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OPTIMIZING THE TIME-COST-QUALITY TRADE-OFF PROBLEM BY CONSIDERING RISK AND EFFICIENCY FROM THE POINT OF VIEW OF THE WEED OPTIMIZATION ALGORITHM

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Abstract:

In previous years, extensive scientific research has been done in the field of time-cost and time-cost-quality balance. Most of them have been to optimize the problem and add other parameters such as quality, delay, etc. In total, all these efforts have tried to bring the most realistic conditions of the project into the problem. One of the essential things that should be considered in any project is the efficiency of each activity. If each of the project activities is implemented in the most efficient way possible, it can be claimed that the project is in an optimal state in terms of performance. In this research, the optimization of the time-cost-quality-risk problem has been done by using the data envelopment analysis method and the weeding algorithm. Then, the proposed approach was evaluated to determine the most efficient implementation method of each of the activities in a case study (construction project). This research approach can help project managers identify the most efficient way of implementing project activities.

Keywords: efficiency, desirable output, undesirable output, data coverage analysis

1. INTRODUCTION

Construction project planning is a fundamental and challenging task in construction project management (PMI, 2017). Determining the resource utilization rate and efficient construction methods is a challenging goal. The challenges of this issue are not only due to the existence of different implementation modes for construction activities; rather, there are several limitations, such as resource availability, technological limitations, and specific requirements that must be considered in the project (Zhou et al., 2013). For example, the cost, time, and quality of excavation work mainly depend on the availability of equipment, technical specifications, and their limited capacity. To reduce the time of excavation activity, the contractor may decide to increase the number of pieces of equipment used and the size of the equipment or increase the working hours, taking into account technical limitations such as the type of soil and the geographical location of the project. However, the number of equipment available to the

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contractor is limited, and additional equipment or the use of equipment and machinery with greater capacity increases the cost of excavation. On the other hand, contractors may decide to operate around the clock; however, in such a situation, additional costs, such as the cost of lighting equipment, etc., should be included in the analysis. In addition, night shift work may jeopardize the quality of work (Wang et al., 2019).

Also, night shifts may bring financial and life risks; Based on this, different implementation methods of construction activities should be analyzed in the planning stage to identify how to use the available resources optimally and achieve the best performance of the project goals in terms of time, cost, quality, and risk; In other words, the execution mode of each activity should be chosen in a way that leads to the optimal use of available resources and finally achieving the best possible combination of project goals. Achieving this goal requires the development of an optimization model that can analyze the existing execution modes for all activities in construction projects in order to simultaneously shorten the duration of the project, minimize the total cost, and maximize the quality of the project and reduce the risk of the whole project; In addition, each activity has an acceptable level of efficiency.

Considering the factors affecting project implementation, trying to reduce project time has always been a challenge for project managers (Baghrepour et al., 2018). The time-cost trade-off problem attracted the attention of project managers in the late 1950s. During different years, the initial time-cost trade-off model was developed by different researchers from different aspects. One of the important development issues of the initial model has been the use of the method of solving these problems. In recent decades, various methods have been presented to optimize the three criteria of time, cost, and quality of project activities. Many researchers introduced mathematical programming models to solve time-cost-quality trade-off problems (Kelly, 1961; Hendrickson et al., 1989; Liu et al., 1995; Abdul Razak et al., 2010; Pagnoni, 2012; Wang et al., 2019; Lotfi et al., 2022; Ahmadi Moghadam et al., 1400; Farooqi et al., 2018 and...). A review of previous studies shows that many researchers such as Kovach et al. (1981), Bright and Howard (1981), and Riddle and Chance (1989) have taken initial steps in searching for factors affecting project performance to improve the expected results of the project (Banihashmi and Khalilzadeh, 2018).

Mohagheghi, V. et al. (2017) Introduced a practical model to select the best and the most proper project portfolio while considering project investment capital, return rate, and risk. The ever-changing and highly uncertain environment of projects is addressed by utilizing interval type-2 fuzzy sets.

Shahriari, M. (2017). Proposed intuitionistic fuzzy VIKOR indicates the degree of satisfaction and dissatisfaction of each alternative with respect to each criterion and the relative importance of each criterion, respectively, by degrees of membership and non-membership. Thus, the ratings for the importance of criteria, DMs, and alternatives are in linguistic variables and expressed in intuitionistic fuzzy numbers. Using IFS aggregation operators and with respect to subjective judgment and objective information, the most suitable alternative is indicated among potential alternatives.

