



Evaluating Efficiency in Construction Projects with the TOPSIS Model and NDEA Method Considering Environmental Effects and Undesirable Data

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Abstract

Today, project stakeholders seek to reduce the total costs and durations of projects while increasing their quality levels. Also, the governments have paid more attention to the environmental effects of projects. This study tackles the time–cost–quality–environmental effects trade-off project scheduling problem. Various activity execution modes are evaluated using the network data envelopment analysis (NDEA) method to select the best modes in order to mitigate the environmental impacts, along with reducing the duration and cost of project implementation and enhancing the overall quality of the project. The method of ideal and anti-ideal virtual units is applied to rank the efficient execution modes. In addition, the TOPSIS method is utilized to rank the different execution modes of each activity. Finally, the results of two methods are compared. The findings show that the selection of an efficient execution mode for each activity leads to a trade-off between the four project objectives including time, cost, quality, environmental impacts. The shortest project duration and the lowest total project cost were obtained using the NDEA-Nuo method, the highest quality level was gained by the NDEA-INP method, and the minimum environmental impacts of the entire project were attained by the TOPSIS method. Also, the lowest amount of resource consumption was obtained using the TOPSIS method, so that the daily consumption amount of each resource was less than the other two methods. As a result, the project management team can apply either the NDEA or TOPSIS method based on the organizational policy.

Keywords Time–cost–quality–environmental trade-off · Data envelopment analysis (DEA) · TOPSIS · Efficiency · Construction project

1 Introduction

Project control and supervision is particularly important for project managers. A review of previous research shows that many researchers such as Covach et al. (1981), Bright and Howard (1981), and Riedel and Chance (1989) have taken early steps in searching for factors affecting project performance, with the main goal of improving the expected results of the project (Banihashemi and Khalilzadeh 2018). Time, cost, and quality are the three main criteria of projects

that all project managers are always looking for successful accomplishment of projects with the minimum possible duration and cost as well as the maximum quality level. Construction projects have been concerned as one of the most important causes of environmental pollution in recent years.

Environmental impact assessment (EIA) is an efficient method for preserving natural resources and protecting the environment. Therefore, most developed countries have introduced EIA into their regulations and the consequent approval of all projects (EPA 2007). This assessment involves forecasting and estimating all the environmental impacts in the execution of the projects. Today there are different methodologies to carry out EIAs (Peche and Rodríguez 2009).

The construction industry is a large, multi-faceted, and dynamic industry which encompasses a variety of engineering construction projects. Despite the fact that completion of construction projects (construction of highways,

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dams, buildings, etc.) has a direct impact on people's welfare and well-being, the implementation and development phases of these projects create numerous unwanted negative effects on their surroundings. Especially in urban areas, due to the high density of construction projects, they are a source of serious discomfort for residents and adjacent businesses. Near the areas where contractors conduct construction operations, they put up a sign saying: "We apologize for the inconvenience and disruption we are causing to the environment" (Çelik et al. 2017), but apology alone does no good for the environment. To ensure the preservation of the environment and to meet the goals of sustainable development, a new scientific approach and management tool called environmental impact assessment (EIA) was introduced in the early 1970s. The purpose of this approach was to ensure compliance with environmental standards, rules, and regulations in proposed policies, programs, proposals, and projects, and to establish a more sustainable form of development. Although it allows for location-setting based on ecological capability and economic needs, it will prevent the implementation of projects that have harmful effects on the environment, because the consequences and impacts of a project can be so extensive that any attempt to control, curb, or eliminate them can cost several times as much as the initial cost and impose enormous economic and social costs on the community. Therefore, EIA is a corrective mechanism for development plans which focuses on reducing undesirable environmental impacts, and even causes some plans to be entirely canceled. This approach enhances public participation, protection of human health, sustainable use of natural resources, and governments accountability, and results in reducing costs and minimizing the risk of environmental hazards (Du Pisani and Sandham 2006).

According to a comprehensive definition, environmental impact assessment "is a process of identifying and predicting the potential environmental impacts ... of proposed actions, policies, programs and projects, and communicating this information to decision makers before they make their decisions on the proposed actions" (Vanclay 2004). It is a planning tool for planners, managers, and decision makers and is intended to identify the type, scope, and probability of direct and indirect social and environmental changes resulted from policies and projects, and to design feasible procedures for alleviating the impacts (Momtaz 2005). In short, the EIA is a tool for managing the conflict between the environment and development and leads to enhancing the assurance that the development path is appropriate. Different aspects of environmental impact assessment are categorized as follows:

- *Physical* Climate, soil, and land
- *Ecological* The quantity and quality of surface water, air, sound, and soil

- *Biological* Plant and animal species, environmentally sensitive areas, natural habitats, and disease carriers
- *Socio-economic* Population, literacy, specialty, income, welfare, employment, and health (Turnley 2002).

Competition in the construction industry is increasing day by day as new firms are entering into market and the existing companies are enlarging their job opportunities. In order to gain competitive advantage against rivals, the construction companies aim to minimize the costs. However, this goal requires excellent planning and scheduling of construction projects. Project total time can be shortened by expediting critical activities with additional costs. Crashing a critical activity increases the construction cost of the activity, while decreases project time (Bettemir and Birgönül 2017). Therefore, due to the importance of time, cost and quality factors that have also been emphasized by the standard of the PMBOK, several studies have been reported recently investigating the trade-off between these two goals (time and cost) or three goals (time, cost, quality) (Taheri Amiri et al. 2018).

The main challenge facing project managers is to choose the right approach to find the optimal combination of time, cost, and quality of project activities in order to simultaneously achieve these three goals.

Reducing the environmental impact of project along with paying attention to the iron triangle, time, cost, and quality are the main focus of this research. In the recent decades, various methods have been proposed to optimize the three criteria of time, cost, and quality of project activities. Many researchers introduced mathematical programming models to deal with this kind of time–cost–quality trade-off problems (Kelley 1961; Meyer and Shaffer 1963; Hendrickson et al. 1989; Liu et al. 1995; Tareghian and Taheri 2006; Rahimi and Iranmanesh 2008; El Razek et al. 2010; Pagnoni 2012; Kosztyán and Szalkai 2018; Ballesteros-Perez et al. 2019).

Data envelopment analysis (DEA) has become a popular tool to evaluate the relative performance of a set of entities called decision-making units (DMUs) (Ghazi et al. 2020).

Hass et al. (2004) say data envelopment analysis (DEA) is the most common method of measuring performance which is widely used to evaluate the efficiency of organizational units. The efficiency of each unit is evaluated in comparison with other units, and each unit with the highest level of performance will be more efficient. DEA is a mathematical programming model that is used to estimate the efficient frontier. This method forms a frontier function which covers all the data, and it is therefore called the overlay analysis of a data set (Charnes et al. 1985).

The concept of frontier analysis suggested by Farrell (1957) forms the basis of DEA, but Charnes et al. (1978) initiated the recent series of studies on DEA.

