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An integrated simulation-DEA approach to multi-criteria ranking of scenarios for execution of operations in a construction project

Mojtaba Torabi*, **Hashem Mahlooji**

Department of Industrial Engineering, Sharif University of Technology, Tehran, Iran

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Abstract

The purpose of this study is to examine different scenarios for implementing operations in the pre-construction phase of a project, based on several competing criteria with different importance levels in order to achieve a more efficient execution plan. This paper presents a new framework that integrates discrete event simulation (DES) and data envelopment analysis (DEA) to rank different scenarios for execution of construction operations. First, a simulation model is developed. Then, the model is run several times for each scenario to arrive at a quantitative evaluation of all competing criteria. Finally, DEA is used to compare the efficiency of different scenarios. To the best of the researchers' knowledge, this is the first study that employs an integrated approach based on computer simulation and DEA to concurrently incorporate several inputs and outputs with different importance levels for ranking scenarios of complex construction operations. Project managers can use this framework for assessment of different scenarios of conducting operations and choose the best one that reduces indices such as resource cost and waste in time, while at the same time enhances other criteria such as resource utilization and labor productivity.

Keywords

Construction operations, Data envelopment analysis, Deep excavation, Multi-criteria ranking, Simulation.

* **Corresponding Author, Email:** mtorabi992@gmail.com

Introduction

Construction is a massive industry worldwide which is one of the major resource consumers and waste generators (Saghafi & Teshnizi, 2011). Large numbers of people are employed in this sector in most countries, so that this sector accounts for around 7% of the total employment worldwide (Horta et al., 2013). On the other hand, this is one of the largest waste producing sectors, generating 77Mt of construction, demolition and excavation waste yearly. The industry in England alone consumes 380Mt of material each year (Hobbs, 2008). Often the causes of these dissipations are inefficient ways for implementing operations and inefficient resource consumption.

In recent years, the emphasis on development of effective measures for minimizing dissipation in construction projects have increased from economic, political and social perspective (Khoramshahi, 2007). Clearly, there is considerable potential within the construction industry to improve dissipation management practices (Williams et al., 2014). Construction processes are commonly concerned with critical decision making that often affect the schedule, cost, and productivity of the operations (Hassan & Gruber, 2008), and therefore have an important role in dissipation production in projects.

Before conducting operations a variety of plans are developed for construction. *Construction plans* consist of an overall outline of how construction operations will be performed as well as a sketch of a work sequence. Contractors also prepare *contingency plans* to guard against changes in the original plan. The third levels of plans are *execution plans* which are implemented at the task level. These plans should include elements such as the skill level required to perform an activity, as well as the materials, tools, and equipment required for each activity. Our focus in this paper is on the plans of the third type, namely *execution plans*. First, the existing planning processes and procedures are evaluated by management personnel to determine whether they should be modified or improved (Yates, 2014). In detailed plans, usually there are various ways and scenarios to conduct operations.

By the time that execution plans get under way, team members review the job layout, equipment operations, work processes, transportation schemes, and so forth in order to highlight any inefficiency in the existing procedures (Yates, 2014). Therefore, several competing criteria can be involved in their decisions and there is a great chance that the importance levels of these criteria vary widely. The problem is ranking different scenarios, where many criteria are involved in the ranking procedure. Besides, when a construction project gets under way, delayed decisions or changes in decisions will lead to wasting the company's time and resources which ultimately amounts to reduced profits. Therefore, it is worthwhile to make decisions before conducting operations.

As a solution, this paper proposes a framework for ranking different scenarios under the stated conditions. Namely, several simultaneous criteria with different importance levels are involved in the ranking process. This framework consists of employing two main tools which are explained below.

Application of simulation in construction

Application of Operational Research has proved difficult and ineffective in modeling real world construction systems (Moradi, 2015). When problems are characterized by uncertainty, complexity in techniques and methods, flexibility in modelling logic and knowledge and when an integrated solution is required, simulation is more effective than other tools (Ndekugri et al., 2010).

Because of the complexity involved in most construction projects, simulation is frequently the best, and sometimes the only possible tool to address issues relevant to construction operations (Martinez, 2010; Alvanchi et al., 2012). According to Abourizk et al. (2011), construction simulation is the science of developing and experimenting with computer based representations of construction systems to understand their underlying behavior. He provides a history of this theory in his paper. According to the results of Abudayyeh et al. (2004) between 1997 and 2002, the top rank in construction research topics was for simulation, and this has helped it to be in fourth place overall, since it was not discussed much at all during the period 1985 to 1990.

Discrete event simulation (DES) methodology is very helpful at the operational level of projects. Simulation of operational processes sheds light on the project condition through considering different discrete variables such as process duration, resource utilization and entities arrival rate (Moradi, 2015).

Simulation studies have been used in the area of construction management for a long time. Several studies in the literature have used simulation to analyze and improve construction operations. Here some of the recent works are mentioned as follows. Hassan and Gruber (Hassan & Gruber, 2008) have used simulation for investigating the impact of equipment combination on the flow of operations and cost-effectiveness of the construction process in asphalt paving operations. Based on the results, 30 trucks, one paver, and two rollers are recommended.