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Nikoomaram, H. et al. (2010). Presented a new TCT based on capital cost that have a great impact on the optimum results in capital- intensive projects, meaning that when crashing in the starting activities in a project, the extra investment will be tied in until the end of the project.

Data Envelopment Analysis (DEA) is the most common performance measurement method widely used to evaluate the efficiency of organizational units. In this method, the efficiency of each unit is evaluated in comparison with other units, and any unit with the highest performance level will be more efficient (Martin et al., 2000). DEA is a mathematical programming model used to estimate the efficient frontier. This method forms a boundary function that covers all the data and is therefore called data envelopment analysis (Charnes et al., 1985).

In this study, an attempt has been made to optimize the time-cost-quality-risk balance problem by considering the level of activity efficiency; the main innovation of the present study compared to other studies is considering the efficiency of each activity in the optimization process and using the data envelopment analysis method. In this regard, the general framework of the present research is as follows: in the second part, the experimental framework and the background of the research are discussed. The third part presents the research methodology and model. The fourth part is dedicated to presenting the results, and the fifth part is dedicated to discussing and summarizing the issue.

2- Experimental framework and research background

Ahmadi Moghadam et al. (1400), in research presenting a model with three objective functions, solve the problem of balancing time, cost, and quality in project planning. In addition to considering different implementation methods for each activity, they define compensatory activities for some activities to prevent quality reduction. Their model also covers various costs, including incentive costs and fines. Genetic algorithm is also used to solve the model. Farooqi et al. (2018), in a research aimed at providing a model and solving the project scheduling problem with limited resources with multiple objectives of reliability, risk, time and cost of the project in a discrete state, show that by considering the ability of multiple compression as well as the same execution modes It is a subset of activities. Mahmoudzadeh and Zare (2017), in research using the DAT model, evaluate the updating of the tunnel's expected time and costs during construction. In this research, during the construction, real geological data is available for the excavated sections of the tunnel, and the geological uncertainties for these sections are completely eliminated. The results of this research showed that updating the data during the construction in order to inform the contractors and employers of the project in accepting the amount of risk and providing suggestions for the construction of the unexcavated sections of the tunnel is very helpful.

Shafiei et al. (2017) by presenting a mathematical dual-objective model, has prepared the conditions for creating a balance between compression, saving money and delaying the execution time of activities, so that a suitable tool is available to decision makers to make decisions regarding the execution time of each activity. The activity should be provided for the completion of the project according to the available facilities and the time available. In an article, Padayar et al. (2016) discussed the optimization of the time-cost problem considering

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the limitations of resources and cash flows. This paper uses the multi-objective gravity search algorithm (MOGSA) to solve the problem. Then, the performance of the proposed algorithm has been compared with the NSGA-II algorithm from several points of view. The results of this research show that the proposed algorithm performs better than the NSGA-II algorithm. Alikhanzadeh et al. (2013) investigate the balance of cost, quality and time. This study uses mathematical models and linear programming to find quantitative answers for project cost, time and quality management. In this research, the quality of the project is separated according to the quality of raw materials and materials and the quality of implementation, and the quality of materials can be selected according to the type of product and its supplier, and the quality of project implementation can also change according to the time constraints of each activity. In a research, Sadeghi and Tavakoli Moghadam (2012) divided the project scheduling problem with limited resources and multi-state activities (the possibility of choosing different implementation methods for activities) into two sub-problems: assigning implementation methods to activities and then scheduling activities in order to minimize the completion time. Project. In this research, after determining each activity's implementation method, the activity's time and resource consumption is determined based on the chosen method for its implementation and a random programming is created for it. Then it performs a local search method to improve the program. This paper proposes a new penalty function for non-sortable lists in terms of non-renewable resources. The performance of the proposed solution method is compared with the best solution methods proposed so far for this problem based on the stopping criteria of the solution time and the number of generated schedules. Mahdizadeh and Mohsenian (2013) analyze the problem of cost-time and quality balance problem in random environments by using multi-objective stochastic programming and using stochastic constrained compromise programming to solve the model. Finally, to ensure the model's effectiveness, it is examined in a real project in the liquid gas tank deployment field. Jovanmardi et al. (2019) in an article titled time-cost optimization considering resource limitations by genetic algorithm, multi-objective model based on meta-exploration search by genetic algorithm (GAs) and based on the NSGA-II techniques, they have presented to improve the two-dimensional time-cost Pareto front. In his research, he showed the concept of multi-objective optimization of the TCO model with a simple manual example, and stated his results that the model is effective in helping project decision makers to achieve optimal time and cost simultaneously.

