] applied CoCoSo for a sustainable supplier selection. They considered 13 criteria, including green warehousing, pollution control cost, green product and eco-design cost, RL cost, green R&D and innovation, air emissions, environmental management system, flexibility, quality, financial risk, health and safety practices, social responsibility, and employment Practices for this evaluation, which shows the importance of environmental issues, along with other issues.

Huynh et al. [27] investigated the time–cost–quality trade-off problem in construction projects while considering carbon dioxide emissions. Maceika et al. [28] used the analytic hierarchy process (AHP) as a multi-criteria decision-making method to evaluate investor behavior in the selection of construction projects, taking sustainability and environmental aspects into account. Wang et al. [29] also conducted another study for evaluating the sustainability of a railroad project in Tanzania.

All relevant studies show the importance of the issue of environmental impacts and sustainability in construction projects, each of which having considered different aspects. According to the literature and research background, sustainable development in the construction industry requires planning and implementing projects while taking the environmental factor, as well as other conventional project goals and objectives, into account. On the other hand, a remarkable number of studies have recently applied various multi-criteria decision-making methods to numerous engineering problems. The multi-criteria decision-making process comprises identifying the most favorable solution among different alternatives regarding the predetermined criteria [30].

Different decision-making methods have been used for supplier selection in the construction industry so far. Yazdani et al. [31] applied the DEMATEL and BWM methods to weight supplier criteria, and exploited the CoCoSo method to rank suppliers in a construction company in Madrid. Zhang et al. [32] employed the BWM and CoCoSo methods for housing development supplier selection. In addition, in other supply chains, such as the drug supply chain, the SWARA and CoCoSo methods have been used to ensure the quality of drugs and to reduce the risks of transportation and storage [33].

In this study, the time–cost–environmental impact trade-off problem is considered using the CoCoSo multi-criteria decision-making method, which is a novel decision-making method improved by a complete ranking index. Different multi-criteria decision-making methods have been proposed to rank the criteria. All of these methods initiate with a decision matrix. The advantage of the CoCoSo method over other ranking methods, such as TOPSIS, VIKOR, ELECTRE, etc., is that the CoCoSo method proposes a combined compromise solution for ranking alternatives: "If the procedure is based on a combination of compromise attitudes, it is entitled combined compromise solution (CoCoSo)" [31]. This method calculates two values of the weighted sum and weighted product for each alternative, and, finally, it uses three strategies to rank the alternatives. The first strategy determines the arithmetic mean of the scores for each alternative. The second strategy calculates the scores of each alternative when comparing to the best. The third strategy is to compromise between the first and second strategies. The final ranking of each alternative is obtained by the arithmetic and geometric mean of the three strategies. As a result, the CoCoSo method has the most flexibility in ranking alternatives compared to other multi-criteria decision-making methods presented so far [30].

The purpose of this study is to examine the environmental effects in three physical, biological, and social aspects throughout the construction projects. The main problem with conventional environmental impact assessment methods is that they are not able to properly support large volumes of qualitative and quantitative information. The fuzzy sets theory is a world-wide recognized approach to deal with the ambiguity and linguistic variables of the environmental impacts of the execution of project activities. Hence, in this research, fuzzy logic is exploited due to the qualitative and verbal variables of environmental conditions resulting from the implementation of project activities.

2. Materials and Methods

It is important to study the extent, trend, and outcome of the environmental impacts of various human activities. These activities affect the physical environment in many ways: overpopulation, pollution, burning fossil fuels, and deforestation, which trigger climate change, soil erosion, poor air quality, and undrinkable water. One of the substantial problems in managing and scheduling construction projects is environmental impact. Environmental impact assessment is a tool to ensure the proper and correct implementation of a project, and can be used to determine, predict, and interpret the environmental impact of a project on the environment. In this study, the Leopold matrix method is used to investigate the environmental effects. An urban construction project is considered as a real case study to evaluate the effectiveness of the proposed method. After determining the environmental impacts of project activities, the best project implementation method is selected using the CoCoSo multi-criteria decision-making technique, taking time and cost factors into account.

2.1. The Leopold Matrix

The Leopold matrix was first introduced by Leopold in 1971 [34] to analyze environmental impacts. One of the main advantages of this matrix can be summarizing the positive and negative effects of the project in the implementation and operation phases. In addition, the simple structure and the ability to perform multi-criteria evaluation are the other advantages of this method. In this method, a matrix of project activities is formed, the columns of which are environmental factors. The range of values for each impact is from +5 to −5. Positive and negative signs indicate the type of impact and numbers indicate its greatness. Positive numbers indicate positive effects and negative numbers indicate negative effects. In summarizing the impacts, the average of positive and negative impacts for each project activity and each environmental factor is calculated [35]. Examining the interactions between project activities and environmental factors is associated with uncertainty and vagueness of information and qualitative evaluation. The fuzzy approach is an appropriate technique for dealing with uncertainty and ambiguity, as well as linguistic and verbal variables. Table 1 shows the ranges of the environmental impacts with triangular fuzzy numbers.

Table 1. Triangular fuzzy numbers corresponding with the ranges of the environmental impacts.