Alvanchi et al. (2012) proposed a framework based on discrete event simulation for improving off-site construction planning for a girder bridge project that considers constraints arising from both the erection process and from off-site steel fabrication shops. Wimmer et al. (2012) used module-based simulation for assessing the impact of the number of trucks on productivity and cost in a project involved with balancing a 14km road surface.

Labban et al. (2013) used simulation for assessment of asphalt paving operations and proposed a method which may potentially make simulation model building easier and faster. Montaser et al. (2014) presented an automated tool for earthmoving operations that employs GPS for capturing actual data from the site and performs adaptive discrete event simulation for estimating operations productivity. Botín et al. (2015) have combined stochastic discrete-event simulation (DES) and Programme Evaluation Review Technique (PERT) for optimization in block-cave mining projects and have investigated fleet combination effect on the duration of pre-production stage and Net Present Value (NPV).

Alsudairi (2015) utilized simulation in reducing cost and time of construction in the building sector. He investigated 4 strategic scenarios for project implementation based on factors including Cycle Time, Total Cost, Productivity and Utilization. Results show significant improvement in the utilization of resources and the consumed energy.

Moradi (2015) proposed a hybrid simulation framework based on system dynamics (SD) and discrete event simulation (DES) which can take into account both the continuous and operational variables affecting the performance of construction projects. Najafi and Tiong (2015) used simulation for evaluating the productivity of horizontal precast concrete installation. Results show a high level of idle ratio for preparation and fixing crew labor. Pradhananga and Teizer (2015) presented a cell-based simulation system which is able to model and visualize the cyclic activities of earthmoving equipment. This paper has used GPS for tracking data from equipment resources and the effects of spatial considerations of varying resource combinations in earthmoving cycles on productivity and site congestion are explored.

Baniassadi et al. (2015) proposed a simulation based framework which concurrently follows safety and productivity improvement in construction projects. Based on their framework, each scenario according to its productivity and safety values has been placed in one of the 4 areas in the proposed color coded two dimensional X-Y diagram. Finally, the work of Hassan et al. (2016) is one of the few papers employing simulation in the design phase of construction in order to design a mall parking facility. This involves both qualitative and quantitative factors to achieve a performance driven design.

In none of the research efforts reviewed above and some other similar studies, ranking and selecting better scenarios has not been based on several simultaneous criteria. Even though in most of these studies several criteria have been considered for evaluation the scenarios have just been ranked for each criterion separately. Our work intends to propose a framework in order to remedy this drawback by employing data envelopment analysis along with simulation. This framework not only considers several simultaneous criteria, it also considers different importance levels for each criterion.

Data envelopment analysis

Data envelopment analysis is a non-parametric linear programming (LP) method capable of evaluating the efficiency of decision making units[1] (DMUs) (Markovits-Somogyi, 2011). It is used for measuring the relative efficiency of homogeneous[2] DMUs with multiple inputs and multiple outputs using a single performance measure called the 'relative efficiency'. This measure is the sum of the weighted outputs divided by the sum of the weighted inputs (Al-Refaie et al., 2014). The most popular DEA technique is the CCR model developed by Charnes et al. (1978). The CCR model measures the DMU’s relative efficiency once by comparing it to a group of other homogeneous DMUs. Hence, if the number of under evaluated DMUs equals to *n* as many as *n* optimizations are needed in order to determine the relative efficiency of units (Al-Refaie et al., 2014). The CCR input-oriented modeling is formulated as follows:

Suppose that there are *n* DMUs, each with *s* outputs and *m* inputs. The relative efficiency score for the under study decision making unit, *DMUo*, is obtained by solving the following LP model:

$$E_o = \text{Max}\,\theta = \sum_{r=1}^{s} u_r y_{ro} \tag{1}$$

Subject to:

$$\sum_{i=1}^{m} v_i x_{io} = 1 \tag{2}$$

$$\sum_{r=1}^{s} u_r y_{rj} \le \sum_{i=1}^{m} v_i x_{ij} \quad ; \qquad for\ j = 1,2,3,\dots,n \tag{3}$$

$$u_1, u_2, \dots, u_s \ge 0 \qquad\qquad v_1, v_2, \dots, v_m \ge 0 \tag{4}$$

1. in our work each scenario is considered as a DMU
2. homogeneous DMUs have the same set of input and output

where, E_0 is the relative efficiency of *DMUo*, θ is a scalar, x_{ij} is the value of the i^{th} input of the j^{th} DMU, y_{rj} is the value of the r^{th} output of the j^{th} DMU and v_i and u_r are the weights of the i^{th} input and the r^{th} output, respectively. The model maximizes the sum of weighted outputs of *DMUo*. The first constraint normalizes inputs' weights and the second constraint makes sure that the relative efficiency of each of the *n* DMUs is less than or equal to one (Baker & Talluri, 1997). The model optimizes the output of each DMU through choosing optimal input/output weights. When we solve the model, the *DMUo* is then identified as CCR-efficient if E_0 equals one.

In order to rank different scenarios an integrated Simulation-DEA-Delphi framework is proposed in this paper. In a number of fields other than construction, the combination of simulation and DEA has been employed for different purposes. Some examples are listed in Table 1.

