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A mathematical model for project scheduling and material ordering problem with sustainability considerations: A case study in Iran

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ABSTRACT

In the traditional project planning approach, the manager first schedules the project activities and then plans the material ordering timetable accordingly. But in this approach, the tradeoff and association between the project implementation costs and ordering expenses are disregarded. This approach is also ill-suited for modern organizations that are under growing public pressure to support inter and intra generational justice and introduce environmental and social objectives to their competitive strategy and business mission. This paper provides an integrated framework for the Project Scheduling and Material Ordering (PSMO) problem with sustainability considerations. The proposed framework consists of two phases: (a) quantifying the environmental and social merits of the potential suppliers of the project resources, and (b) constructing and solving a mathematical model based on the acquired data. The model is able to determine the activities schedule, material ordering time and quantity, and the supplier selection that maximize the project NPV and the environmental and social benefits of its suppliers. The presented model falls within the class of NP-Hard problems, so two multi-objective meta-heuristic algorithms, namely NSGA-II and MOPSO were modified to serve as solution methods for this model. For small problems, the performance of these methods was compared with that of second version of the augmented e-constraint (AUGMECON2) method, but for larger problems, where the exact method was unable to produce a solution within a reasonable time, these two algorithms were compared with each other. The results showed that regardless of problem size, NSGA-II outperforms MOPSO in the majority of evaluation metrics. The paper also includes a case study conducted on the trackbed construction project in Section 5 of Mianeh-Bostanabad-Tabriz railway in Iran, which demonstrates the applicability of the proposed model and provide an illustrative example of its implementation.

1. Introduction

Proper project management can be expected to result in successful completion of the project, increased revenue, reduced cost and therefore increased profit for the organization. Devising a project schedule considered as a significant step of project management process to serve as a platform for the project implementation and completion. One of the issues that may strongly effect the project scheduling is the management of materials, inventories, or non-renewable resources needed for the completion of activities. This aspect of management is important because keeping a full stock of required materials eliminates the chance of material shortage and the resulting inefficiency but also leads to a significant increase in inventory holding costs. Also, smaller procurement amount of materials entails a higher probability of delay in individual activities and therefore postponement of project completion. In the traditional planning approach, the manager first devises a broader project schedule and then plans the material ordering schedule accordingly. However, this approach neglects the tradeoff between project costs, such as ordering costs, holding inventory expenses, and penalties/bonuses due to delayed-early completion of the project (Okubo et al., 2015). This topic is also becoming increasingly involved with the notion of sustainable development, which is one of the key issues of the 21st century (Habibi, Barzinpour, & Sadjadi, 2018). An organization's tendency to plan its activities and resource utilization program in such a way as to respect the rights of future generations to environmental resources can highlight its commitment to embracing the theory of sustainable economy and taking positive steps towards sustainable development. In this study, the Project Scheduling and Material Ordering (PSMO) problem is formulated with real-world applicable assumptions, in order to provide a framework for project scheduling and devising a material procurement plan in line with sustainability goals.