Triangular Fuzzy Number	Value	Linguistic Variable
(0,0.1,0.3)	1	Very low impact
(0.1,0.3,0.5)	2	Low impact
(0.3,0.5,0.7)	3	Medium impact
(0.5,0.7,0.9)	4	High impact
(0.7,0.9,1)	5	Very high impact

Fuzzy sets theory was introduced by Lotfizadeh [36]. Fuzzy number $\widetilde{A}$ is defined with membership function μ_A in α cut:

$$A = \{X_i : \mu_{\widetilde{A}}(X_i) \geq \alpha\ ,\ x_i \in X\} \tag{1}$$

in which, $\widetilde{A^\alpha}$ are the members of $\widetilde{A}$ whose degree of membership is greater than or equal to α. If the membership degree is greater than α, it is called a strong cut:

$$A = \{X_i : \mu_{\widetilde{A}}(X_i) > \alpha\ ,\ x_i \in X\} \tag{2}$$

A fuzzy number is a convex and normal fuzzy set that is usually expressed as triangular or fuzzy numbers (Figure 1). The triangular fuzzy number $\widetilde{M}$ is represented as $\widetilde{M} = (l, m, u)$ and its membership function is defined as follows [37]:

$$\mu_{\widetilde{A}}(x) = \begin{cases} 0 & x < l \\ \frac{x-l}{m-l} & l \leq x \leq m \\ \frac{u-x}{u-m} & m \leq x \leq u \\ 0 & x > u \end{cases} \tag{3}$$

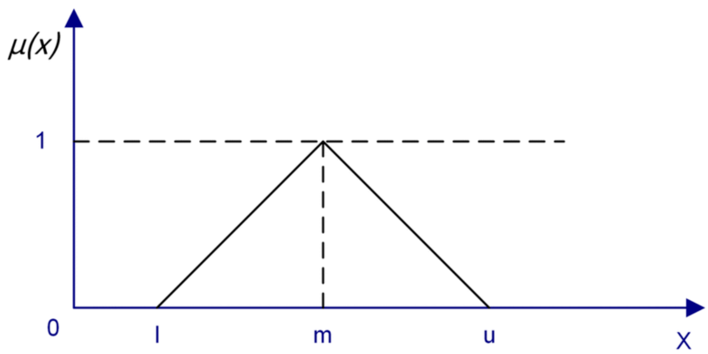

Figure 1. Triangular fuzzy number.

Each fuzzy set is defined with its α cuts. For each α value in the interval [0,1], an α cut of each triangular fuzzy number is a closed interval of real numbers.

2.2. Fuzzy Combined Compromise Solution (CoCoSo) Multi-Criteria Decision-Making Method

Combined compromise solution (CoCoSo) method is one of the new multi-criteria decision-making techniques and was introduced by Yazdani et al. in 2019 [30]. This method provides a compromise combination solution for ranking alternatives. This method consists of an integrated model of weighted sum model (WSM) and weighted product model (WPM), the steps of which are as follows [38]:

Step 1: Forming a decision matrix

In fact, the first step in all multi-criteria decision-making methods is to form a decision matrix. X_{mn} matrix is the evaluation of alternative m according to criterion n, which can be based on both linguistic expressions and real (quantitative) data. The decision matrix based on fuzzy data is as follows:

$$\widetilde{X} = \begin{bmatrix} \widetilde{x}_{11} & \cdots & \widetilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \widetilde{x}_{m1} & \cdots & \widetilde{x}_{mn} \end{bmatrix} = \begin{bmatrix} \left(\widetilde{x}^{l}_{11}, \widetilde{x}^{m}_{11}, \widetilde{x}^{u}_{11}\right) & \cdots & \left(\widetilde{x}^{l}_{1n}, \widetilde{x}^{m}_{1n}, \widetilde{x}^{u}_{1n}\right) \\ \vdots & \ddots & \vdots \\ \left(\widetilde{x}^{l}_{m1}, \widetilde{x}^{m}_{m1}, \widetilde{x}^{u}_{m1}\right) & \cdots & \left(\widetilde{x}^{l}_{mn}, \widetilde{x}^{m}_{mn}, \widetilde{x}^{u}_{mn}\right) \end{bmatrix} \tag{4}$$

Step 2: Normalizing decision matrix

In this step, the decision matrix becomes normal. For positive and negative criteria, two different equations are used:

$$\widetilde{X}^{N} = \left[\widetilde{x}^{N}_{ij}\right],\ \widetilde{x}^{N}_{ij} = \begin{cases} \left(\frac{\widetilde{x}^{l}_{ij}}{max_i\ \widetilde{x}^{u}_{ij}}, \frac{\widetilde{x}^{m}_{ij}}{max_i\ \widetilde{x}^{u}_{ij}}, \frac{\widetilde{x}^{u}_{ij}}{max_i\ \widetilde{x}^{u}_{ij}}\right) & Positive\ Criteria \\ \left(\frac{min_i\ \widetilde{x}^{l}_{ij}}{\widetilde{x}^{u}_{ij}}, \frac{min_i\ \widetilde{x}^{l}_{ij}}{\widetilde{x}^{m}_{ij}}, \frac{min_i\ \widetilde{x}^{l}_{ij}}{\widetilde{x}^{l}_{ij}}\right) & Negative\ Criteria \end{cases} \tag{5}$$

Step 3: Calculating weighted sum and weighted product values

In this step, the values of weighted sum (SB) and weighted product (PB) are calculated for each alternative. Fuzzy normalized weighted Bonferroni mean is used to calculate these values [39]. In the following two equations, W_j is the weight of the criterion j entered as input in the CoCoSo method. This weight can be calculated directly by the decision maker or through methods such as Shannon entropy, AHP, BWM, etc.