Table 1. Combination of simulation and DEA in the literature

Research, year	Purpose
McMullen & Frazier (1998)	to compare assembly line balancing strategies
Greasley, 2005	to guide operating units of police forces to improve performance
Azadeh, Ghaderi & Izadbakhsh (2008)	railway system improvement and optimization
Min & Park, 2008	to measure capacity utilization and throughput efficiency of container terminals
Azadeh et al. (2009)	vendor selection problem
Weng et al. (2011)	to identify solutions in reducing patient time in the emergency departments
Khalili-damghani et al. (2011)	measure the efficiency of agility in dairy supply chain
Al-Refaie et al. (2014)	to improve performance of emergency department in a hospital by cellular service system
Aslani & Zhang (2014)	to determine the most efficient patient appointment scheduling model
Dev et al. (2014)	to analyze the efficiency of total supply chain in context of average fill rate performance
Rani et al. (2014)	to improve production system of a food manufacturing
Sheikhalishahi (2014)	to plan maintenance activities for a system consisting of 3 machines in series.

Continue Table 1. Combination of simulation and DEA in the literature

Research, year	Purpose
Azadeh et al. (2015a)	to optimize facility layout design problem in a polymer products company
Azadeh et al. (2015b)	to increase the quality of service in a neurosurgical intensive care unit (ICU)
Sameie & Arvan (2015)	to decide on the optimum location for a wind farm

This paper employs a customized version of the combination (Simulation-DEA) for the first time, in order to rank scenarios in construction projects under the following conditions:

1. Several criteria are involved in decision making.
2. The criteria have different importance levels.
3. Decisions should be based on several simultaneous criteria (i.e., each criterion with any importance level has a say in the final ranking).

The rest of this paper is outlined in the following sequence. Section 2 describes the methodology. Section 3 proposes a hypothetical example in order to test different features of the proposed framework. Section 4 proposes a case study in a deep excavation project. Finally, conclusions are presented in section 5.

Methodology

Before a construction project gets under way an attempt is made to examine different ways and scenarios in conducting the project. Through such a process the more appropriate scenarios should be selected based on several criteria that are not necessarily at the same level in terms of importance.

The purpose of this study is evaluating different scenarios for execution of construction operations before they are started, according to several criteria with different importance levels and providing a ranking of the scenarios based on all of these criteria simultaneously. For this objective, we propose a conceptual framework based on Figure 1 that uses two main tools: simulation and data envelopment analysis.

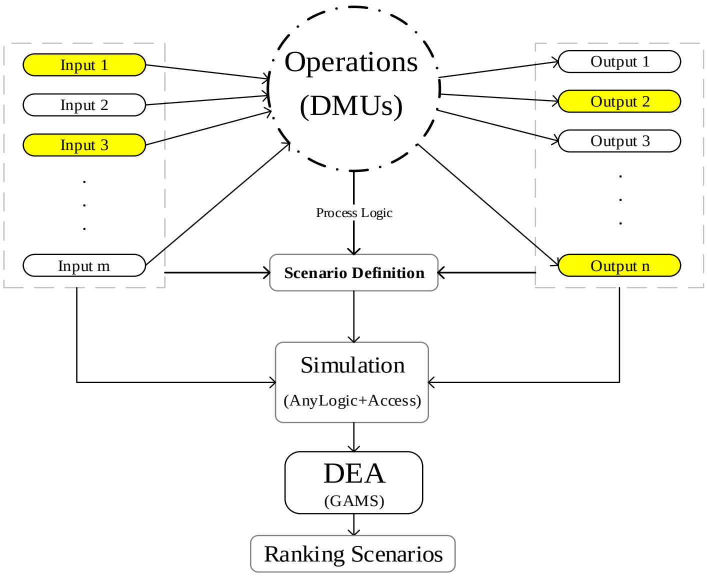

Fig. 1. The proposed framework conceptual model

By simulation, we extract and estimate the values of some criteria that just can be determined after the operations are executed. Data Envelopment Analysis is used for ranking scenarios based on several inputs/outputs criteria simultaneously (inputs must be frugally spent while outputs must be raised).

In practice, the methodology that will be adopted based on the conceptual framework to achieve the objectives is outlined below and shown in Figure 2:

1. Recognition of operations, process mapping for them, data collecting for simulation and defining several feasible scenarios for execution.
2. Determination of criteria and their relative importance based on experts' opinions (with Delphi Method).
3. Modeling all defined scenarios, model verification and output analysis.

   Hint. Since we are evaluating scenarios for unexecuted operations, it is impossible to collect data for validation purposes, perhaps there might be a slim chance that the historical data related to a similar project can be helpful.

It is necessary to mention that the easiest way to arrive at probability density functions (pdf) of activities durations with a desirable accuracy is seeking expert's opinions of those activities.

4. Evaluating scenarios and ranking them by data envelopment analysis models.

   Hint. Defined scenarios are homogeneous DMUs, because they are related to one project so that all these scenarios have the same set of input/output data.