Depending on the type and nature of the units evaluated, DEA is divided into two classical and network categories. If we consider the units evaluated as a black box that converts inputs into outputs, we are dealing with the former or classical concept in data envelopment analysis. The standard DEA models were developed to measure the efficiency of a DMU without considering its internal structure, while in real cases internal processes and sub-processes should be considered. The network DEA, on the other hand, refers to multi-stage processes, which internal structures play a key role in the efficiency assessment (Sharahi et al. 2019). Network DEA models are classical models that take into account the internal structure of the units being evaluated. These models were first introduced and presented by Fare and Grosskopf (2000).

The objective of DEA is to identify the DMU that produces the largest outputs by consuming the least inputs; such a DMU is considered efficient, with an efficiency score of 1. The efficiency scores are computed by using mathematical programming, which converts multiple input and output measures into a single measure of efficiency that is defined as the ratio of total weighted output to the total weighted input. The weights associated with the inputs and outputs of each DMU are obtained by performing the mathematical formulation so that the relative efficiency score for each DMU can be optimized (Huang et al. 2015).

All life cycle stages of projects with different characteristics and conflicting criteria require several decision makings; therefore, multi-criteria decision-making methods have been widely used in construction industry. Zhang et al. (2013) applied the fuzzy TOPSIS method to identify and rank the risks of hydropower projects. Maghsoodi and Khalilzadeh (2018) ranked the critical success factors of construction projects using the fuzzy TOPSIS technique taking time, cost, quality, and safety criteria, into consideration. Chen et al. (2020) used multi-criteria decision-making methods to optimize the investment portfolio of oil companies. They applied the TOPSIS method to determine the best compromise solution based on investor preferences. Ma et al. (2020) studied the project selection problem considering sustainability in an uncertain environment. They implemented their model in a paper company using the TOPSIS method. Tavana et al. (2020) developed a two-stage dynamic mathematical programming model taking uncertainty into account to select projects and exploited the fuzzy TOPSIS method for project evaluation. Given the fact that each project activity can be performed in several execution modes that are measured based on project main factors including time, cost, quality, and environmental impacts, the decision-making techniques can be used for selecting the best possible activity execution mode. Therefore, in this study, the TOPSIS method is used to identify the best execution modes of project activities.

A look at the research on efficiency evaluation in project management areas shows that although many studies have

been done on evaluating the efficiency of project management, these studies have a classic view on the project and evaluate the projects as a black box compared to other projects. In this study, the efficiency of the project is addressed from a different point of view, so that the structure of each project consisting of activities is considered as a multi-segment DEA model. Efficiency of the activities is evaluated based on the input sources of each activity and its desirable and undesirable outputs including cost, time, quality, and environmental effects (three basic factors of the project triangle plus environmental factor).

In the present study, the appraisal of efficiency in project management goes beyond the classical aspect and evaluates the activities within a project. For this purpose, the network structure of a project is considered as a model of parallel DEA for analyzing the data generated by the activities. Then, by taking account of the input sources of each activity and its important outputs, which are the three factors of time, cost, quality, and environmental impacts, the efficiency of each activity in different execution modes is evaluated. In other words, in the multi-mode resource-constrained project scheduling problem (MRCPSP), several modes are considered for the activities, and the optimal execution mode of each activity is determined through planning methods. In this study, the DEA method is used to evaluate the most efficient mode of executing each activity. In other words, the important innovation of this research is that the DEA method and efficiency evaluation of each activity's execution modes are used to examine the best combination of project execution modes.

To the best of the authors' knowledge, this method has not been used in the project scheduling literature so far. Therefore, the innovation of this research can be summarized in two points: First, in the field of project scheduling, the four factors of time, cost, quality, and environmental impacts are considered as the output of each activity, and project optimization is based on these four factors. Second, DEA is used to select the best execution mode for each activity. Performance evaluation is carried out with regard to inputs (resources) and outputs (time, cost, quality, and environmental impacts) and the outputs are divided into desirable and undesirable categories.

2 Mathematical Formulation

The Technique for the Order Preference by Similarity to Ideal Solution (TOPSIS) method was introduced by Hwang and Yoon (1981). The ordinary TOPSIS method is based on the concept that the best alternative should have the shortest Euclidian distance from the ideal solution (positive ideal solution) and at the same time the farthest from the anti-ideal solution (negative ideal solution). It is a compensatory aggregation method that compares a set of alternatives by identifying weights for each criterion (Wang et al. 2003).

In this method, an alternative that is nearest to the Positive Ideal Solution and farthest from the Negative Ideal Solution is chosen as optimal. A Positive Ideal Solution is composed of the best performance values for each alternative, whereas the Negative Ideal Solution consists of the worst performance values. The steps of the TOPSIS method are as follows:

Step 1: Structure the decision matrix by m alternative and n criteria (Eq. 1)

Step 2: Normalize decision matrix (Eq. 2).

Step 3: Construct weighted normalized decision matrix (Eq. 3).

Step 4: Determine the Positive Ideal Solution and Negative Ideal Solution (Eq. 4).

Step 5: Calculate the Euclidean distance between each alternative and Positive Ideal Solution and Negative Ideal Solution (Eq. 5).

Step 6: Calculate the relative closeness coefficient (Eq. 6).

Step 7: Rank the alternatives. The alternative with the largest value of closeness coefficient is considered as the best alternative (Petrović et al., 2019).

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \cdots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix}, \quad i = 1, 2, \dots, m, \quad j = 1, 2, \dots, n \quad (1)$$

$$W = [w_1 \ w_2 \ \cdots \ w_n]$$

$$R = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \cdots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix}, \quad r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (2)$$

$$v_{ij} = w_j * r_{ij}, \quad i = 1, 2, \dots, m, \quad j = 1, 2, \dots, n \quad (3)$$

$$A^+ = \{v_1^+, v_2^+, \dots, v_j^+, \dots, v_n^+\} = \{(\max_j v_{ij} | i \in I), (\min_j v_{ij} | i \in J)\}$$

$$A^- = \{v_1^-, v_2^-, \dots, v_j^-, \dots, v_n^-\} = \{(\min_j v_{ij} | i \in I), (\max_j v_{ij} | i \in J)\} \quad (4)$$

$$S_i^+ = \sqrt{\sum_{j=1}^n (V_{ij} - V_j^+)^2} \quad (5)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (V_{ij} - V_j^-)^2}$$

$$C_i = \frac{S_i^-}{S_i^- + S_i^+} \quad (6)$$

A review of studies using the DEA model in project management shows that these studies can be divided into two categories. The first category includes research projects that

examine the efficiency of different projects using a specific input and output set. These investigations are among the classic issues of data envelopment analysis. The second category includes research projects that use the DEA method to select a project portfolio and to rank different projects for investment. In other words, in a project portfolio management system, management is applied to a combination of projects with specific goals and conditions and is considered a higher level of project management in organizations. In this management system, the main purpose is to design and execute projects that can help the project-oriented organization achieve its strategic goal. Selection of appropriate projects, proper allocation of limited organization resources, fulfillment of strategic statement assertions, coordination and synergies in the portfolio of the organization's projects, and ensuring the health of organizational relationships of project managers are the most important theoretical foundations of this system (Ghasemzadeh et al. 1999).