$$SB^{p,q}_{i} = \left(\sum_{\substack{i,j=1 \\ i \neq j}}^{n} \frac{w_i w_j}{1-w_i} \widetilde{x}^{Np}_{i} \widetilde{x}^{Nq}_{j} \right)^{\frac{1}{p+q}} = \begin{pmatrix} \sum_{\substack{i,j=1 \\ i \neq j}}^{n} \frac{w_i w_j}{1-w_i} \widetilde{x}^{(l)p}_{i} \widetilde{x}^{(l)q}_{j}, \\ \sum_{\substack{i,j=1 \\ i \neq j}}^{n} \frac{w_i w_j}{1-w_i} \widetilde{x}^{(m)p}_{i} \widetilde{x}^{(m)q}_{j}, \\ \sum_{\substack{i,j=1 \\ i \neq j}}^{n} \frac{w_i w_j}{1-w_i} \widetilde{x}^{(u)p}_{i} \widetilde{x}^{(u)q}_{j} \end{pmatrix}^{\frac{1}{p+q}} \tag{6}$$

$$PB^{p,q}_{i} = \frac{1}{p+q} \prod_{\substack{i,j=1 \\ i \neq j}}^{n} \left(p\widetilde{x}^{N}_{i} + q\widetilde{x}^{N}_{j}\right)^{\frac{w_i w_j}{1-w_i}} = \begin{pmatrix} \frac{1}{p+q} \prod_{\substack{i,j=1 \\ i \neq j}}^{n} \left(p\widetilde{x}^{(l)}_{i} + q\widetilde{x}^{(l)}_{j}\right)^{\frac{w_i w_j}{1-w_i}}, \\ \frac{1}{p+q} \prod_{\substack{i,j=1 \\ i \neq j}}^{n} \left(p\widetilde{x}^{(m)}_{i} + q\widetilde{x}^{(m)}_{j}\right)^{\frac{w_i w_j}{1-w_i}}, \\ \frac{1}{p+q} \prod_{\substack{i,j=1 \\ i \neq j}}^{n} \left(p\widetilde{x}^{(u)}_{i} + q\widetilde{x}^{(u)}_{j}\right)^{\frac{w_i w_j}{1-w_i}} \end{pmatrix} \tag{7}$$

In the above equations, p and q parameters represent the stabilization parameters and changes in them may affect the prioritization of the final results. For the initial solution, $p = q = 1$.

Step 4: Determining the evaluation scores of the alternatives using three strategies

In this step, the final score of each alternative is calculated. In fact, this equation represents the sum of the geometric mean and arithmetic mean of the three strategies of the previous step. The higher the score k of each alternative, the better it is.

$$k_{ia} = \frac{PB_i + SB_i}{\sum_{i=1}^{m}(PB_i + SB_i)} \tag{8}$$

$$k_{ib} = \frac{SB_i}{min_i(SB_i)} + \frac{PB_i}{min_i(PB_i)} \tag{9}$$

$$k_{ic} = \frac{(1-\lambda)PB_i + \lambda SB_i}{(1-\lambda)max_i(PB_i) + \lambda max_i(SB_i)}, \; 0 \leq \lambda \leq 1 \tag{10}$$

$$k_i = \frac{1}{(k_{ia}k_{ib}k_{ic})^3} + \frac{(k_{ia} + k_{ib} + k_{ic})}{3} \tag{11}$$

In multi-criteria decision-making problems, various methods have been proposed to rank the criteria. All of these methods initiate with a decision matrix. The CoCoSo method is one of the new multi-criteria decision-making techniques. The advantage of this method over other ranking methods, such as TOPSIS, VIKOR, ELECTRE, etc., is that this method proposes a combined compromise solution for ranking alternatives. This method uses three strategies for ranking alternatives. The first strategy is the arithmetic mean of the scores of each alternative. The second strategy determines the scores of each option compared to the best ones. The third strategy is a compromise between the first and second strategies. The final rank of each alternative is obtained by using the arithmetic and geometric mean of the three strategies. Therefore, the CoCoSo method has the most flexibility in ranking alternatives compared to other methods presented so far.

The advantages of using the CoCoSo method can be summarized as follows:

(1) The CoCoSo model enables flexible decision making, taking into account the interaction between multi-input attributes;
(2) The model considers the interactions between attributes and eliminates the impact of extreme/awkward data;
(3) The model is characterized by flexibility, which is expressed by the parameters l, *p*, and *q*;
(4) The model allows for checking the robustness of the results by varying the parameters l, *p*, and *q* and checking their influence on the final decision.

3. Results

A rural water supply project including 16 activities is considered to examine and implement the proposed model. This water transmission construction project with a length of 3 km between two villages of Birjand in Iran is given as a case study. The project includes excavating the route, laying pipes, and constructing two concrete tanks with a volume of 300 cubic meters along the route. The first and last activities are dummy activities and the type of relationship between the activities is finish-to-start with zero time lag.

Figure 2 shows the network of project activities, and Table 2 illustrates the project activities.