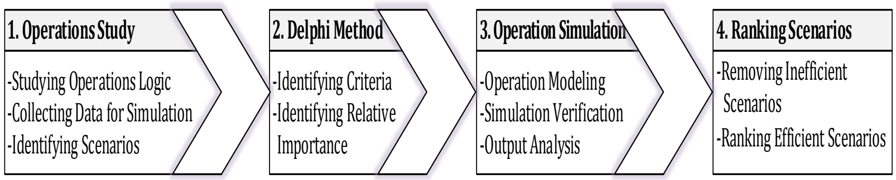

Fig. 2. The process of the proposed framework

The proposed framework in this research helps decision makers to rank scenarios for execution of construction operations based on several criteria with different importance levels concurrently. The results of implementation of this framework for a typical project can be a basis for choosing appropriate scenarios based on several different criteria in the planning stage of a project.

Since different input/output combinations will produce different efficiency rankings of DMUs, an important decision in DEA modeling is the selection of inputs and outputs. In order to define input and output criteria in the DEA model, Delphi technique is used. Delphi technique produces useful results which are accepted and supported by the majority in an expert community.

The effect of each criterion in ranking scenarios is different in terms of their importance level, and it must be determined based on experts' opinions. In order to consider this fact, the effect of relative importance of a criterion has been considered in the DEA model in the form of some additional constraints on the weights of input/output criteria (i.e., v_i and u_r).

Hypothetical example

To test the merits of the proposed framework, we resort to a hypothetical case related to the roof tile installation operations. The core of this example is borrowed from (Baniassadi et al., 2015) while some modifications such as defining various scenarios and tile depot layouts have been added to it. Since this is not a real project, in this test we skip some steps such as operations recognition, Delphi, and simulation validation.

Operations description

In this case there is one worker on the ground as the hoist operator who loads and hoists roof tiles to the top. Another worker as tile installer works on the roof top who first, depots tiles on the roof and then installs them. Operations process has been shown in Figure 3. Based on the norms of the domestic construction market, hourly wage of 300,000 IRR is considered for the hoist operator, and hourly wage of 500,000 IRR is considered for the tile installer.

The roof area is 9 meters long and 4 meters wide. Furthermore, tiles have dimensions of 25 cm by 35 cm. With tiles overlapping, the effective dimensions are 20 cm by 30 cm. Hence, we need a total of 600 tiles to cover the roof completely.

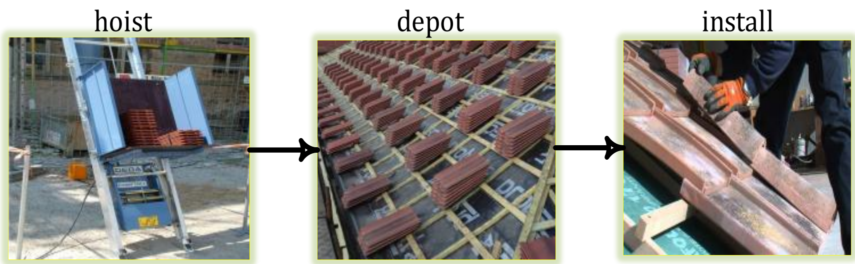

Fig. 3. Tile installation process

Scenarios

Twelve different scenarios are considered which are evaluated and compared in this example. Different scenarios, as shown in Table 2, are created as a result of using different depot arrangements, different types of hoists with different capacities and different depot and installation orders. In Table 2, the first row shows depot and installation orders so that S1 means installation begins after the depot of all tiles, and S2 means installation begins after the depot of each hoist bucket.

Table 2. Main characteristics of different operation scenarios

Characteristic	Scenario											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Tile depot and installation order	S1	S1	S1	S1	S1	S1	S2	S2	S2	S2	S2	S2
Hoist bucket capacity (tiles)	10	15	20	10	15	20	10	15	20	10	15	20
The number of depot zones	60	60	60	40	40	40	60	60	60	40	40	40
Break time for tile installer (minute)	15	20	30	15	20	30	0	0	0	0	0	0
Hourly rental fee of hoist (10,000 IRR)	30	35	40	30	35	40	30	35	40	30	35	40
Elevation duration within a bucket (second)	Normal(60,7)	Normal(75,10)	Normal(100,10)	Normal(60,7)	Normal(75,10)	Normal(100,10)	Normal(60,7)	Normal(75,10)	Normal(100,10)	Normal(60,7)	Normal(75,10)	Normal(100,10)
Installation duration within a bucket (minute)	Triangular(4,9,5)	Triangular(6,12,8)	Triangular(8,14,10)	Triangular(4, 9, 5)	Triangular(6,12,8)	Triangular(8,14,10)	Triangular(4, 9, 5)	Triangular(6,12,8)	Triangular(8,14,10)	Triangular(4, 9, 5)	Triangular(6,12,8)	Triangular(8,14,10)

Normal(m, v) stands for a Normal distribution with mean m and variance v.
Triangular(a, b, c) represents a Triangular distribution with lower limit a, upper limit b and mode c.

Figure 4 illustrates the two main depot arrangement types on the roof that are used in different scenarios. In the first case we have 60 depot zones, and in the second we have 40 depot zones on the roof.