Lotfi et al. (2022) investigate the problem of time-cost-quality-energy-environment in the implementation of projects using a solid approach and shows its feasibility in the form of a case study (bridge building project in Tehran). This study has been done to consider the elements of sustainability in project scheduling and uncertainties in their modeling. To model the study problem, robust nonlinear programming that includes cost, quality, energy, and pollution level objectives is applied with resource constraints. Ekin et al. (2021) propose a stochastic model to analyze the balance problem between time, cost and quality and compare its results with two meta-heuristic algorithms (particle swarm optimization and genetic algorithm). They showed that the proposed model provides better solutions than these algorithms regarding total project cost during different execution times. Askarifar et al. (2021)

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presented a multi-objective model with four objective functions, including minimum cost, risk, and social and environmental effects, to reduce project delay and use the epsilon constraint method to solve the model. Then a case study has been developed to implement the different stages of the proposed model. Tomak and Jaskoski (2021) provide criteria to evaluate the preferences of construction project managers for sustainable planning and organization of construction projects, emphasizing the criterion of project time reduction and cost reduction. This information was obtained from surveys conducted among management employees of different levels (74 people). Alzard et al. (2019) uses the fuzzy multi-criteria decision-making model, the optimization algorithm based on fuzzy logic and the analytic hierarchy process to analyze the trade-off between time and cost and choose the best option in construction projects. In a research, Mahmoudi and Faizzadeh (2018) investigated the failure of projects based on the factors of cost, time, quality, risk and discount rate and presented a model that has reduced the existing uncertainties to a significant extent by fully covering the project risk. In this research, the factors affecting the compression of the project were first investigated and then a gray linear programming model was proposed to solve it. The findings of this research showed that not paying attention to project risks reduces the probability of project success in the future. The model proposed by the researchers reduces the existing uncertainties to a significant extent by fully covering the risks of the project. Zhai et al. (2017) presented a dynamic scheduling method to minimize the cost of electricity that uses renewable energy from wind turbines. The model used in this research is the multi-objective genetic algorithm, which mostly provided a mathematical model for this problem. This algorithm updates the cost of electricity and wind power every hour. Su et al. (2017) simplified a classic project planning to solve complex and large problems.

The simplification of the project made the non-linear mathematical models of the time-cost balancing problem of the project to be solved through precise methods and to have more reliability while accelerating the achievement of results. Using NSGAII and sorting in non-dominated data, Shahriari (2016) presents a solution for the discrete time-cost trade-off problem, which ultimately leads to the presentation of a function to consider the decision-maker's utility in the compression problem by considering the time value of money and trade-off criteria. It was compressed by the amount. Ahadian et al. (2016) in a research optimized the objective functions of time, cost and quality by considering project delays. Seputra and Latifiati (2015) presented a model to measure project reliability, considering time and cost as objectives concerning resource availability under uncertainty. They also used Monte Carlo simulation to solve this problem and obtained acceptable results. Zarei and Hasanpour (2015), reported that they presented a multi-objective project scheduling problem considering resource constraints with positive and negative cash flow. This research aims to increase the net present value and reduce the project completion time. Since this problem is considered one of the most difficult problems, meta-heuristic algorithms have been used to solve this problem. Their results showed that spending more money can affect the dimensions of the problem, including time. It is clear that spending more money in exchange for resources such as specialized labor, advanced equipment and machinery, etc., reduces project completion time. Another factor that

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changes in response to higher costs is the quality of the project. Therefore, the quality of the project should also be considered between the goals of the project to balance.

Noura, AA. Et al. focused on the latter work in proposing a new method that requires considerably less computation. Then, by proving a selected theorem, we show that our proposed methodology is indeed equivalent to that of Cooper et al. Aziz et al. (2014) in research entitled, intelligent optimization for massive construction projects using artificial intelligence, presented a developed model that includes the basic concept of critical path method and multi-objective genetic algorithm simultaneously. The main purpose of this model is to introduce practical support for the horizontal and vertical combination of large construction planners who need to optimize the utilization of resources to minimize the project's duration and costs while simultaneously maximizing its quality. For this purpose, they introduced a software called Intelligent Critical Path Method System (SCPMS). Their results showed that this software has the necessary efficiency for time compression. Kim et al. (2012) proposed a project scheduling method in terms of three variables: quality, cost, and time. They used the mixed integer programming method to solve the model and evaluated the model in a manufacturing plant to test its efficiency of the model. Tariqian and Taheri (2006) developed three binary integer programming models in the DTCQTP problem on the three parameters of cost, time, and quality, in which the cost and quality of the activities were presented discretely and with a non-renewable resource. The review of the literature related to the research topic shows that no research examines the issue of time, cost, quality, risk, and efficiency at the same time. In the current research, the data envelopment analysis method has been used to evaluate the most efficient mode of execution of each activity; In other words, the important innovation of this research is that the DEA method and the evaluation of the efficiency of the implementation modes of each activity are used to investigate the best combination of project implementation modes.