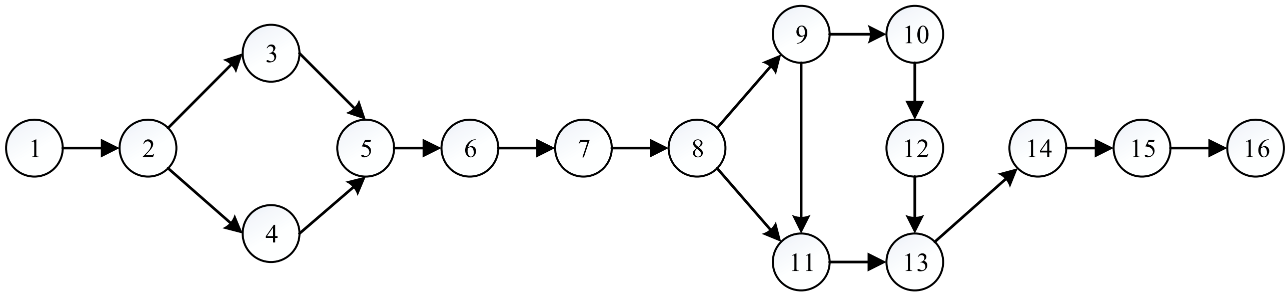

Figure 2. Network of project activities.

Table 2. Project activities.

Code	Activity	Code	Activity
1	Dummy start activity	**9**	Leveling and regulating the tank floor
2	Lining and drilling the canal floor	**10**	Drilling and excavating the path
3	Spinning pipes	**11**	Drilling and underpinning the tank place
4	Regulating and leveling the canal floor	**12**	Concreting
5	Welding and transferring pipes to the floor of the canal	**13**	Preparing and reinforcing, form working, and concreting floor
6	Piping and screening operations	**14**	Reinforcing and molding walls and ceilings
7	Testing	**15**	Concreting roof and walls
8	Embanking the canal	**16**	Dummy finish activity

Project contractors decide on how to carry out each of these activities. The environmental effects of each project activity in different execution modes are studied to evaluate the environmental effects of the entire project. For each project activity, five execution modes are considered, which are described as follows:

- The first execution mode indicates that each project activity is performed with the least amount of resources (M1);
- The second execution mode is the most probable execution mode and is performed with the most available resources (M2);
- The third execution mode is the mode in which each activity is performed within the shortest possible duration (M3);
- The fourth execution mode is the mode in which each activity is performed at the lowest possible cost (M4);
- The fifth execution mode is the mode in which each activity is performed in the most pessimistic condition (M5).

To investigate the environmental effects of project activities in each execution mode, the Leopold matrix method is used with the application of fuzzy logic considering five indicators, including the physical–chemical and biological environment, as well as two indicators that include the socio-economic environment. These indicators have been selected by interviewing with experts in the field of project management and environmental science and considering the project characteristics and surrounding environment. Indicators of the physical–chemical environment are considered with a negative impact and indicators of the socio-economic environment are considered with a positive impact. Indicators of the physical–chemical environment and biological environment are as follows:

- Soil texture and pollution, erosion, and sedimentation (EI1);
- Surface and groundwater pollution (EI2);
- Air pollution and dust (EI3);
- Noise pollution (EI4);
- Plant species, wildlife, and habitats (EI5).
- The indicators of the socio-economic environment are as follows:
- Increasing employment and reducing migration in the region (EI6);
- Increasing facilities and services in the region and improving people's income levels (EI7).

Positive and negative environmental impact assessments have been performed for different execution modes of project activities. Table 3 shows the results of these calculations.

Table 3. Decision matrix of positive and negative fuzzy environmental effects of the activity execution modes.

Activity Mode	EI1	EI2	EI3	EI4	EI5	EI6	EI7
	-	-	-	-	-	+	+
M$_1$	(0.08,0.25,0.45)	(0.11,0.3,0.5)	(0.05,0.2,0.4)	(0.1,0.3,0.5)	(0.014,0.12,0.32)	(0,0.1,0.3)	(0,0.1,0.3)
M$_2$	(0.18,0.36,0.56)	(0.24,0.44,0.64)	(0.14,0.32,0.52)	(0.15,0.35,0.55)	(0.014,0.12,0.32)	(0.053,0.20,0.40)	(0.028,0.15,0.35)
M$_3$	(0.18,0.36,0.56)	(0.31,0.51,0.71)	(0.17,0.34,0.54)	(0.3,0.5,0.7)	(0.016,0.13,0.33)	(0.34,0.54,0.74)	(0.21,0.42,0.57)
M$_4$	(0.2,0.4,0.6)	(0.31,0.51,0.71)	(0.24,0.42,0.62)	(0.18,0.38,0.58)	(0.016,0.13,0.33)	(0.041,0.18,0.38)	(0.06,0.22,0.42)
M$_5$	(0.18,0.36,0.56)	(0.24,0.44,0.64)	(0.18,0.36,0.56)	(0.25,0.45,0.65)	(0.014,0.12,0.32)	(0.27,0.47,0.67)	(0.1,0.26,0.46)

Each of the execution modes has different effects on environmental factors. The triangular fuzzy numbers in Table 3 are defuzzified using Equation (12) [40] in order to determine the amount of the impact of each of the environmental factors on the entire project in each execution mode.

$$R_i = \frac{l_i + 4m_i + u_i}{6} \quad (12)$$

According to Table 3, the defuzzified amount of the environmental effects in three physical environments (EI1, EI2, EI3, EI4), the biological environment (EI5), and the socio-economic environment (EI6, EI7) is shown in Figure 3.