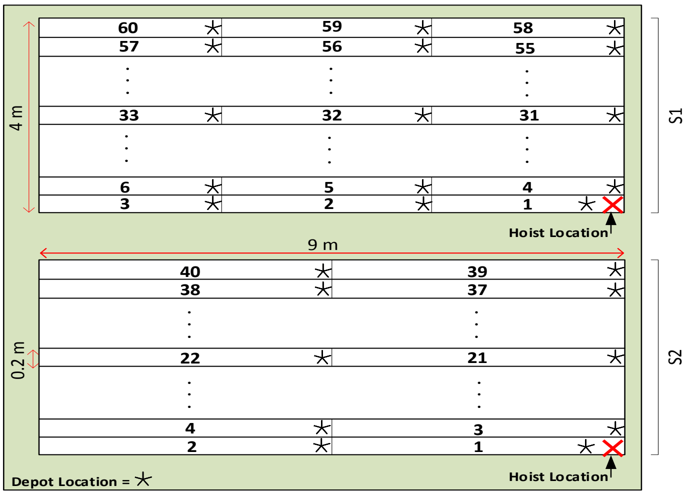

Fig. 4. Two tile depot layouts on the roof used in different scenarios

Additional assumptions adopted in the example are as follows:

1. Tile installer can haul at most 10 tiles per turn in one batch. Therefore, he hauls 5 or 10 tiles per turn.
2. Duration of putting 10 tiles in the hoist by the hoist operator is considered based on triangular (30, 60, 45) seconds. For 5 tiles this duration is multiplied by 0.8. Since the weight of 5 tiles is less than 10 tiles and hauling 5 tiles is easier, it takes less time.
3. Depot duration for each bucket is calculated based on the distance that tile installer must walk to the desired unloading (installing) zone. This duration consists of moving and unloading times. Suppose that unloading duration is 60 sec. and movement of a batch with 10 tiles takes 10 sec. for each meter. For a batch with 5 tiles this duration is 3 sec. per meter.
4. In scenarios 1-6 after depot completion, the hoist operator is released and the rest of the work is done just by tile installer.

The criteria

In this example, we consider 5 criteria for evaluating scenarios as shown in Table 3. Since this is not a real project, we consider 4 conditions for importance levels of these criteria as shown in Table 4 in order to indicate the effect of relative importance of each criterion on ranking scenarios. In this table, $\overline{X}$ denotes the importance level of X. For instance, for Condition 1, the importance level of the duration is more than twice the importance level of the unit cost, and more than triple the importance level of the cycle time. On the other hand, the importance level of unit cost is more than twice the importance level of the cycle time. Finally, the importance level of utilization of hoist operator is more than twice the importance level of utilization for tile installer. For Condition 4 importance level of all criteria has been considered to be equal. Furthermore, the corresponding constraints on decision variables which should be used in DEA models have been shown in the table for each condition.

Table 3. Criteria for evaluating scenarios

Criteria	Unit	Criteria type		Description
		Input	Output	
Average duration (D)	hours	√		Duration of operations
Average unit cost (UC)	IRR	√		Only time-dependent costs are considered for calculating this criterion
Average cycle time (CT)	minute	√		The interval between the end of bucket Installation and the start of its filling
Average worker1 utilization (UL1)	percent		√	Utilization of hoist operator
Average worker2 utilization (UL2)	percent		√	Utilization of tile installer

Table 4. Conditions for relative level of importance of some criteria

Condition	Constraints			
1	$\overline{UL1} \geq 2.\overline{UL2}$	$\overline{UC} \geq 2.\overline{CT}$	$\overline{D} \geq 3.\overline{CT}$	$\overline{D} \geq 2.\overline{UC}$
	$u_1 \geq 2u_2$	$v_2 \geq 2v_3$	$v_1 \geq 3v_3$	$v_1 \geq 2\, v_2$
2	$\overline{UL2} \geq 2.\overline{UL1}$	$\overline{CT} \geq 2.\overline{UC}$	$\overline{CT} \geq 3.\overline{D}$	$\overline{UC} \geq 2.\overline{D}$
	$u_2 \geq 2u_1$	$v_3 \geq 2v_2$	$v_3 \geq 4v_1$	$v_2 \geq 2v_1$
3	$\overline{UL2} \geq 3.\overline{CT}$		$\overline{UC} \geq 4.\overline{CT}$	$\overline{UC} \geq 2.\overline{D}$
	$u_2 \geq 3v_3$		$v_2 \geq 4v_3$	$v_2 \geq 2v_1$
4	Without any constraint			

The simulation model

Simulation models are developed in *Anylogic* simulation Package using its Enterprise Library so that we can adjust the model to the desired scenario just by changing related parameters such as the bucket capacity. Figure 5 shows the flowchart of simulation model.