3. RESEARCH METHODOLOGY

In this research, the DEA method has been used to evaluate each activity's most efficient implementation mode. The research model has n activities (i=1,...,n) where each activity has 3 execution methods (j=1,...,3) and each of the execution methods has time $\widetilde{T} = (t_1, t_2, t_3)$, cost $\tilde{C} = (c_1, c_2, c_3)$, the quality $\widetilde{Q} = (q_1, q_2, q_3)$ and the risk $\widetilde{R} = (r_1, r_2, r_3)$are specific to the project contractor.

In this research, efficiency evaluation is done based on inputs (resources) and outputs (time, cost, quality, and risk) and the outputs are divided into two categories, favorable and unfavorable.

DEA is a non-parametric performance evaluation model to estimate the efficiency of a unit compared to units with similar characteristics and objectives (Mardani et al., 2017; Korunakos et al., 2019). In data coverage analysis, there are different models to measure efficiency. The CCR model is the first data envelopment analysis model introduced by Charnes, Cooper, and Rhodes (1978) to estimate the relative efficiency of decision-making units (DMUs). In this model, to determine the highest efficiency ratio and involve the number of inputs and outputs

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of other decision-making units in determining the optimal weights for the unit under investigation, the following basic model was proposed:

$$\begin{aligned}&\text{Max } \frac{\sum_{r=1}^{s} u_r y_{ro}}{\sum_{r=1}^{s} v_i x_{ro}}\\ &\text{s.t.}\\ &\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{r=1}^{s} v_i x_{ij}} \leq 1\,, j = 1,2,\dots,n\\ &u_r \geq 0\,, v_i \geq 0\end{aligned} \tag{1}$$

With the suggestion of Charnes and Cooper, the CCR model was specified as follows for ease of calculation by applying the restriction

$\sum_{i=1}^{m} v_i\, x_{i0} = 1$:

$$\begin{aligned}&\text{Max} \sum_{r=1}^{s} u_r y_{ro}\\ &\text{s.t.}\\ &\sum_{i=1}^{m} v_i x_{io} = 1\,, \sum_{r=1}^{s} u_r y_{rj} - \sum_{r=1}^{s} v_i x_{ij} \leq 0\,, \qquad j = 1,2,\dots,n\\ &u_r \geq 0\,, v_i \geq 0\end{aligned} \tag{2}$$

This model is known as CCR.I multiple model which is input oriented.

Another common model in DEA, which is also used in this research, is the CCR.IO model, which is both input and output oriented. In this model, the goal is to provide a model to improve the performance of inefficient units that have both input-oriented and output-oriented nature; In other words, the goal is to present a model that follows the reduction of inputs and the increase of outputs at the same time as a solution to improve the efficiency of inefficient units.

$$\begin{aligned}&\text{Max} \sum_{r=1}^{s} u_r' y_{ro} - \sum_{r=1}^{s} v_i' x_{io}\\ &\text{s.t.}\\ &\sum_{r=1}^{s} u_r' y_{rj} - \sum_{i=1}^{m} v_i' x_{ij} \leq 1\,, \qquad j = 1,2,\dots,n\\ &\qquad u_r' \geq 0\,, v_i' \geq 0\end{aligned} \tag{3}$$

In this research, following Banihashmi and Khalilzadeh (2020) and taking into account the presence of desirable output (quality level of each activity) and undesirable output (time, cost

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and risk of each activity) in the model, the output vector is divided into two parts: desired output Y_d and output Unwanted Y_{ud} is split and unwanted output is treated as input. In analyzing the efficiency of activities, inputs mean the resources used in each activity, which in this research are divided into three categories: machinery and equipment, skilled human resources, and simple manpower. Based on the efficiency analysis and considering the activities' prerequisites, the execution mode of each activity's price, time, cost, quality and risk level is determined. Also, the efficiency level of each activity is determined in the optimal execution mode.