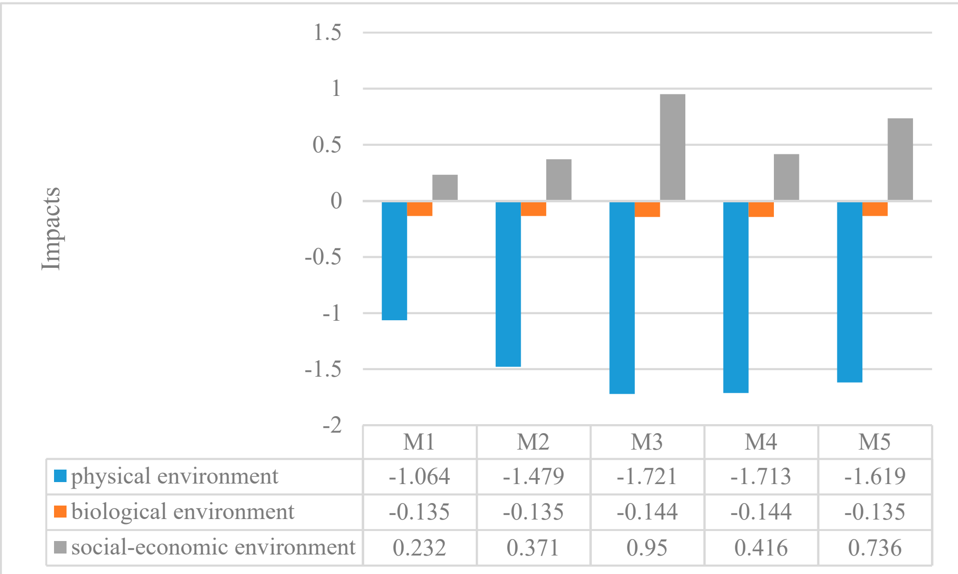

Figure 3. Physical, biological, and socio-economic environmental effects of the whole project corresponding with five different activity execution modes.

According to Figure 3, the amount of positive effects in the third execution mode is higher than the other activity execution modes. On the one hand, the amount of negative environmental effects of this execution mode is higher than the other execution modes. On the other hand, since each project activity can be separately performed in each execution mode, it will have a different duration, cost, and positive and negative environmental effects. The data of the urban water supply project are presented in Table 4.

Table 4. Project data based on duration, cost, and environmental impact of project activities.

Activity	Activity Mode	Duration	Cost	Environmental Impacts (Negative)	Environmental Impacts (Positive)
		-	-	-	+
2	M1	(11,14,17)	(990,1260,1530)	(0.08,0.26,0.46)	(0,0.1,0.3)
	M2	(7,10,13)	(854,1220,1586)	(0.16,0.34,0.54)	(0,0.1,0.3)
	M3	(4,7,10)	(860,1376,1892)	(0.36,0.54,0.74)	(0.3,0.5,0.7)
	M4	(5,8,11)	(584,1022,1460)	(0.16,0.34,0.54)	(0,0.1,0.3)
	M5	(9,12,15)	(1098,1464,1830)	(0.24,0.42,0.62)	(0.05,0.2,0.4)
3	M1	(21,25,29)	(640,960,1280)	(0,0.1,0.3)	(0,0.1,0.3)
	M2	(16,20,24)	(640,800,960)	(0.05,0.2,0.4)	(0.1,0.3,0.5)
	M3	(8,12,16)	(672,896,1120)	(0.15,0.3,0.5)	(0.15,0.3,0.5)
	M4	(12,16,20)	(336,400,464)	(0.25,0.4,0.6)	(0.1,0.3,0.5)
	M5	(18,22,26)	(720,880,1040)	(0.15,0.3,0.5)	0
4	M1	(4,5,6)	(128,160,192)	(0.03,0.16,0.36)	(0,0.1,0.3)
	M2	(3,4,5)	(168,224,280)	(0.13,0.3,0.5)	(0,0.1,0.3)
	M3	(2,3,4)	(160,240,320)	(0.2,0.36,0.56)	(0.3,0.5,0.7)
	M4	(3,4,5)	(104,208,312)	(0.26,0.43,0.63)	(0.05,0.2,0.4)
	M5	(4,5,6)	(224,280,336)	(0.13,0.3,0.5)	(0.2,0.4,0.6)
5	M1	(4,5,6)	456,570,684)	(0.15,0.35,0.55)	(0,0.1,0.3)
	M2	(2,3,4)	(276,414,552)	(0.3,0.5,0.7)	(0,0.1,0.3)
	M3	(1,2,3)	(366,488,610)	(0.15,0.35,0.55)	(0.3,0.5,0.7)
	M4	(3,4,5)	(154,308,462)	(0.3,0.5,0.7)	(0.05,0.2,0.4)
	M5	(4,5,6)	(448,610,732)	(0.3,0.5,0.7)	(0.3,0.5,0.7)
6	M1	(19,22,25)	(608,704,800)	(0.05,0.2,0.4)	(0,0.1,0.3)
	M2	(17,20,23)	(680,800,920)	(0.1,0.3,0.5)	(0.1,0.3,0.5)
	M3	(12,15,18)	(672,840,1008)	(0.2,0.4,0.6)	(0.4,0.6,0.8)
	M4	(14,17,20)	(672,816,960)	(0.3,0.5,0.7)	(0,0.1,0.3)
	M5	(16,19,22)	(784,952,1120)	(0.1,0.3,0.5)	(0,0.1,0.3)
7	M1	(9,11,13)	(72,88,104)	(0.1,0.3,0.5)	0
	M2	(5,7,9)	(80,112,144)	(0.2,0.4,0.6)	(0.1,0.3,0.5)
	M3	(1,2,3)	(48,96,144)	(0.2,0.4,0.6)	(0,0.1,0.3)
	M4	(2,4,6)	(32,64,96)	(0.3,0.5,0.7)	0
	M5	(6,8,10)	(96,128,160)	(0.2,0.4,0.6)	(0.1,0.3,0.5)
8	M1	(17,19,21)	(1088,1216,1344)	(0.05,0.2,0.4)	(0,0.1,0.3)
	M2	(13,15,17)	(1040,1200,1360)	(0.1,0.25,0.45)	(0.1,0.3,0.5)
	M3	(3,5,7)	(456,684,912)	(0.2,0.4,0.6)	(0.15,0.3,0.5)
	M4	(5,7,9)	(390,650,910)	(0.2,0.4,0.6)	(0,0.1,0.3)
	M5	(14,16,18)	(1120,1280,1440)	(0.05,0.2,0.4)	(0.5,0.7,0.9)