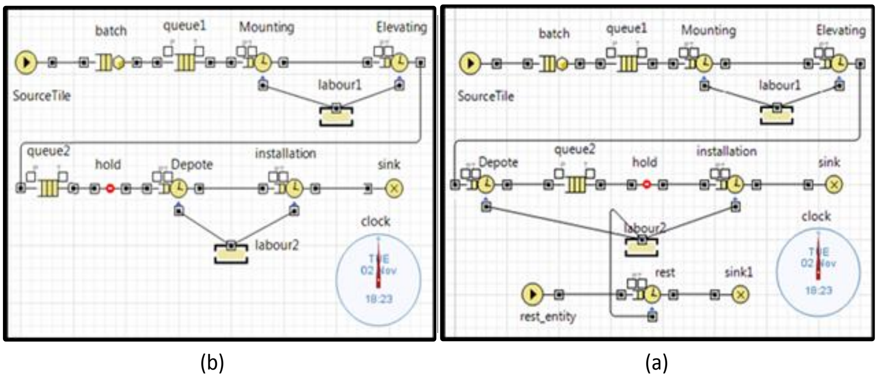

Fig. 5. Screenshot of the flowchart of simulation model scenarios 1-6, (b) scenarios 7-12

Validation is not applicable for this example. But some experiments such as sensitivity analysis and trace report assessment have been done to ensure model verification. As shown in Figure 6 with increasing the duration of "mounting" activity (Fig. 5), the utilization of hoist operator (labor1) has increased and utilization of tile installer has decreased, as expected.

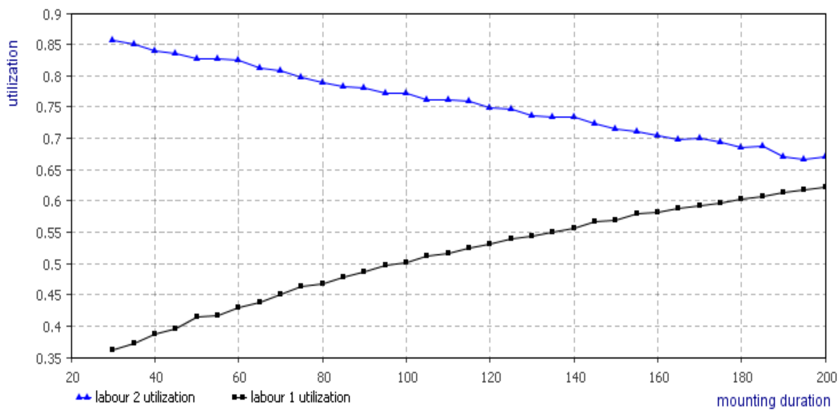

Fig. 6. An example of sensitivity analysis for verifying the simulation model

Discussion

The simulation model has been run 50 times for each scenario and the relevant data concerning the pre-defined criteria have been imported directly into Access database which is connected to the model. The average of runs for each criterion has been considered as a point estimate for that criterion. Table 5 shows the relevant data for every criterion across all scenarios.

If we consider only one criterion for decision making, the best scenario is decided according to what is shown in the last row of Table 5. In the case that several concurrent criteria with different importance levels are involved in decision-making, rank of the scenarios will certainly change.

Table 5. Simulation results for 5 criteria

Scenario	D (hours)	UC (IRR)	CT (minute)	UL1 (%)	UL2 (%)
1	10.6480	1325.6924	339.6922	39.93	83.56
2	10.5985	1369.0017	342.1191	38.70	83.62
3	10.0017	1324.7389	332.1359	37.46	84.23
4	10.5190	1304.6153	335.0722	40.84	83.38
5	10.3789	1327.0209	335.0459	40.63	83.30
6	9.9530	1311.7484	329.2772	38.21	84.12
7	13.3308	2443.9879	23.8218	13.11	99.78
8	9.8706	1891.8729	25.1620	17.51	99.57
9	8.0277	1605.5389	26.3850	19.81	99.35
10	13.2535	2429.8123	23.7685	13.21	99.78
11	9.6706	1853.5377	24.8806	17.91	99.56
12	7.9463	1589.2669	26.2021	19.95	99.34
Best	12	4	10	4	7,10

The defined scenarios are homogeneous DMUs, as mentioned before in section 2. Therefore, in this step for each of conditions in Table 4 a DEA model based on Equations (1)-(4) in addition to constraints of Table 4 has been developed using the data contained in Table 5. Then, the models are solved by *GAMS* software. The outcome for ranking scenarios across all four conditions has been shown in Table 6.

Table 6. Obtained ranking of scenarios

Condition 1			Condition 2			Condition 3			Condition 4		
Rank	Scenario	Score	Rank	Scenario	Score	Rank	Scenario	Score	Rank	Scenario	Score
1	4	1	1	12	1	1	4	1	1	4	1
1	6	1	1	10	1	1	6	1	1	6	1
1	12	1	1	11	1	1	12	1	1	11	1
1	5	1	2	7	0.9978	2	3	0.9915	1	12	1
2	9	0.9879	3	9	0.9924	3	9	0.99	1	5	1
3	3	0.9857	4	8	0.9877	4	1	0.9851	1	10	1
4	1	0.9764	5	4	0.7894	5	5	0.983	2	7	0.9978
5	2	0.9512	6	6	0.7868	6	2	0.9538	3	9	0.9925
6	11	0.8094	7	5	0.7792	7	11	0.86	4	3	0.9919
7	8	0.7884	8	3	0.7774	8	8	0.8427	5	8	0.9879
8	10	0.5579	9	1	0.7754	9	10	0.6581	6	1	0.9851
9	7	0.5538	10	2	0.7531	10	7	0.6543	7	2	0.9539

As shown in Table 6 for Condition 4 half of the scenarios are efficient, but due to considering the relative importance for some criteria under other conditions, the ranking of scenarios has changed. For example, scenario 10 under Conditions 2 and 4 is known as an efficient scenario (rank=1), but the very same scenario is not efficient anymore under the Conditions 1 and 3 due to considering some constraints and has dropped to rank 8 and 9, respectively.