In order to evaluate undesirable data, direct and indirect methods are used. The indirect methods convert the undesirable output values to desirable ones using a uniform descending function so that the converted data can become desirable outputs in the production possibility set. This is the same for undesirable inputs. In the direct method, the undesirable data are directly inserted into the main DEA models. The model hypotheses have therefore been modified to address the undesirable data (Liu et al. 2010).

Although direct methods directly involve undesirable outputs in DEA models, they change the principles of the technology sets structure so that the desirable outputs are properly taken into account. These methods are divided into three groups based on the type of disposability assumed for undesirable outputs: direct methods with weak disposability assumption for undesirable outputs, direct methods with extended strong disposability assumption for undesirable outputs, and direct methods with extended weak or strong disposability assumption for undesirable outputs according to their technical nature.

The assumption of weak disposability of outputs means that if an output vector is feasible, that is, it can be generated with an input vector, then any proportional reduction of the vector is also feasible. The basic idea of this definition is that undesirable outputs may not be able to be reduced freely and alone. In other words, reducing undesirable outputs comes with a cost (i.e., reducing desirable outputs or increasing inputs). The extended strong disposability assumption states that if more input is used, the undesirable outputs will increase, and the desirable outputs will decrease. Therefore, looking at undesirable outputs in the feasible production set reveals that they are similar to inputs.

Model (8) was presented by Yang and Pollitt (2010) in which x is the input vector and y^D , y^{US} , and y^{UW} are, respectively, desirable outputs, undesirable outputs with

strong disposability, and undesirable outputs with weak disposability. The model takes the undesirable outputs into account with two strong and weak disposability. Equation (7) represents the related technology.

$$T_V = \left\{ (x, y^D, y^{US}, y^{UW}) \left| \begin{array}{l} x \geq \sum_{j=1}^n \lambda_j x_j \\ y^D \leq \sum_{j=1}^n \lambda_j y_j^D \\ y^{US} \leq \sum_{j=1}^n \lambda_j Y_j^{US} \\ y^{UW} = \sum_{j=1}^n \lambda_j Y_j^{UW} \\ \sum_{j=1}^n \lambda_j = 1 \end{array} \right. \right\} \quad (7)$$

In Eq. (7), inequality constraints require that they follow the principle of strong disposability, and that equality constraints follow the principle of weak disposability. The condition that the sum of Lambda variables must be equal to one applies the principle of variable returns to scale to the model.

min θ

s.t.

$$\begin{aligned} \theta x_p &\geq \sum_{j=1}^n \lambda_j X_j \\ y_p^D &\geq \sum_{j=1}^n \lambda_j Y_j^D \\ \theta y_p^{US} &\geq \sum_{j=1}^n \lambda_j Y_j^{SU} \\ \theta y_p^{UW} &= \sum_{j=1}^n \lambda_j Y_j^{UW} \\ \sum_{j=1}^n \lambda_j &= 1 \end{aligned} \quad (8)$$

Due to the structure of activities in a project management network, the model presented in this study falls into the category of parallel multi-segment network models. In this section, the DEA model designed to evaluate this network structure is presented.

We use absolute or relative efficiency to evaluate units' performance. Absolute efficiency compares the unit under evaluation with existing standards. In relative efficiency, the unit under evaluation is compared with similar units available. Given the existence of desirable outputs (quality factor of each activity) and the undesirable outputs (time, cost, and environmental effects of each activity), the output vector will be divided into Y^D and Y^U , so that the undesirable outputs will be treated like inputs.

The Nuo model is one of the models used in the direct method, assuming weak disposability for the outputs. In this model, inputs are not taken into account, and the input-oriented CCR envelopment model is represented by Eq. (9).

min θ

s.t.

$$\begin{aligned} y_p^D &\geq \sum_{j=1}^n \lambda_j Y_j^D \\ \theta y_p^{UW} &= \sum_{j=1}^n \lambda_j Y_j^{UW} \\ \sum_{j=1}^n \lambda_j &= 1 \end{aligned} \quad (9)$$

The relevant dual problem is the problem of maximizing the ratio of the weighted sum of desirable outputs to the weighted sum of undesirable outputs.

The INP model assumes a strong feasibility for undesirable outputs in the direct method. In this model, undesirable outputs are considered as inputs. Model (10) shows this relationship.

min θ

s.t.

$$\begin{aligned} \theta x_p &\leq \sum_{j=1}^n \lambda_j X_j \\ y_p^D &\geq \sum_{j=1}^n \lambda_j Y_j^D \\ \theta y_p^U &\leq \sum_{j=1}^n \lambda_j Y_j^U \\ \sum_{j=1}^n \lambda_j &= 1 \end{aligned} \quad (10)$$

The dual of this problem is the problem of maximizing the ratio of the weighted sum of desirable outputs to the weighted sum of undesirable outputs plus the weighted sum of inputs.

Ideal and anti-ideal method was used to rank efficient decision-making units.

Assume that there are n DMUs to be evaluated, each DMU with m inputs and s outputs. We denote by x_{ij} ($i = 1, \dots, m$) and y_{rj} ($r = 1, \dots, s$) the values of inputs and outputs of DMU _{j} ($j = 1, \dots, n$), which are all known and positive. An IDMU and an ADMU can be defined as:

Definition 1 An IDMU is a virtual DMU, which can use the least inputs to generate the most outputs.

If we assume a strong disposability, in the INP method, where undesirable output is considered as input, IDMU is defined as the minimum undesirable inputs and outputs and the maximum desirable outputs. Assuming the principle of weak disposability based on the Nuo method, the ideal virtual unit is considered as the minimum of undesirable outputs and the maximum of desirable outputs.

Definition 2 An ADMU is a DMU, which consumes the most inputs only to produce the least outputs.

Due to having desirable and undesirable outputs, as more inputs are used, less desirable outputs and more undesirable outputs are produced.

Note that a virtual IDMU may not exist in practical production activity at least at current technical level, while a virtual ADMU may exist in practical production activity because the waste of resources is always allowed in the theory of PPS (Wang and Luo 2006).

According to the above definitions, we denote by x_i^{\min} , $y_r^{D\max}$, and $y_r^{U\min}$ the inputs, desirable outputs, and undesirable outputs of the IDMU, and by x_i^{\max} , $y_r^{D\min}$, and $y_r^{U\max}$ the inputs, desirable outputs, and undesirable outputs of the ADMU, respectively, where x_i^{\min} and x_i^{\max} are the minimum and the maximum of the i th input, $y_r^{D\min}$ and $y_r^{D\max}$ are the minimum and the maximum of the r th desirable outputs, and $y_r^{U\min}$ and $y_r^{U\max}$ are the minimum and the maximum of the r th undesirable outputs.