Table 4. *Cont.*

Activity	Activity Mode	Duration	Cost	Environmental Impacts (Negative)	Environmental Impacts (Positive)
		-	-	-	+
9	M1	(5,7,9)	(280,392,504)	(0.03,0.16,0.43)	(0,0.1,0.3)
	M2	(5,6,7)	(490,588,686)	(0.25,0.45,0.65)	(0,0.1,0.3)
	M3	(2,3,4)	(344,516,688)	(0.1,0.23,0.43)	(0.5,0.7,0.9)
	M4	(3,4,5)	(160,240,320)	(0.35,0.55,0.75)	(0.1,0.3,0.5)
	M5	(6,7,8)	(588,686,784)	(0.3,0.5,0.7)	(0.1,0.3,0.5)
10	M1	(11,13,15)	(990,1170,1350)	(0.08,0.26,0.46)	(0,0.1,0.3)
	M2	(7,9,11)	(854,1098,1342)	(0.16,0.34,0.54)	(0.1,0.3,0.5)
	M3	(5,7,9)	(1032,1376,1720)	(0.36,0.54,0.74)	(0.3,0.5,0.7)
	M4	(6,8,10)	(730,1022,1314)	(0.16,0.34,0.54)	(0.05,0.2,0.4)
	M5	(8,10,12)	(976,1220,1464)	(0.24,0.42,0.62)	(0.1,0.3,0.5)
11	M1	(6,8,10)	(144,192,240)	(0,0.1,0.3)	(0,0.1,0.3)
	M2	(4,6,8)	(128,192,256)	(0.13,0.3,0.5)	(0,0.1,0.3)
	M3	(1,2,3)	(120,160,200)	(0.06,0.23,0.43)	(0.3,0.5,0.7)
	M4	(3,4,5)	(48,96,144)	(0.2,0.36,0.56)	(0,0.1,0.3)
	M5	(5,7,9)	(160,224,288)	(0.06,0.23,0.43)	(0.3,0.5,0.7)
12	M1	(2,3,4)	(40,60,80)	(0.07,0.25,0.45)	(0,0.1,0.3)
	M2	(1,2,3)	(38,59,89)	(0.17,0.35,0.55)	(0.05,0.2,0.4)
	M3	(1,1,2)	(38,38,89)	(0.17,0.35,0.55)	(0.5,0.7,0.9)
	M4	(1,2,3)	(30,58,89)	(0.17,0.35,0.55)	(0.05,0.2,0.4)
	M5	(2,3,4)	(60,90,120)	(0.17,0.35,0.55)	0
13	M1	(18,22,26)	(1872,2288,2704)	(0.06,0.23,0.43)	(0,0.1,0.3)
	M2	(16,20,24)	(1920,2400,2880)	(0.06,0.23,0.43)	(0.05,0.2,0.4)
	M3	(13,17,21)	(2184,2856,3528)	(0.13,0.3,0.5)	(0.5,0.7,0.9)
	M4	(16,21,24)	(1920,2550,2880)	(0.13,0.3,0.5)	(0.1,0.3,0.5)
	M5	(18,22,26)	(2160,2640,3120)	(0.06,0.23,0.43)	(0.1,0.3,0.5)
14	M1	(22,26,30)	(2992,3536,4080)	(0.13,0.3,0.5)	(0,0.1,0.3)
	M2	(20,24,28)	(3040,3648,4256)	(0.13,0.3,0.5)	(0.1,0.3,0.5)
	M3	(18,22,26)	(3168,3872,4576)	(0.2,0.36,0.56)	(0.3,0.5,0.7)
	M4	(19,23,27)	(2888,3496,4104)	(0.13,0.3,0.5)	(0,0.1,0.3)
	M5	(21,25,29)	(3192,3800,4408)	(0.13,0.3,0.5)	(0.5,0.7,0.9)
15	M1	(4,6,7)	(227,341,398)	(0.16,0.36,0.56)	(0,0.1,0.3)
	M2	(3,5,7)	(185,308,431)	(0.23,0.43,0.63)	(0,0.1,0.3)
	M3	(1,2,3)	(156,234,312)	(0.23,0.43,0.63)	(0.3,0.5,0.7)
	M4	(2,3,4)	(81,162,242)	(0.23,0.43,0.63)	(0.1,0.3,0.5)
	M5	(4,6,8)	(246,370,493)	(0.23,0.43,0.63)	(0.3,0.5,0.7)

Any project activity can be performed in any of the given execution modes. Therefore, the total of different execution modes for the whole project is equal to 145. For example, the third execution mode with the shortest duration of 7 days is the best execution mode of activity 2 in terms of the duration. The fourth execution mode of activity 2, with a cost of USD 1022, is the best execution mode in terms of the cost. The first execution mode of activity 2, with an amount of negative environmental effects of 0.263, is the best execution mode, and the third execution mode of activity 2, with an amount of positive environmental effects of 0.5, is the best execution mode, which is depicted in Figure 4.