For Condition 1 in comparison with Condition 4, based on Table 4 it is expected that the rank of scenarios which have a larger D value increases and the rank of scenarios which have a smaller D value decreases. For example the rank of scenario 7 due to having a larger D value has reduced to 9th. On the other hand, scenario 7 has a very lower CT value in comparison with scenario 6, but this cannot help 7 to raise its ranking, because the importance of CT is rather low. Similar arguments can be used to justify the rankings under other conditions.

Case study

This case study deals with a heavy *deep excavation* project in Iran. The total anchored and nailed walls used in this project are about 10500 square meters and consist of 14 types (Fig. 7) according to arrangement of nails and anchors in those types. The average depth of the excavation is about 30 m.

Fig. 7. The aerial map of deep excavation project

Moreover, for the sake of technical requirements, each type is divided into a number of panels each of which has the following attributes: 1. panel number, 2. the type which panel belongs to, 3. total number of bores within the panel, 4. panel length (at most is 8 m), 5. panel width (at most is 4 m), 6. total number of nails within the panel, 7. total number of strands within the panel, 8. length of bores within the panel, and 9. the row which the panel is located in. The total number of panels over all the walls (in 14 types) is 606. Note that each panel may contain several bores where each bore is either nailed or anchored.

The process of construction for each panel is briefly mentioned in Figure 8.

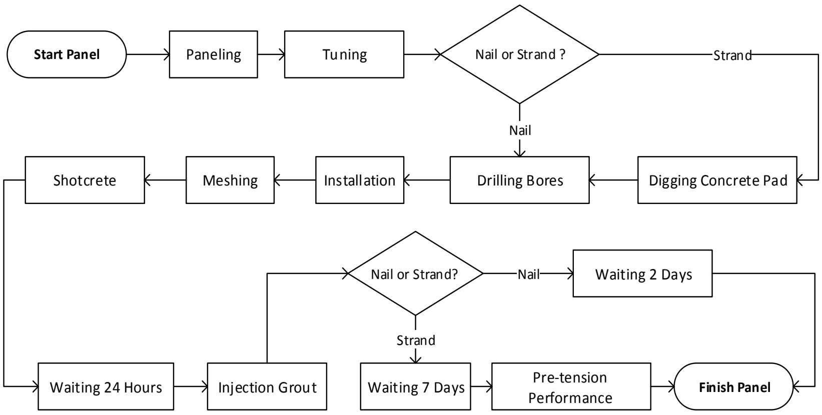

Fig. 8. The process of deep excavation operation with nailing method

Along with the nailing operation, there is an earthmoving operation under way to move the soil to outside. Durations of important operations were obtained based on experts' opinion (8 people) and expressed in triangular distributions as shown in Table 7.

Table 7. Duration of operations in deep excavation operations case study

Operation Name	Triangular (minute)	Unit
Paneling	Triangular (14, 17, 26)	m^2
Tuning	Triangular (3, 6, 13)	m^2
Digging Concrete Pad	Triangular (5, 7.5, 10)	1/6 of pad volume
Drilling Bores	Triangular (3, 6, 45)	m
Installation	Triangular (5, 10, 15)	Bore
Meshing	Triangular (3, 6, 16)	m^2
Shotcrete	Triangular (5, 7, 8)	m^2
Injection Grout	Triangular (40, 60, 120)	Bore
Pre-tension Performance	Triangular (20, 40, 60)	Anchored Bore
Loading Trucks by excavator	Triangular (20, 28, 30)	Truck
Loading Trucks by Loader	Triangular (10, 18, 20)	Truck
Truck Trip	Triangular (60, 65, 80)	Truck

Subsequently, 30 different scenarios as listed in Table 8 have been defined based on different combinations of equipment and labor involved in each tasks. These scenarios are based on experts' opinion, as well.

Table 8. Main characteristics of scenarios in case study

Scenario	Loader	Excavator	Truck	Drill Wagon	Basic Labor	Pulling Labor
1	0	2	10	3	8	4
2	1	1	10	2	6	4
3	1	1	10	2	10	4
4	1	1	10	2	8	6
5	1	1	12	2	6	4
6	1	1	12	2	10	4
7	1	1	12	2	8	6
8	0	2	10	3	6	4
9	0	2	10	3	10	4
10	0	2	10	3	8	6
11	0	2	12	3	6	4
12	0	2	12	3	10	4
13	0	2	12	3	8	6
14	1	2	10	3	6	4
15	1	2	10	3	10	4
16	1	2	10	3	8	6
17	1	2	12	3	6	4
18	1	3	12	4	10	4
19	1	2	12	3	10	4
20	1	2	12	3	8	6
21	0	3	10	4	6	4
22	0	3	10	4	10	4
23	0	3	10	4	8	6
24	0	3	12	4	6	4
25	0	3	12	4	10	4
26	0	3	12	4	8	6
27	1	3	10	4	6	4
28	1	3	10	4	10	4
29	1	3	10	4	8	6
30	1	3	12	4	6	4

Simulation runs have been conducted in Anylogic simulation Package based on an integrated database oriented and object oriented architecture. The 9 characteristics relevant to all 606 panels are stored in an input data base. Then this data is made available to the simulation model. Finally, after running the model the evaluation criteria are determined and directly imported to another output database.