The seminal works on the integration of material ordering into

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project scheduling are the studies carried out by Aquilano and Smith (1980) and Smith-Daniels and Aquilano (1984), where they introduced several heuristic algorithms to solve this problem. The first mathematical model for PSMO was introduced in Smith-Daniels and Smith-Daniels (1987b). Later, Smith-Daniels and Smith-Daniels (1987a) presented a new approach and model for project Net Present Value (NPV) maximization with material and budget constraints. Shtub (1988) examined the scheduling of expensive projects with relatively long ordering lead times and ultimately provided a rationale for minimizing the cost of such projects. Dodin and Elimam (2001) developed a model that accounts for factors such as the variability of activities duration, the variability of project value, bonuses/penalties due to early/delayed completion of the project, and the quantity discount applied to purchases. To further develop their previous work, Dodin and Elimam (2008) also provided a model which considers the impact of the use of special and expensive equipment on project cost and schedule. Sajadieh, Shadrokh, and Hassanzadeh (2009) also provided a model for the PSMO problem, where the goal is to determine the optimal activities duration and finish time and the material ordering schedules that minimize the total cost. In that work, the PSMO model of Dodin and Elimam (2001) was developed such that material ordering schedule would be determined for each activity separately. Najafi, Zoraghi, and Azimi (2011) extended the work of Sajadieh et al. (2009) to develop a new optimization model for the PSMO problem with holding inventory and ordering cost minimization objective. Another breakthrough in the PSMO literature was the study of Fu (2014), where they presented a multi-mode problem capable of accounting for the association of activity duration with the quantity of resources to be used depending on how the activity is performed. The main merit of the PSMO problem is the provision of a tradeoff analysis with cost minimization goal, and one of the most important issues in this regard is the quantity discounts provided by suppliers. Hence, Shahsavar, Abbasi, and Zoraghi (2015) studied the impact of suppliers' quantity discount policies on the project schedule. Tabrizi and Ghaderi (2015a) provided a bi-objective mathematical PSMO model, which minimizes the project cost and maximizes the schedule robustness. Tabrizi and Ghaderi (2015b) also developed a MIP model with quantity discounts and space capacity constraint incorporated into formulations. In the model developed by Tabrizi and Ghaderi (2015c), the notion of quantity discount was formulated for several suppliers to improve the material procurement decision-making. Despite the importance of using non-deterministic parameters to make the model more realistic, the majority of mentioned works have followed a deterministic approach. Hence, Tabrizi and Ghaderi (2016) provided a MIP model for minimizing total cost while maximizing schedule robustness. Zoraghi, Shahsavar, Abbasi, and Van Peteghem (2017) developed a model for the Multi-mode PSMO problem, which also included a bonus/penalty policy for project completion in order to achieve a higher degree of realism. They also presented three hybrid metaheuristic algorithms for obtaining efficient solutions.

A summarized list of research works on the PSMO problem is presented in Table 1.

The notable innovations of the present paper as compared to similar works include:

- The comprehensive model developed for project activities scheduling and material order planning enables the decision-makers to consider a tradeoff between project costs and other objectives.
- Formulation of the PSMO problem with sustainability objectives enables the decision-makers to analyze the project's NPV, environmental effects, and social impacts together and simultaneously.
- Formulation of the problem with realistic assumptions such as simultaneous utilization of renewable and non-renewable resources over the course of the project, ordering lead times, multiple suppliers, discount policy, and bonus/penalty for early/delayed project completion allow us to achieve a higher degree of realism.
- AUGMECON2, NSGA-II, and MOPSO are modified for solving the

Table 1
Review of project scheduling and material ordering problems.

Article	Number of objective(s)		Type of objective(s)					Characteristic(s)				Resource type		Case study	Solving method
	Single	Multiple	Cost	NPV	Environmental	Social	Robustness	Lead time	Multi-supplier	Discount policy for multi-supplier	Bonus and penalty	Renewable	Non-renewable		
Smith-Daniels and Smith-Daniels (1987a)	✓			✓				✓					✓		
Smith-Daniels and Smith-Daniels (1987b)	✓		✓										✓		
Dodin and Elimam (2001)	✓		✓					✓			✓		✓		
Dodin and Elimam (2008)	✓		✓								✓	✓			EFL
Sajadieh et al. (2009)	✓		✓					✓			✓		✓		GA
Najafi et al. (2011)	✓		✓										✓		SA-GA
Zoraghi, Najafi, and Akhavan Niaki (2012)	✓		✓										✓		SA-GA
Fu (2014)	✓		✓								✓	✓	✓		HS-GA
Zoraghi, Najafi, and Niaki (2014)	✓		✓									✓	✓		GA-GA, SA-GA
Tabrizi and Ghaderi (2015a)		✓	✓				✓	✓			✓		✓		E-Constraint
Tabrizi and Ghaderi (2015b)	✓		✓					✓			✓		✓		
Tabrizi and Ghaderi (2015c)	✓			✓				✓	✓	✓			✓		GA
Shahsavar et al. (2015)	✓		✓									✓	✓		GA-PSO
Tabrizi and Ghaderi (2016)		✓	✓				✓	✓			✓	✓	✓		NSGA-II
Zoraghi et al. (2017)	✓		✓								✓	✓	✓		PSO-GA,GA-GA, SA-GA
Proposed model		✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	AUGMECON2, NSGA-II, MOPSO