Figure 4. The best execution modes of activity 2 in terms of duration, cost, and positive and negative environmental effects.

The best execution modes of the other project activities are determined likewise. Therefore, based on the fuzzy CoCoSo multi-criteria decision-making method, the execution modes of each project activity are ranked. The criteria of time, cost, and negative environmental effects should be minimized and the criteria of positive environmental effects should be maximized. As a result, the ranking of the execution modes has been independently conducted 14 times for each project activity. Table 5 shows the findings of the best execution mode for each project activity (they are highlighted).

Table 5. Final ranking of project activities based on time–cost–environmental impact trade-off.

Activity	Activity Mode	Crisp SB	Crisp PB	K(ia)	K(ib)	K(ic)	K(i)
2	M1	0.3217	0.3214	0.1788	2.0852	0.6897	1.6208
	M2	0.3252	0.3245	0.1806	2.1065	0.2871	1.3365
	M3	**0.4664**	**0.4660**	**0.2593**	**3.0235**	**0.4120**	**1.9180**
	M4	0.3778	0.3763	0.2097	2.4451	0.3332	1.5512
	M5	0.3085	0.3083	0.1715	2.0000	0.2726	1.2689
3	M1	0.2579	0.2510	0.1628	4.2322	0.5607	2.3805
	M2	0.3351	0.3343	0.2141	5.5819	0.3375	2.7837
	M3	0.3946	0.3925	0.2518	6.5620	0.3969	3.2725
	M4	**0.4548**	**0.4529**	**0.2903**	**7.5674**	**0.4577**	**3.7737**
	M5	0.1553	0.0976	0.0809	2.0000	0.1276	1.0108

Table 5. *Cont.*

Activity	Activity Mode	Crisp SB	Crisp PB	K(ia)	K(ib)	K(ic)	K(i)
4	M1	0.3629	0.3600	0.1991	2.4430	0.7780	1.8635
	M2	0.2980	0.2938	0.1630	2.0000	0.2600	1.2473
	M3	**0.4650**	**0.4642**	**0.2559**	**3.1401**	**0.4083**	**1.9580**
	M4	0.3407	0.3391	0.1872	2.2970	0.2987	1.4325
	M5	0.3541	0.3539	0.1949	2.3925	0.3111	1.4920
5	M1	0.2736	0.2734	0.1525	2.0000	0.5308	1.4397
	M2	0.3002	0.3001	0.1673	2.1948	0.2600	1.3314
	M3	**0.5153**	**0.5152**	**0.2872**	**3.7676**	**0.4463**	**2.2851**
	M4	0.3497	0.3497	0.1949	2.5571	0.3029	1.5511
	M5	0.3556	0.3554	0.1981	2.5992	0.3079	1.5767
6	M1	0.4480	0.4434	0.1964	2.3374	0.7587	1.8013
	M2	0.4713	0.4697	0.2073	2.4677	0.3308	1.5554
	M3	**0.5875**	**0.5874**	**0.2588**	**3.0809**	**0.4130**	**1.9417**
	M4	0.3908	0.3781	0.1694	2.0160	0.2703	1.2708
	M5	0.3846	0.3788	0.1682	2.0016	0.2683	1.2617
7	M1	0.1914	0.1831	0.1353	2.0000	0.5336	1.4146
	M2	0.3144	0.3142	0.2271	3.3588	0.3635	1.9688
	M3	**0.3510**	**0.3508**	**0.2535**	**3.7497**	**0.4058**	**2.1979**
	M4	0.2350	0.2331	0.1691	2.5012	0.2707	1.4663
	M5	0.2977	0.2973	0.2150	3.1791	0.3440	1.8635
8	M1	0.2291	0.2288	0.1429	2.0000	0.5564	1.4418
	M2	0.2705	0.2704	0.1688	2.3625	0.2689	1.4089
	M3	**0.4120**	**0.4111**	**0.2568**	**3.5948**	**0.4092**	**2.1435**
	M4	0.3125	0.3085	0.1938	2.7122	0.3088	1.6173
	M5	0.3815	0.3805	0.2377	3.3277	0.3788	1.9843
9	M1	0.2749	0.2738	0.1804	2.8729	0.5953	1.8922
	M2	0.1920	0.1899	0.1256	2.0000	0.1930	1.1379
	M3	**0.4620**	**0.4597**	**0.3031**	**4.8261**	**0.4658**	**2.7450**
	M4	0.3746	0.3726	0.2457	3.9123	0.3776	2.2254
	M5	0.2210	0.2208	0.1453	2.3133	0.2233	1.3161
10	M1	0.3799	0.3791	0.1674	2.0000	0.7313	1.5922
	M2	0.4742	0.4737	0.2091	2.4977	0.3405	1.5785
	M3	**0.5191**	**0.5188**	**0.2290**	**2.7349**	**0.3728**	**1.7283**
	M4	0.4681	0.4666	0.2062	2.4629	0.3358	1.5565
	M5	0.4268	0.4265	0.1883	2.2485	0.3065	1.4210