In order to verify the simulation model some sensitivity analysis were carried out, and it was decided that the model works reasonably well. Also, comparison of the duration in simulation model for the base scenario (scenario 1) (about 365 days), and the actual planned duration (380 days) revealed that the variation was as small as 3.94 percent.

In consultation with operations experts 5 different criteria for evaluating the project were defined as demonstrated in Table 9. Besides, the relative importance levels of some criteria are defined in the last row of this table.

Table 9. Criteria and their relative importance in case study

Criteria	Unit	Criteria type		Description
Criteria Name		Input	Output	
Duration (D)	days	√		Average duration of operations
Cost (C)	10^7 IRR	√		Only time-dependent costs are considered for calculating this criterion
Cycle time (CT)	days	√		The interval between the end of panel pulling and the start of its paneling
Performance index (PI)	$(m^2)^2$ / days. 10^7IRR		√	Production capacity divided by resource consumption
Excavator utilization (SU)	percent		√	Average utilization of shovels
Relative Importance				
$\overline{C} \geq 3.\overline{D}$	$\overline{CT} \geq 2.\overline{PI}$	$\overline{D} \geq 4.\overline{SU}$		$\overline{PI} \geq 4.\overline{SU}$

Simulation model for each scenario has been run 10 times and the value for each criterion has been determined as the average of runs. Then a customized DEA model based on Equations (1)-(4) has been coded in GAMS to arrive at the ranking for all scenarios. Results for simulation runs and scenario ranking are summarized in Table 10. As shown in the table, the best scenario (scenario 27) is a strong scenario based on some important criteria and is a weak scenario based on less important criteria, compared with other scenarios.

Table 10. Simulation and ranking result

Scenario	Duration	Cost	CT	PI	SU	Rank	Score
1	365.364	3594.727	21.396	83.053	0.895	18	0.567566
2	489.400	3541.500	30.323	62.935	0.931	24	0.386654
3	487.200	3636.300	30.224	61.572	0.932	25	0.372478
4	487.750	3710.667	30.277	60.270	0.932	27	0.359705
5	488.500	3697.500	30.286	60.391	0.931	26	0.361206
6	488.300	3800.400	30.294	58.780	0.931	28	0.345408
7	488.400	3876.400	30.259	57.615	0.931	29	0.334393
8	365.000	3544.400	21.382	84.317	0.894	17	0.581887
9	364.500	3610.600	21.357	82.885	0.895	19	0.565043
10	364.200	3671.300	21.361	81.581	0.895	20	0.549812
11	365.500	3868.800	21.411	77.142	0.894	21	0.510523
12	364.700	3933.300	21.366	76.043	0.895	22	0.504309
13	364.300	3997.800	21.334	74.898	0.895	23	0.497461
14	364.900	3081.000	21.469	97.024	0.894	12	0.736251
15	364.818	3155.091	21.505	94.767	0.895	14	0.707271
16	364.636	3210.909	21.489	93.165	0.895	15	0.687224
17	365.800	3139.400	21.499	94.987	0.894	13	0.711379
18	303.100	3080.000	17.043	116.845	0.865	5	0.971461
19	364.900	3212.200	21.494	93.063	0.895	16	0.686232
20	364.900	3212.200	21.494	93.063	0.895	16	0.686232
21	302.800	3045.600	17.001	118.280	0.865	3	0.985821
22	303.200	3112.200	17.020	115.599	0.865	7	0.9624
23	303.400	3157.500	17.016	113.869	0.865	8	0.94822
24	303.500	3203.700	17.043	112.187	0.865	9	0.932734
25	302.900	3263.600	16.995	110.345	0.865	10	0.92001
26	304.000	3312.000	17.060	108.335	0.864	11	0.89981
27	303.200	2990.100	17.049	120.320	0.865	1	1
28	302.900	3052.400	17.038	117.979	0.865	4	0.981177
29	303.000	3097.500	17.023	116.223	0.865	6	0.967424
30	302.636	3012.636	17.041	119.643	0.865	2	0.99484

Conclusions

In this research, we proposed a new integrated Simulation-DEA framework for evaluating and ranking the feasible scenarios of construction operations based on several concurrent criteria with different importance levels. The framework helps construction project managers to select the best alternative operation scenarios based on several different aspects concurrently in the planning stage of a project so that some indices such as resource cost and waste in time are reduced and other indices such as resource utilization and labor productivity are enhanced, simultaneously. In order to assess the proposed framework we applied it to a hypothetical example as well as a real case in a deep excavation project. Result show that the proposed framework works well in evaluating and ranking scenarios in construction operations. Some future studies which can improve the proposed framework include: using fuzzy simulation or some qualitative methods such as AHP for covering qualitative criteria, using hybrid simulation, using cellular simulation, and using extended DEA models.

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