Although the IDMU is a virtual DMU, its production behavior should become the goal of each DMUs pursuing. According to the implication of efficiency, the efficiency of the IDMU (INP and Nuo methods) can be defined as:

$$\theta_{\text{IDMU-INP}} = \frac{\sum_{r=1}^{s'} U_r y_r^{D\max}}{\sum_{i=1}^m V_i x_i^{\min} + \sum_{r=s'+1}^s U_r y_r^{U\min}} \tag{11}$$

$$\theta_{\text{IDMU-Nuo}} = \frac{\sum_{r=1}^{s'} U_r y_r^{D\max}}{\sum_{r=s'+1}^s U_r y_r^{U\min}} \tag{12}$$

As such, the efficiency of the ADMU (INP and Nuo method) can be defined as:

$$\varphi_{\text{ADMU-INP}} = \frac{\sum_{r=1}^{s'} U_r y_r^{D\min}}{\sum_{i=1}^m V_i x_i^{\max} + \sum_{r=s'+1}^s U_r y_r^{U\max}} \tag{13}$$

$$\varphi_{\text{ADMU-Nuo}} = \frac{\sum_{r=1}^{s'} U_r y_r^{D\min}}{\sum_{r=s'+1}^s U_r y_r^{U\max}} \tag{14}$$

where U_r and V_i are the factor weights assigned to the r th output and the i th input.

It is obvious that the IDMU should be able to achieve the highest possible relative efficiency and ADMU efficiency is evidently worse than any other DMUs. Therefore, we may construct the following fractional and linear programming model in IDMU-INP method:

$$\begin{aligned} \text{Maximize } \theta_{\text{IDMU-INP}} &= \frac{\sum_{r=1}^{s'} U_r y_r^{D\max}}{\sum_{i=1}^m V_i x_i^{\min} + \sum_{r=s'+1}^s U_r y_r^{U\min}} \\ \text{st :} & \\ & \frac{\sum_{r=1}^{s'} U_r y_{rj}^D}{\sum_{i=1}^m V_i x_{ij} + \sum_{r=s'+1}^s U_r y_{rj}^U} \leq 1 \\ & U_r, V_i \geq \epsilon, \quad j = 1, \dots, n \end{aligned} \tag{15}$$

$$\begin{aligned} \text{Maximize } \theta_{\text{IDMU-INP}} &= \sum_{r=1}^{s'} U_r y_r^{D\max} \\ \text{st :} & \\ & \sum_{i=1}^m V_i x_i^{\min} + \sum_{r=s'+1}^s U_r y_r^{U\min} = 1 \\ & \sum_{r=1}^{s'} U_r y_{rj}^D - \sum_{r=s'+1}^s U_r y_{rj}^U - \sum_{i=1}^m V_i x_{ij} \leq 0 \\ & U_r, V_i \geq \epsilon, \quad j = 1, \dots, n \end{aligned} \tag{16}$$

And the following fractional and linear programming model in IDMU-Nuo method:

$$\begin{aligned} \text{Maximize } \theta_{\text{IDMU-Nuo}} &= \frac{\sum_{r=1}^{s'} U_r y_r^{D\max}}{\sum_{r=s'+1}^s U_r y_r^{U\min}} \\ \text{st :} & \\ & \frac{\sum_{r=1}^{s'} U_r y_{rj}^D}{\sum_{r=s'+1}^s U_r y_{rj}^U} \leq 1 \\ & U_r, V_i \geq \epsilon, \quad j = 1, \dots, n \end{aligned} \tag{17}$$

$$\text{Maximize } \theta_{\text{IDMU-Nuo}} = \sum_{r=1}^{s'} U_r y_r^{D \max}$$

st :

$$\sum_{r=s'+1}^s U_r y_r^{U \min} = 1 \tag{18}$$

$$\sum_{r=1}^{s'} U_r y_{rj}^D - \sum_{r=s'+1}^s U_r y_{rj}^U \leq 0$$

$$U_r, V_i \geq \epsilon, \quad j = 1, \dots, n$$

As an ADMU, the following fractional and linear programming model (INP method) is thus constructed:

$$\text{Minimize } \varphi_{\text{ADMU-INP}}$$

$$= \frac{\sum_{r=1}^{s'} U_r y_r^{D \min}}{\sum_{i=1}^m V_i x_i^{\max} + \sum_{r=s'+1}^s U_r y_r^{U \max}}$$

st :

$$\frac{\sum_{r=1}^{s'} U_r y_{rj}^D}{\sum_{i=1}^m V_i x_{ij} + \sum_{r=s'+1}^s U_r y_{rj}^U} \geq 1$$

$$U_r, V_i \geq \epsilon, \quad j = 1, \dots, n$$

$$\text{Minimize } \varphi_{\text{ADMU-INP}} = \sum_{r=1}^{s'} U_r y_r^{D \min}$$

st :

$$\sum_{i=1}^m V_i x_i^{\max} + \sum_{r=s'+1}^s U_r y_r^{U \max} = 1 \tag{20}$$

$$\sum_{r=1}^{s'} U_r y_{rj}^D - \sum_{r=s'+1}^s U_r y_{rj}^U - \sum_{i=1}^m V_i x_{ij} \geq 0$$

$$U_r, V_i \geq \epsilon, \quad j = 1, \dots, n$$

And the following fractional and linear programming model in ADMU-Nuo method:

$$\text{Minimize } \varphi_{\text{ADMU-Nuo}} = \frac{\sum_{r=1}^{s'} U_r y_r^{D \min}}{\sum_{r=s'+1}^s U_r y_r^{U \max}}$$

st :

$$\frac{\sum_{r=1}^{s'} U_r y_{rj}^D}{\sum_{r=s'+1}^s U_r y_{rj}^U} \geq 1 \tag{21}$$

$$U_r, V_i \geq \epsilon, \quad j = 1, \dots, n$$

$$\text{Minimize } \varphi_{\text{ADMU-Nuo}} = \sum_{r=1}^{s'} U_r y_r^{D \min}$$

st :

$$\sum_{r=s'+1}^s U_r y_r^{U \max} = 1 \tag{22}$$

$$\sum_{r=1}^{s'} U_r y_{rj}^D - \sum_{r=s'+1}^s U_r y_{rj}^U \geq 0$$

$$U_r, V_i \geq \epsilon, \quad j = 1, \dots, n$$

Let $\theta_{\text{IDMU-INP}}^*$ and $\theta_{\text{IDMU-Nuo}}^*$ be the optimum efficiency of the IDMU (INP or Nuo method). Since there exists such a possibility that the above LP model (Eq. 16 or 18) may have multiple optima, we utilize the following fractional programming model to determine the best possible relative efficiency of DMU_p under the condition that the best possible relative efficiency of the IDMU remains unchanged (Eq. 23 for INP method, Eq. 24 for Nuo method):