Table 5. *Cont.*

Activity	Activity Mode	Crisp SB	Crisp PB	K(ia)	K(ib)	K(ic)	K(i)
11	M1	0.1660	0.1629	0.1501	2.3953	0.4546	1.5471
	M2	0.1393	0.1354	0.1253	2.0000	0.1898	1.1344
	M3	**0.3635**	**0.3600**	**0.3302**	**5.2692**	**0.4999**	**2.9876**
	M4	0.2146	0.2050	0.1915	3.0547	0.2899	1.7324
	M5	0.2241	0.2206	0.2029	3.2385	0.3072	1.8365
12	M1	0.3316	0.3311	0.1709	3.1011	0.5182	1.9137
	M2	0.3728	0.3720	0.1921	3.4860	0.2891	1.9013
	M3	**0.6394**	**0.6392**	**0.3298**	**5.9842**	**0.4963**	**3.2632**
	M4	0.3822	0.3813	0.1969	3.5733	0.2964	1.9489
	M5	0.2141	0.2133	0.1102	2.0000	0.1659	1.0910
13	M1	0.4504	0.4460	0.1794	2.0000	0.7476	1.6208
	M2	0.4903	0.4877	0.1957	2.1822	0.3162	1.4115
	M3	**0.5995**	**0.5995**	**0.2399**	**2.6753**	**0.3876**	**1.7302**
	M4	0.4731	0.4714	0.1890	2.1073	0.3053	1.3630
	M5	0.4901	0.4891	0.1959	2.1848	0.3166	1.4131
14	M1	0.5129	0.5110	0.1740	2.0000	0.7444	1.6105
	M2	0.5845	0.5838	0.1985	2.2822	0.3221	1.4611
	M3	0.6228	0.6225	0.2116	2.4326	0.3433	1.5573
	M4	0.5369	0.5345	0.1821	2.0928	0.2954	1.3399
	M5	**0.6878**	**0.6877**	**0.2338**	**2.6869**	**0.3792**	**1.7201**
15	M1	0.2632	0.2629	0.1448	2.0224	0.5237	1.4326
	M2	0.2602	0.2601	0.1432	2.0000	0.2244	1.1901
	M3	**0.5024**	**0.5023**	**0.2764**	**3.8616**	**0.4333**	**2.2973**
	M4	0.4317	0.4316	0.2376	3.3183	0.3723	1.9742
	M5	0.3603	0.3594	0.1980	2.7664	0.3104	1.6460

According to Table 5, the project can be implemented with the best execution mode of each activity within 102 days, at the total cost of USD 13,113, negative environmental effects of 5.2817, and positive environmental effects of 7.1250.

4. Discussion

In this research, five execution modes were considered for each project activity in order to obtain different combinations of duration, cost, and environmental impacts of the project. Environmental indicators of the case study construction project were identified using experts' opinions in three physical–chemical, biological, and socio-economic aspects. Then, the environmental impact of each execution mode of the project activities was evaluated using the Leopold matrix in terms of the identified indicator. The results showed that if the project activities are implemented with the third execution mode, the negative and positive environmental effects will increase. In addition, performing the project activities with the first execution mode leads to the least negative and positive environmental effects. In other words, the implementation of each project activity based on each execution mode has different positive and negative environmental effects, along with a different duration and cost. For example, the best execution mode in terms of the duration for activity 2 is the third execution mode, since it has the shortest duration. However, the third execution mode of activity 2 increases the cost by 34% compared to the execution mode with the lowest cost. In addition, the amount of negative environmental effects increases by approximately 106%. The amount of positive environmental effects of the third execution mode of activity 2 is optimal. Therefore, two criteria of the duration and positive environmental effects are desirable in the third execution mode of activity 2, whereas the other criteria of the cost and negative environmental effects are unfavorable compared to other execution modes of activity 2.

The CoCoSo multi-criteria decision-making method was exploited to rank the activity executive modes based on the four factors of duration, cost, positive environmental effects, and negative environmental effects. The execution modes of each project activity were ranked using the CoCoSo method based on these four criteria. The highest ranked execution mode was selected as the best execution mode for each project activity and the entire project was implemented based on the best execution mode of each activity. The findings showed that the duration of the entire project is approximately 7% longer than when all project activities are performed with their third execution modes. However, the improvement in the cost factor is 4% and the improvement in the positive environmental impact is 3%. In addition, the cost of the project is approximately 19% higher than when all project activities are performed with their fourth execution modes (which has the lowest cost), but a significant improvement of 14%, 7%, and 173% is achieved in terms of the duration, negative environmental impact, and positive environmental impact, respectively.

5. Conclusions

Today, the issue of environmental impacts in construction projects is of great importance. In addition to optimizing conventional project objectives, such as the duration and cost, project managers must also consider the environmental impacts of project activities. The environmental effects of each project activity depend on the resources used to execute that activity. The duration of an activity also has a relationship with the environmental impact. Moreover, reducing negative environmental effects and increasing positive environmental effects will have an impact on project costs [20].

The problem of minimizing the duration, cost, and environmental impacts of the implementation of construction projects is one of the most substantial challenges facing the executive managers of organizations. Therefore, in this study, a multi-criteria decision-making model was used to assist project managers and planners with selecting the best possible execution modes of project activities.

A lack of relevant research works, as well as difficulties in calculating and estimating the duration, cost, and environmental effects of each execution mode of project activities, can be mentioned as the main limitations of the present research. For future studies, it is suggested to apply the proposed method to other construction projects. In addition, other methods, such as LCA and ICOLD, should be used to calculate and evaluate the environmental effects of project activities. As another suggestion, it may be possible to calculate and evaluate the environmental effects of construction projects after accomplishment and during exploitation. Moreover, more attention can be given to greenhouse gas emissions for assessing the environmental impact. Furthermore, other project management criteria, such as the quality, risk, resources, etc., can also be considered for each activity execution mode.

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