The research aims to determine the weights of the inputs and outputs so that the risk, cost and time are at the minimum possible amount and efficiency and quality are at the maximum. For this purpose, weed optimization algorithm has been used. The weed optimization algorithm is a numerical optimization algorithm inspired by the growth of weeds. Weeds are very stable and adaptable to environmental changes; therefore, a strong optimization algorithm can be reached by taking inspiration and simulating their characteristics. One of the important features of weeds is their high stability and adaptability in nature, which is the basis of optimization in the weed algorithm. Weed is a phenomenon that is searching for optimality and finding the best environment for life and quickly adapts itself to environmental conditions and is resistant to changes. At first, the weed seeks to produce a large number of children, which increases the quantity and also covers the available environment; then due to the limitation of capacity, it continues to grow competitively by increasing the quality. In general, the purpose of weeds is to find the best environment to live.

The simulation steps in the weeding algorithm include the following:

First step: spreading seeds in the desired space

The second stage: the growth of seeds according to the desirability (procreation) and environmental dispersion

The third stage: survival of grasses with greater usefulness (competitive elimination)

Fourth step: Continue the process until reaching the plants with the best interest

4. RESEARCH RESULTS

The case study in this research is related to the implementation of a construction project. Figure 1 shows that the project network consists of 14 activities.

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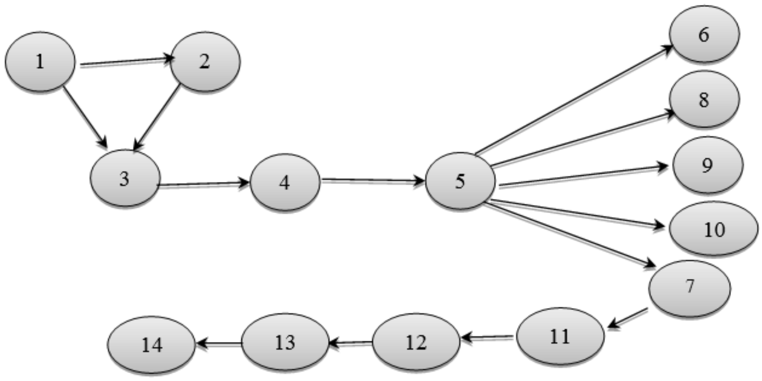

Figure 1: Network of activities in the research case project

Prerequisite relationships for activities are start-to-start; this means that the start of each activity has a temporal relationship with the start of its prerequisite activity. Each project activity has different sources and outputs. Resources include three sources of labor, materials, equipment, and machinery, and output includes each activity's time, cost, quality, and risk. Each activity consists of 3 execution modes. Since there are 14 different activities in this project and each activity can be executed in 3 different ways, the number of execution modes of the project will be $14^3 = 2744$ modes. Carrying out the project using each mode will have different effects on time, cost, quality and risk.

The project contractor and the employer's representative estimated the amount of resources used for each activity in each implementation method along with the time required to perform the activity. The cost of each activity execution mode was also estimated based on the cost of input resources and the duration of the activity execution. Based on the project execution mode, the risk and quality of the project will also be different, and the project contractor estimates these indicators.

Due to the uncertain and estimated nature of the available data, fuzzy variables are assigned to each project activity using triangular fuzzy numbers that represent the minimum, most likely, and maximum values for each objective. Time in days, cost in millions of Rials, quality on a scale of 0-100% while risk is measured on a scale of 0-1.

According to the announcement of the project contractor, the resources needed to implement each activity are as described in Table 1. As can be seen in the table, in some activities (workshop equipment and cleaning and dismantling of the workshop) there is no need for skilled human resources and machines are only used in some activities.

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Table 3: Resources used in each of the activities according to the contractor's announcement

Row	Type of Activity	Skilled human resources	Worker	Machinery
1	Equipping the ingot workshop	-	2	-
2	Mapping and implementation of P	2	5	4
3	Implementation of concrete skeleton	1	7	3
4	Implementation of skylights and roofs	1	5	2
5	Implementation of internal and external partitions	1	4	1
6	Installation of door and window frames and closets	1	3	-
7	plastering of the ceiling and walls	1	4	-
8	Façade and implementation of the garden	1	5	1
9	Implementation of mechanical and electrical installations	2	4	-
10	Flooring floors	1	3	-
11	Whitening of ceilings and walls	1	4	-
12	Painting the ceiling and walls	2	1	1
13	Installation of doors, windows and cabinets and sanitary ware	2	2	-
14	Cleaning and dismantling the workshop	-	3	2