$$\text{Maximize } \theta_{p\text{-INP}} = \frac{\sum_{r=1}^{s'} U_r y_{rp}^D}{\sum_{i=1}^m V_i x_{ip} + \sum_{r=s'+1}^s U_r y_{rp}^U}$$

st :

$$\theta_{\text{IDMU-INP}}^* = \frac{\sum_{r=1}^{s'} U_r y_r^{D \max}}{\sum_{i=1}^m V_i x_i^{\min} + \sum_{r=s'+1}^s U_r y_r^{U \min}} \tag{23}$$

$$\theta_j = \frac{\sum_{r=1}^{s'} U_r y_{rj}^D}{\sum_{i=1}^m V_i x_{ij} + \sum_{r=s'+1}^s U_r y_{rj}^U} \leq 1$$

$$U_r, V_i \geq \epsilon, \quad j = 1, \dots, n$$

$$r = 1, \dots, s, \quad i = 1, \dots, m$$

$$\text{Maximize } \theta_{p\text{-Nuo}} = \frac{\sum_{r=1}^{s'} U_r y_{rp}^D}{\sum_{r=s'+1}^s U_r y_{rp}^U}$$

st :

$$\theta_{\text{IDMU-Nuo}}^* = \frac{\sum_{r=1}^{s'} U_r y_r^{D \max}}{\sum_{r=s'+1}^s U_r y_r^{U \min}} \quad (24)$$

$$\theta_j = \frac{\sum_{r=1}^{s'} U_r y_{rj}^D}{\sum_{r=s'+1}^s U_r y_{rj}^U} \leq 1$$

$$U_r, V_i \geq \varepsilon, j = 1, \dots, n$$

$$r = 1, \dots, s$$

where p is the DMU under evaluation and $\theta_{\text{IDMU-INP}}^*$ is the best possible relative efficiency of the IDMU (INP method) and $\theta_{\text{IDMU-Nuo}}^*$ is the best possible relative efficiency of the IDMU (Nuo method).

Let $\varphi_{\text{ADMU-INP}}^*$ and $\varphi_{\text{IDMU-Nuo}}^*$ be the worst efficiency of the ADMU for INP and Nuo methods. Then the following fractional programming model can be used to determine the worst possible relative efficiency of DMU _{p} under the condition that the worst possible relative efficiency of the ADMU keeps unchanged (Eq. 25 for INP method, Eq. 26 for Nuo method):

$$\text{Minimize } \varphi_{p\text{-INP}} = \frac{\sum_{r=1}^{s'} U_r y_{rp}^D}{\sum_{i=1}^m V_i x_{ip} + \sum_{r=s'+1}^s U_r y_{rp}^U}$$

st :

$$\varphi_{\text{ADMU-INP}}^* = \frac{\sum_{r=1}^{s'} U_r y_r^{D \min}}{\sum_{i=1}^m V_i x_i^{\max} + \sum_{r=s'+1}^s U_r y_r^{U \max}} \quad (25)$$

$$\varphi_j = \frac{\sum_{r=1}^{s'} U_r y_{rj}^D}{\sum_{i=1}^m V_i x_{ij} + \sum_{r=s'+1}^s U_r y_{rj}^U} \geq 1$$

$$U_r, V_i \geq \varepsilon, j = 1, \dots, n$$

$$r = 1, \dots, s, i = 1, \dots, m$$

$$\text{Minimize } \varphi_{p\text{-Nuo}} = \frac{\sum_{r=1}^{s'} U_r y_{rp}^D}{\sum_{r=s'+1}^s U_r y_{rp}^U}$$

st :

$$\varphi_{\text{ADMU-Nuo}}^* = \frac{\sum_{r=1}^{s'} U_r y_r^{D \min}}{\sum_{r=s'+1}^s U_r y_r^{U \max}} \quad (26)$$

$$\varphi_j = \frac{\sum_{r=1}^{s'} U_r y_{rj}^D}{\sum_{r=s'+1}^s U_r y_{rj}^U} \geq 1$$

$$U_r, V_i \geq \varepsilon, j = 1, \dots, n$$

$$r = 1, \dots, s$$

Definition 3 Let $\theta_{\text{IDMU-INP}}^*$ and $\theta_{p\text{-INP}}^*$ be the best possible relative efficiencies of IDMU and $\theta_{\text{ADMU-INP}}^*$ and $\varphi_{p\text{-INP}}^*$ be the worst possible relative efficiencies of ADMU for INP method. The relative closeness index of DMU _{p} to IDMU is defined as:

$$RC_{p\text{-INP}} = \frac{\varphi_{p\text{-INP}}^* - \varphi_{\text{ADMU-INP}}^*}{(\varphi_{p\text{-INP}}^* - \varphi_{\text{ADMU-INP}}^*) + (\theta_{\text{IDMU-INP}}^* - \theta_{p\text{-INP}}^*)} \quad (27)$$

$$RC_{p\text{-Nuo}} = \frac{\varphi_{p\text{-Nuo}}^* - \varphi_{\text{ADMU-Nuo}}^*}{(\varphi_{p\text{-Nuo}}^* - \varphi_{\text{ADMU-Nuo}}^*) + (\theta_{\text{IDMU-Nuo}}^* - \theta_{p\text{-Nuo}}^*)} \quad (28)$$

Note that the TOPSIS approach employs the distances of utility to define the relative closeness, while the RC index in this paper is defined using the distances of efficiency. Since the RC index integrates both the best and the worst possible relative efficiencies of each DMU, it thus provides an overall assessment for each DMU, based on which an overall ranking for the n real DMUs can be easily obtained.

3 Results and Discussion

The case study in this research is related to the implementation of a rural water pipeline project. Figure 1 shows the project network was comprised of 8 activities. The prediction relationships for the activities were Finish to Start type