developed model and their performance for various problems sizes is evaluated.
- The applicability of the model is verified and illustrated by a case study on the trackbed construction project in Section 5 of Mianeh-Bostanabad-Tabriz railway in Iran.

The rest of this paper is formed as follows: The second part of this paper describes the problem definition and explains how the framework and mathematical model are developed. In Section 3, the solution approaches are proposed and their results are presented in Section 4. Sections 5 and 6 provides the details and results of a case study carried out to explain the performance of the presented model. Finally, Section 7 presents conclusion and suggests some directions for future research.

2. Methodology

2.1. Problem definition

As shown in Fig. 1, the system studied in this paper includes a project and multiple suppliers. The project includes n activities that should be carried out without delay. The project network is represented by the Activity-On-Node (AON) graph $Gr(N, A)$, where N and A stand for the nodes and arcs sets respectively. In this graph, nodes serve as the project activities and arcs represent their corresponding finish-to-start precedence relationships. Graph nodes are numbered topologically in the ascending order of precedence. In this graph, the nodes (activities) 1 and n are dummy with zero duration and resource consumption and express the start and end points of the project. All project activities can be performed in only one mode and each activity needs a set of renewable and non-renewable resources to be completed. In each period, there will be a constant amount of renewable resources available for activities, but non-renewable resources (materials) need to be purchased from suppliers. Each supplier has its own quantity discount policy. It is assumed that the choice of supplier is a function of not only their discounts but also their environmental and social impacts. Thus, environmental and social objectives are pursued indirectly through the choice of supplier. The other assumptions are as follows:

- All candidate suppliers are able to supply any quantity of the ordered materials.
- For an activity to start, all of its materials must be available at once.
- Materials will be consumed uniformly over the course of the activity.
- The NPV of the project is calculated assuming that payments will be made according to the Payments of Activities (PAC) model, (i.e. payment of each activity will be made immediately after its completion).

2.2. Problem solving structure

The decisions to be made in the model can be divided into two groups: the project scheduling decisions (sequence and start time of project activities), and material ordering decisions (order quantity and time, and supplier), which will be made according to sustainability objectives (cost, environmental, and social considerations). These decisions will be made in two phases. In the first phase, a Fuzzy Inference System (FIS) will be used to evaluate and rate all candidate suppliers according to a series of environmental and social measures. In the second phase, the obtained data will be used in a mathematical optimization model. The general structure of problem solving is illustrated in Fig. 2.

These steps are described in the following:

- **Project definition:** The project profile and specifications including the information about activities and their resources are obtained.
- **Recognition of candidate suppliers:** The suppliers that are able to provide the materials listed in the previous step should be Identified.
- **Determining the costs:** The cost parameters (including the ordering cost, holding inventory cost, purchasing cost according to suppliers' discounts, and bonus/penalty for early/delayed project completion) are determined.
- **Defining the environmental and social sub-criteria and effective indicators:** In this step, the appropriate sub-criteria and effective indicators needed for the evaluation of candidate suppliers in terms of their environmental and social impacts are identified.