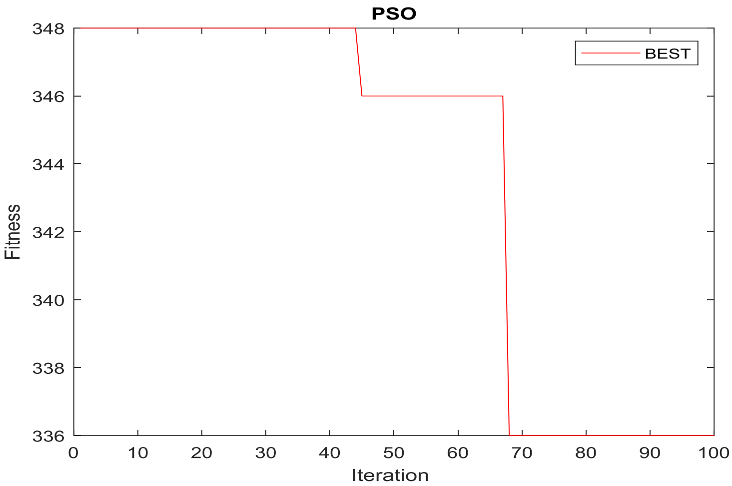

Figure 2: Efficiency of the proposed algorithm

The proposed model was coded and executed in MATLAB software version 2019 under a personal computer with Intel Core i5 processor, 3.2 GHz processor, 8 GB memory, Windows 10 and 64-bit operating system. The optimization results were obtained after 100 iterations in less than 10 seconds (6.5643 seconds). Figure 2 shows the fitting function of the weed optimization algorithm for the research model.

Below table shows the sequence of project activities after optimization.

Table 2: Sequence of activities after optimization

14	13	12	9	8	10	6	11	7	5	4	3	2	1

The output of the calculations will be the execution mode of each activity, their start and start time, the amount of cost, quality, risk and efficiency of each activity, which is presented in

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Table 3 and Chart 1. Based on the results, the total project implementation time is 336 days, the total cost of the project is equal to 7 billion and 533 million Tomans, the average quality of activities is 99.1% and the average risk score is 0.33.

Table 3: The results of the proposed algorithm

Activity No	execution mode	start time	end time	Cost	Quality	Risk
1	1	1	1	30000	100	0.08
2	2	1	29	3000	99	0.15
3	1	30	118	12000	100	0.64
4	3	119	196	1300	98	0.8
5	3	197	212	2200	98	0.24
7	2	213	232	1000	99	0.15
11	2	233	252	850	99	0.15
6	2	213	283	350	99	0.15
10	1	213	241	38	100	0.08
8	1	213	254	1900	100	0.64
9	1	213	236	13000	100	0.64
12	2	253	295	1100	99	0.15
13	3	296	335	8300	98	0.6
14	3	336	336	300	98	0.16
Total			336	75338	99.1	0.33

Table 4: Comparing the efficiency of activities

Activity No.	efficiency
A1	0.5
A2	0.62
A3	0.88
A4	0.96
A5	0.99
A6	1
A7	1
A8	1
A9	1
A10	1
A11	1
A12	1
A13	1
A14	1

As seen in Figure 1, 9 project activities will operate at the highest possible efficiency level. Also, the activities of mapping and implementation of foundations and internal and external partitioning will be less efficient than other project activities.

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5. CONCLUSION

Project scheduling is one of the most important and challenging project management issues. Time, cost, quality, and risk are among the key criteria of a project, that all project managers are always looking for the successful completion of projects with the shortest possible time, the lowest possible cost, the highest level of quality, and the lowest risk. If each project activity is implemented in the most efficient way possible, it can be claimed that the project has achieved the optimal combination of its performance criteria.

In this research, in order to obtain an effective combination of activities implementation modes, taking into account the level of risk, quality, time and cost of the project, the data envelopment analysis method and the weed optimization algorithm have been used. The results showed that in the conditions where the efficiency of the project activities is maximized, the total project time will be equal to 336 days, the project costs will be equal to 75 billion and 338 million Rials, the average quality of the activities will be 99.1% and the average project risk score will be 0.33.

The approach of this study can help project managers to choose the most efficient execution modes for their activities, so that the project is associated with the lowest time, cost and risk along with the highest possible quality.

The approach of the present study can be expanded in different ways by other researchers; among the things that can be mentioned are as follows:

• Adding social and environmental indicators to the objective function

• Applying the proposed approach in other projects and checking its performance

• Using other advanced methods in optimizing the objective function

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