Table 1 Project data

Activity number	Project activities	Execution modes	Resources			Time (undesirable output)	Cost \$ (undesirable output)	Quality (undesirable output)	Environmental impacts (undesirable output)
			Excavator (R1)	Unskilled labor (R2)	Skilled labor (R3)				
1	Equipping the ingot workshop	1	0	2	0	2	1000	0.80	0.30
2	Canal lining and drilling	1	0	3	1	14	1260	0.78	0.36
		2	0	7	1	10	1220	0.80	0.44
		3	0	5	2	8	1376	0.83	0.64
		4	0	10	1	7	1022	0.82	0.44
		5	0	7	1	12	1464	0.84	0.52
		6	0	5	2	10	1720	0.87	0.64
		7	0	10	1	10	1460	0.88	0.48
3	Spin the pipes	1	0	2	0	25	400	0.74	0.20
		2	0	5	0	20	800	0.80	0.30
		3	0	7	0	16	896	0.83	0.40
		4	0	10	0	12	960	0.90	0.50
		5	0	5	0	22	880	0.82	0.40
		6	0	7	0	18	1008	0.85	0.50
		7	0	10	0	14	1120	0.92	0.50
4	Channel regression and leveling	1	0	4	0	5	160	0.77	0.27
		2	0	7	0	4	224	0.80	0.40
		3	0	10	0	3	240	0.83	0.47
		4	0	13	0	2	208	0.86	0.53
		5	0	7	0	5	280	0.85	0.40
		6	0	10	0	4	320	0.88	0.53
		7	0	13	0	3	312	0.90	0.53
5	Welding and transfer of pipes to the floor of the canal	1	1	3	1	5	570	0.76	0.45
		2	2	3	1	3	414	0.80	0.60
		3	1	4	1	4	488	0.75	0.45
		4	2	5	1	2	308	0.85	0.60
		5	2	3	1	4	552	0.86	0.60
		6	1	4	1	5	610	0.82	0.45
		7	2	5	1	3	462	0.92	0.60
6	Tubing and steaming operations	1	0	4	0	22	704	0.78	0.30
		2	0	5	0	20	800	0.80	0.40
		3	0	6	0	17	816	0.81	0.50
		4	0	7	0	15	840	0.82	0.60
		5	0	5	0	22	880	0.82	0.40
		6	0	6	0	19	912	0.83	0.60
		7	0	7	0	17	952	0.84	0.60
7	Testing	1	0	1	0	11	880	0.82	0.40
		2	0	2	0	7	112	0.80	0.50
		3	0	3	0	4	96	0.81	0.50
		4	0	4	0	2	64	0.84	0.60
		5	0	2	0	8	128	0.83	0.50
		6	0	3	0	5	120	0.83	0.60
		7	0	4	0	3	96	0.87	0.60

Table 1 (continued)

Activity number	Project activities	Execution modes	Resources			Time (undesirable output)	Cost \$ (undesirable output)	Quality (undesirable output)	Environmental impacts (undesirable output)
			Excavator (R1)	Unskilled labor (R2)	Skilled labor (R3)				
8	Channel filling	1	0	8	0	19	1216	0.82	0.30
		2	0	10	0	15	1200	0.80	0.35
		3	0	6	1	6	684	0.74	0.50
		4	0	8	1	5	650	0.76	0.50
		5	0	10	0	16	1280	0.81	0.30
		6	0	6	1	7	798	0.75	0.44
		7	0	8	1	6	780	0.77	0.44

- The required resources for activity execution are changed and relocated in the third and fourth execution methods, which in turn affect the durations and costs of activities.
- In the fifth, sixth, and seventh execution methods, it is assumed that the required amount of resources for performing activities are constant; however, the activity durations are prolonged. This increase in activity duration affects other project objectives including cost, quality, and environmental impact.

The ideal and anti-ideal approach was used to rank decision-making units (activities' execution modes). The ideal virtual unit had the fewest inputs with the most outputs. Also, the anti-ideal unit had the highest input and the lowest output (Anagnostopoulos and Kotsikas 2010).

In the DEA method, the outputs are divided into two categories of desirable and undesirable outputs. Strong and weak feasibility is assumed for the undesirable outputs, and the DMUs are ranked with two methods of INP and Nuo. In addition, the TOPSIS method is used for ranking the DMUs. The basic principle of the TOPSIS method is to find the solution that has the shortest distance to the positive ideal solution and the maximum distance to the negative ideal solution. In this problem, undesirable inputs and outputs are negative and desirable outputs are positive. Table 2 displays the final ranking results.

According to the data analysis (Table 2), the most efficient execution mode for each activity ranks first. Table 3, Table 4, and Table 5 show the specifications for the most efficient execution mode of each activity by Network DEA (INP and Nuo methods) and TOPSIS model.

Implementation of this project is one of the top-ranked execution methods (DEA-INP) that resulted in a project duration of 63 days (Fig. 2), at a cost of \$5652, quality of 0.82375, and environmental impacts of 0.465.

Implementation of this project is one of the top-ranked execution methods (DEA-Nuo) that resulted in a project duration of 62 days, at a cost of \$4808, quality of 0.8175, and environmental impacts of 0.45125.

Implementation of this project is one of the top-ranked execution methods (TOPSIS) that resulted in a project duration of 87 days, at a cost of \$5144, quality of 0.79, and environmental impacts of 0.36.

The total cost of the project was derived from the sum of the costs of the activities and the quality and environmental impacts of the entire project from the average quality and environmental impact of each project activity. It should be noted that the first project activity had a fixed time, cost, quality, and environmental impact, and there was only one implementation mode.

The minimum duration of each activity based on the available execution methods was 45 days, and the maximum duration of each activity was 98 days. It also ranged between \$4308 and \$7130 for a cost factor of 0.77 and 0.86875, and an environmental impact factor of 0.3225 and 0.53375.

Figure 3 shows the status of the four objectives of time, cost, quality, and environmental impacts through using the two methods of network data envelopment analysis (INP and Nuo) and TOPSIS throughout the project. As shown in Fig. 3, the DEA method outperforms the two methods in terms of time and cost assuming weak feasibility (DEA-Nuo). Higher quality in the project is also related to the DEA method with the assumption of strong feasibility. The TOPSIS method has the lowest value of the environmental impact of the project. Comparison between these three methods shows that the DEA method is better than the other two methods, assuming the weak feasibility of undesirable outputs. Finally, the choice of each of these methods and determining the best execution mode for each project activity

Table 2 Results of project

Activity number	Execution modes	Network DEA				TOPSIS	
		RC (Nuo)	Rank	RC (INP)	Rank	RC	Rank
1	1
2	1	0.55452	4	0.365854	4	0.6615	1
	2	0.578206	3	0.374669	3	0.6146	2
	3	0.401571	6	0.375116	2	0.4862	5
	4	0.71615	1	0.387088	1	0.5437	3
	5	0.430957	5	0.339324	6	0.5153	4
	6	0.385569	7	0.340762	5	0.4184	7
	7	0.619697	2	0.335831	7	0.4547	6
3	1	0.408418	1	0.254948	3	0.6819	1
	2	0.28363	4	0.255998	2	0.5468	2
	3	0.292507	3	0.261674	1	0.4135	4
	4	0.355891	2	0.251662	4	0.3348	5
	5	0.209079	6	0.233754	6	0.4483	3
	6	0.20647	7	0.239766	5	0.3198	6
	7	0.266442	5	0.232233	7	0.286	7
4	1	0.269429	4	0.254966	4	0.6137	1
	2	0.251039	5	0.257063	3	0.5321	2
	3	0.31073	3	0.259013	2	0.4459	4
	4	0.381729	1	0.260831	1	0.4478	3
	5	0.201986	6	0.206258	6	0.4135	5
	6	0.1932	7	0.209579	5	0.2662	7
	7	0.313014	2	0.205456	7	0.2989	6
5	1	0.300518	5	0.296419	2	0.4671	4
	2	0.27457	7	0.303468	1	0.5211	3
	3	0.39376	4	0.295041	3	0.5284	2
	4	0.471549	2	0.294593	4	0.5418	1
	5	0.276044	6	0.285922	7	0.3781	7
	6	0.4125	3	0.288958	6	0.4116	5
	7	0.471965	1	0.289202	5	0.4049	6
6	1	0.290368	5	0.359299	2	0.6925	1
	2	0.331919	4	0.351052	3	0.5915	2
	3	0.406805	2	0.371794	1	0.4229	4
	4	0.418783	1	0.343636	4	0.3275	5
	5	0.25607	6	0.296806	5	0.5186	3
	6	0.228156	7	0.266039	7	0.2433	6
	7	0.348039	3	0.29213	6	0.2427	7
7	1	0.257417	7	0.179565	6	0.5180	3
	2	0.275844	4	0.20229	2	0.5559	1
	3	0.466843	1	0.208347	1	0.4873	5
	4	0.462622	2	0.191476	3	0.4881	4
	5	0.264481	6	0.18534	5	0.5383	2
	6	0.26897	5	0.185744	4	0.4710	6
	7	0.437299	3	0.176485	7	0.4704	7