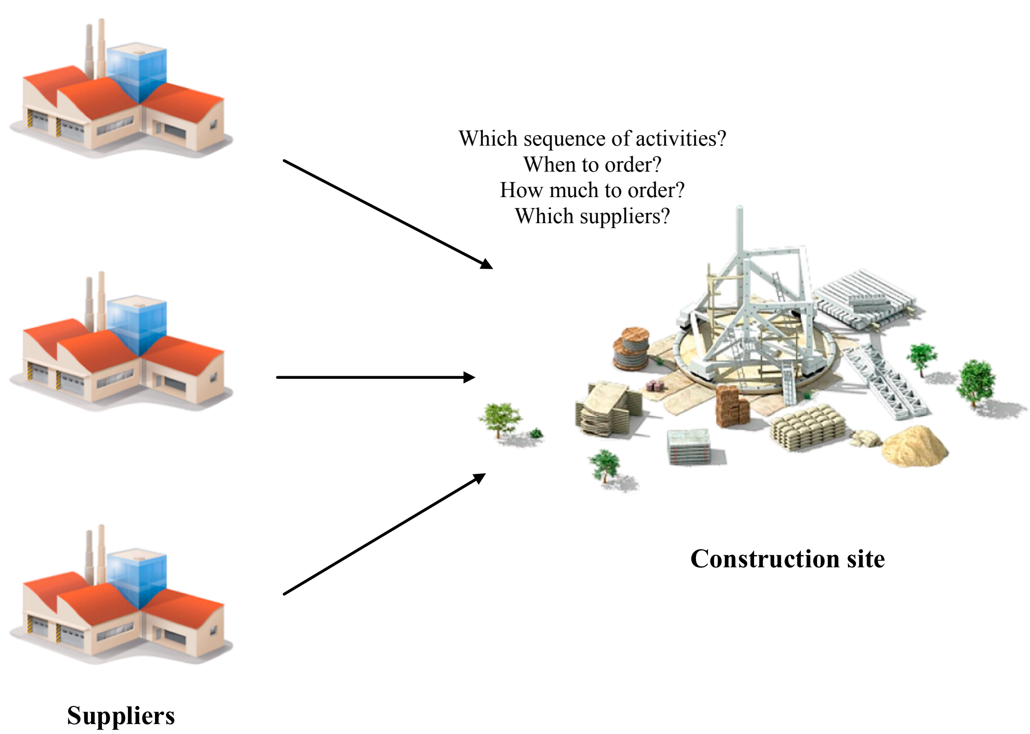


Fig. 1. The overall structure of the considered system.