Table 2 (continued)

Activity number	Execution modes	Network DEA				TOPSIS	
		RC (Nuo)	Rank	RC (INP)	Rank	RC	Rank
8	1	0.345023	6	0.155232	7	0.5180	3
	2	0.363536	5	0.239126	1	0.5559	1
	3	0.321089	7	0.176252	5	0.4873	5
	4	0.382121	4	0.212965	3	0.4881	4
	5	0.435064	2	0.217068	2	0.5383	2
	6	0.40772	3	0.158553	6	0.4710	6
	7	0.474649	1	0.191993	4	0.4704	7

Table 3 The most efficient way of executing each activity: Network DEA method (INP)

Activity number	Execution modes	Resources			Time (undesirable output)	Cost \$ (undesirable output)	Quality (undesirable output)	Environmental Impacts (undesirable output)
		Excavator (R1)	Unskilled labor (R2)	Skilled labor (R3)				
1	1	0	2	0	2	1000	0.80	0.30
2	4	0	10	1	7	1022	0.82	0.44
3	3	0	7	0	16	896	0.83	0.40
4	4	0	13	0	2	208	0.86	0.53
5	2	2	3	1	3	414	0.80	0.60
6	3	0	6	0	17	816	0.81	0.50
7	7	0	4	0	3	96	0.87	0.60
8	2	0	10	0	15	1200	0.80	0.35

Table 4 The most efficient way of executing each activity: Network DEA method (Nuo)

Activity number	Execution modes	Resources			Time (undesirable output)	Cost \$ (undesirable output)	Quality (undesirable output)	Environmental impacts (undesirable output)
		Excavator (R1)	Unskilled labor (R2)	Skilled labor (R3)				
1	1	0	2	0	2	1000	0.80	0.30
2	4	0	10	1	7	1022	0.82	0.44
3	1	0	2	0	25	400	0.74	0.20
4	4	0	13	0	2	208	0.86	0.53
5	7	2	5	1	3	462	0.92	0.60
6	4	0	7	0	15	840	0.82	0.60
7	3	0	3	0	4	96	0.81	0.50
8	7	0	8	1	6	780	0.77	0.44

depends on the policy of the project executive team, which of these four goals will have the highest priority.

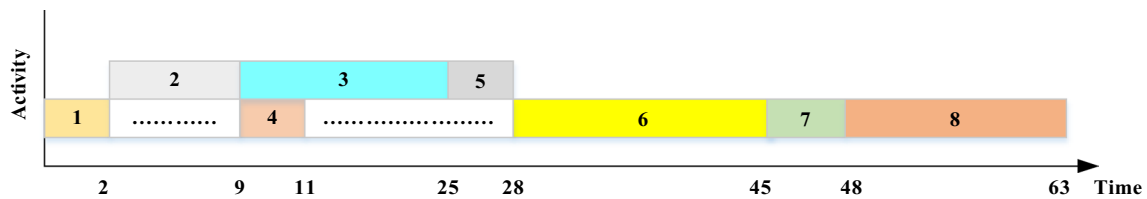
The use of resource R1 (excavator) in all three solution methods (TOPSIS, NDEA-Nuo, NDEA-INP) is equal. It should be noted that only activity 5 needs two excavators and the other activities do not require this type of resource. The highest fluctuation in resource usage is related to resource R2 (unskilled labor). As shown in Fig. 4, the lowest usage rate of the unskilled labor per day belongs to the TOPSIS

method, and the NDEA-INP method has the highest daily usage rate of the unskilled labor.

Also, the NDEA-INP method has the lowest usage rate of resource R3 (skilled labor). According to this method, the skilled labor is used for two activities for a period of 10 days. The duration is 16 days for 3 activities in DEA-Niu method and 16 days for 2 activities in TOPSIS method. This change in the resource usage and their replacement has affected the project goals. In the TOPSIS

Table 5 The most efficient way of executing each activity: TOPSIS method

Activity number	Execution modes	Resources			Time (undesirable output)	Cost \$ (undesirable output)	Quality (undesirable output)	Environmental impacts (undesirable output)
		Excavator (R1)	Unskilled labor (R2)	Skilled labor (R3)				
1	1	0	2	0	2	1000	0.80	0.30
2	1	0	3	1	14	1260	0.78	0.36
3	1	0	2	0	25	400	0.74	0.20
4	1	0	4	0	5	160	0.77	0.27
5	4	2	5	1	2	308	0.85	0.60
6	1	0	4	0	22	704	0.78	0.30
7	2	0	2	0	7	112	0.80	0.50
8	2	0	10	0	15	1200	0.80	0.35

**Fig. 2** Project scheduling (Network DEA-INP)

method, the project duration is the highest, the project cost is middle, the project quality is the lowest level, and the environmental impacts are the lowest compared to the other two methods. Therefore, the NDEA-Nuo method has the best performance in terms of time and cost, the NDEA-INP method has the best performance in terms of quality, and the TOPSIS method has the best performance in terms of environmental impacts.

4 Conclusions

One of the tasks of project managers is project planning so that they can accomplish the project with the highest quality within the least time, cost, and environmental impacts. In project scheduling, it is often possible to speed up project completion time by reducing the time spent on some activities and paying additional costs which may lead to either decreasing or increasing the quality of activities. Hence, in project scheduling problems, several execution

modes with different combinations of time, cost, quality, and environmental impacts with consumable resources are considered for the activities, and the best possible combination of execution modes is sought out for each activity using different methods. In this paper, the DEA method was used to evaluate the performance of the execution modes of each activity in the project network. For this purpose, the project network was considered as a DEA model consisting of parallel activities, and the efficiency of different execution modes for each activity was calculated by defining the inputs and outputs of each activity. The input of each activity consists of different sources, and its outputs are time, cost, quality, and environmental impacts of its execution. Due to the nature of numbers, the DEA models with desirable and undesirable outputs were used. In order to rank the decision-making units (execution mode of each activity) the ideal and anti-ideal virtual units method was used in desirable and undesirable output mode. The results showed that using the efficient execution method in each execution mode (DEA-Nuo) led to

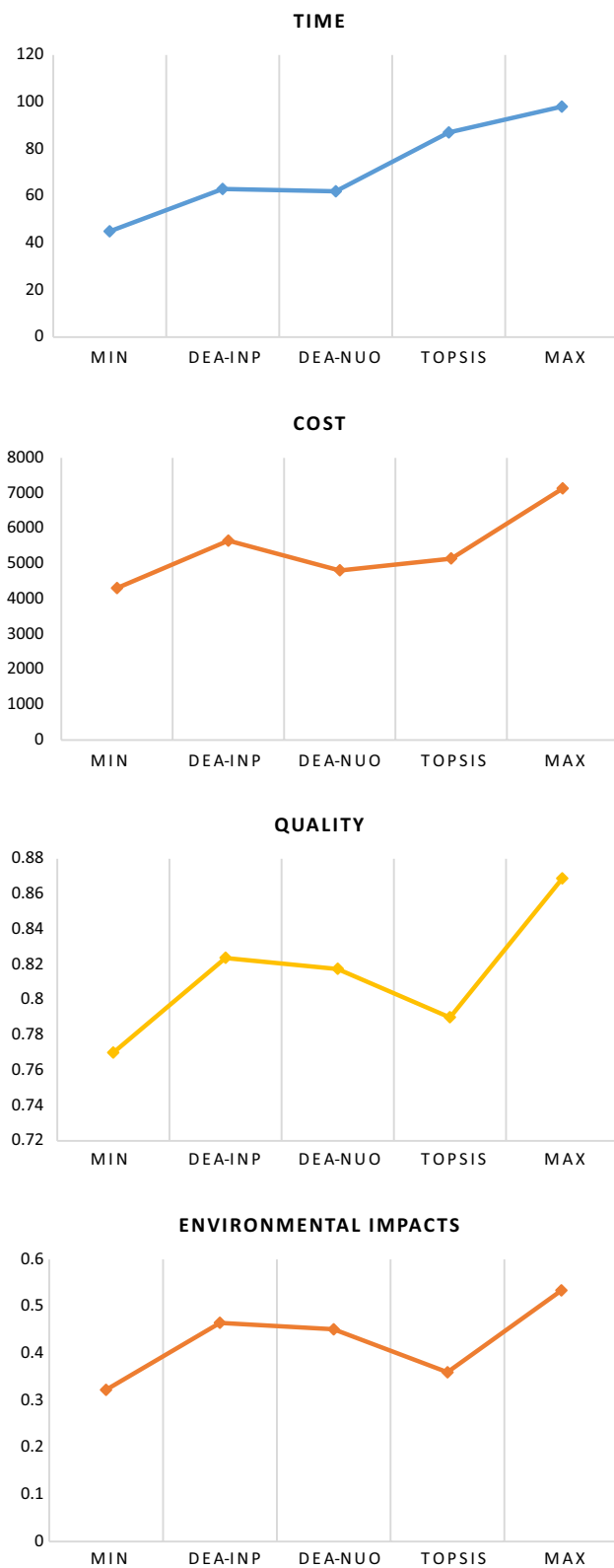


Fig. 3 Time–cost–quality–environmental impacts of project (DEA and TOPSIS)

project execution with the highest quality and within the least time and at the least cost and with the least amount of environmental impacts.

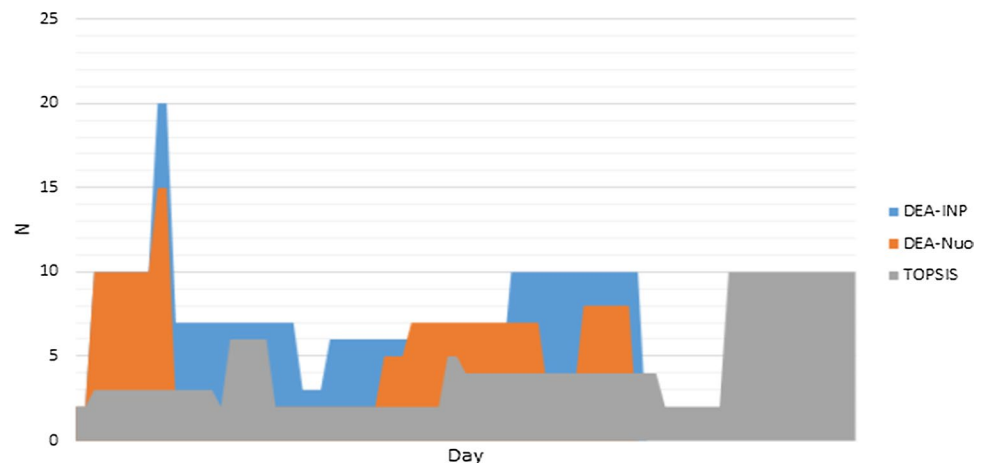
Time, cost, and quality are the three key criteria of a project that all project managers are always looking for successful accomplishment of projects with the shortest possible time, the lowest possible cost, and the highest level of quality. Past studies have not addressed the environmental impact factor of project implementation. The main challenge facing project managers is to choose the right approach to find the optimal combination of time, cost, quality and environmental impact of project activities. The main goal of this research is how to trade-off these four criteria in the project with regard to the inputs consumed by each activity. In this paper, the DEA method was used to evaluate the efficiency of different modes of performing activities. Therefore, this study can help project managers to choose the most appropriate execution modes for their activities to complete projects with the lowest time, cost, and environmental impacts along with the highest quality.

Furthermore, ranking of the execution modes of activities was calculated using TOPSIS method, which is also compared using the network data envelopment analysis method. The use of either of these two methods to evaluate the optimal execution modes of the activities depends on the project managers’ idea of which of the four objectives of time, cost, quality, and environmental impacts are more important for themselves, the stakeholders, and the environment around the project. The NDEA method was used to evaluate the efficiency of the different execution modes of project activities, and the TOPSIS method was applied to rank the activity execution modes. These methods can be implemented in large projects with several activities.

In order to reduce the calculations, a part of a construction project was considered as a real case study in this paper.

Lack of research resources as well as difficulties in calculating and estimating the four factors of time, cost, quality, and environmental impacts in each execution mode of project activities are the limitations of the present research. Based on the results of this study, it is suggested that researchers implement the proposed method in other construction projects or use other methods to rank inefficient units for future studies. Also a comparison between the methods used in this study with other four-objective planning methods in equilibrium problems is suggested as a worthwhile effort. Furthermore, to better deal with uncertain environment, fuzzy sets should be applied.

Fig. 4 The comparison of the usage rate of resource R2 per day (obtained by the three methods)



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