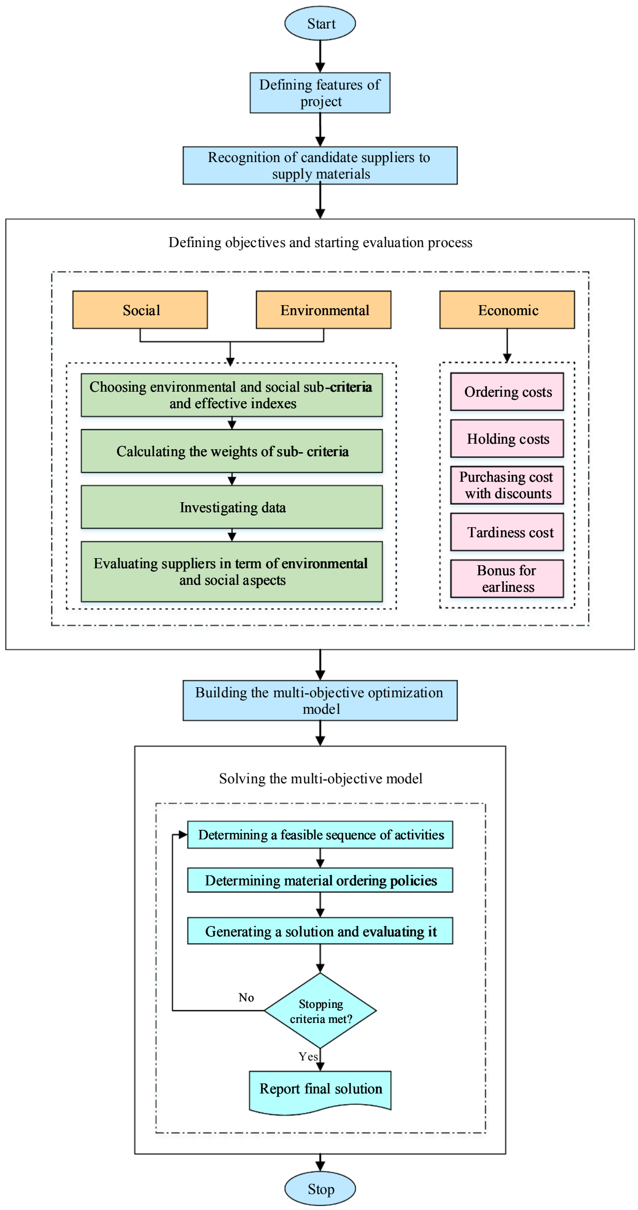


Fig. 2. Steps to solve the project scheduling and material ordering problem with sustainability considerations.

These sub-criteria and effective indicators are determined by systematic reviewing of the related literature followed by an evaluation process conducted by the experts of the organization (project). An example of the sub-criteria and effective indicators obtained from the review of the recent literature are presented in Table 2 (the numbers in parenthesis are the number of times each effective indicator is repeated in the listed articles). The indicators presented in this table are derived from the studies Afful-Dadzie, Afful-Dadzie, and Turkson (2016), Al-Jebouri, Saleh, Raman, Rahmat, and Shaaban (2017), Azadnia, Saman, and Wong (2015), Bottani, Gentilotti, and Rinaldi (2017), Feil, de Quevedo, and Schreiber (2015), Feil, de Quevedo, and Schreiber (2017), Fritz, Schöggl, and Baumgartner (2017), Helleno, de Moraes, and Simon (2017), Heravi, Fathi, and Faeghi (2015), Joung, Carrell, Sarkar, and Feng (2013), Kamali and Hewage (2017), Kopacz, Kryzia, and Kryzia (2017), Leeben, Soni, and Shivakoti (2013), Ocampo, Clark, and Promentilla (2016), Schöggl, Fritz, and Baumgartner (2016), and Zhong and Wu (2015).

- **Evaluating environmental and social aspects:** Here, a fuzzy inference method is presented and used to evaluate the suppliers. As shown in Fig. 3, first all environmental and social data are converted into degrees of membership so that they can be used as the inputs of the Fuzzy Inference System (FIS). Then, the purpose values of input variables, which express their minimum and maximum values, are defined. Also, for easier analysis of output values, the purpose range is set to [0, 1]. After that, the fuzzy rules, which constitute the basis of this fuzzy approach, must be defined. These “if-then” fuzzy rules are defined based on the awareness of the experts of the organization (project). These rules are then utilized in the Fuzzy Inference System (FIS) to convert the inputs to the proper outputs. Finally, fuzzy values are converted to crisp numerical values. In the end, using Eq. (1), the grade of each supplier in environmental or social criteria is determined:

$$\zeta_n = \sum_m w_{m\,n}\, \zeta_{m\,n} \tag{1}$$

where m and n are the indexes of sustainability sub-criteria and criteria respectively, ζ_n is the supplier’s grade in term of n-th sustainability criterion, $w_{m\,n}$ expresses the weight of the m-th sub-criterion in the n-th criterion, and $\zeta_{m\,n}$ is the supplier's grade in the m-th sub-criterion in the n-th criterion. It should be noted that the weights of sub-criteria are determined with the Fuzzy Analytic Hierarchy Process (FAHP) suggested by Chang (1996).

- **Building the optimization model:** Here, a multi-objective optimization model is constructed to solve the problem. This model allows us to determine the project scheduling and material procurement variables that optimize the project NPV and the environmental and social grades of the suppliers.
- **Solving the model and analyzing the results:** In this step, the mathematical model obtained from the previous step is solved by the use of methodologies that produce Pareto optimal solutions, and the results are visualized for the decision maker(s).

2.3. Mathematical model

Sets	
$i,\ j$	Set of project activities; $i, j \in (1,\ 2,\ ...,n)$ which 1 and n are dummy activities
L	Set of renewable resources
F	Set of Non-renewable resources (Required materials)
T	Set of periods of time
S	Set of suppliers
$K_{f\,s}$	Set of price discount ranges; $(\forall\ f \in F, \forall\ s \in S)$
$Pr\,(j)$	Set of direct predecessors for activity j
Parameters	
d_j	Processing time of activity j
DD	Deadline for project completion
T	Planning horizon
$r_{j\,l}$	Quantity of renewable resource type l which is needed for activity j in each period of processing time
$u_{j\,f}$	Amount of material type f which is required to carry out activity j
$R_l^{\max}$	Amount of renewable resource type l which is available in each period.
$A_{f\,s}$	Cost of ordering related to material type f from supplier s
H_f	Unit holding cost related to material type f in each period of time
P	Penalty cost due to late project completion for each period
B	Bonus due to early project completion for each period
EST_j	Earliest starting time for activity j
LST_j	Latest starting time for activity j
CF_j^+	Cash inflow due to activity j
CF_j^-	Cash outflow due to activity j
$C_{f\,k\,s}$	Unit purchasing cost related to material type f in range k which is ordered from supplier s
$LT_{f\,s}$	Lead time of purchasing material type f from supplier s
$\gamma_{f\,k\,s}$	Limitation on range k related to material type f for supplier s
$K_{f\,s}$	Number of discount intervals for purchasing material type f which is suggested by supplier s

Ir	Interest rate
$\left(P/F,\ Ir\%,\ t\right)$	P/F discount factor with interest rate $Ir\%$ and number of periods t
η_{fs}	Grade of supplier s for material type f in environmental criteria
ρ_{fs}	Grade of supplier s for material type f in social criteria
Decision variables	
x_{jt}	A zero-one variable that equals 1 if activity j is started in period t, 0 otherwise
y_{fkst}	A zero-one variable that equals 1 if material type f is ordered within range k from supplier s in time period t, 0 otherwise
z_{fksjt}	A zero-one variable that equals 1 if material type f is ordered within range k from supplier s for activity j in time period t, 0 otherwise
I_{ft}	Inventory level of material type f in period t

Model structure

The mathematical model is presented as follows:

$$
\begin{aligned}
\text{Max}\, Z_1 = & \textstyle\sum_{j=1}^{n} \sum_{t=EST_j}^{LST_j} CF_j^{+} x_{jt} \left(P/F,\ Ir\%,\ t + d_j\right) \\
& - \textstyle\sum_{j=1}^{n} \sum_{t=EST_j}^{LST_j} CF_j^{-} x_{jt} \left(P/F,\ Ir\%,\ t\right) \\
& - \textstyle\sum_{f=1}^{F} \sum_{s=1}^{S} \sum_{t=1}^{LST_n - LT_{fs}+1} A_{fs} \sum_{k=1}^{K_{fs}} y_{fkst} \left(P/F,\ Ir\%,\ t\right) \\
& - \textstyle\sum_{f=1}^{F} \sum_{t=1}^{LST_n + d_n - 1} H_f I_{ft} \left(P/F,\ Ir\%,\ t\right) \\
& - \textstyle\sum_{f=1}^{F} \sum_{s=1}^{S} \sum_{j=1}^{n} \sum_{t=1}^{LST_n - LT_{fs}+1} \sum_{k=1}^{K_{fs}} C_{fks} u_{jf} z_{fksjt} \left(P/F,\ Ir\%,\ t\right) \\
& - \textstyle\sum_{t=DD+1}^{T} P(t - DD) x_{nt} \left(P/F,\ Ir\%,\ t\right) \\
& + \textstyle\sum_{t=EST_n}^{DD-1} B(DD - t) x_{nt} \left(P/F,\ Ir\%,\ t\right)
\end{aligned}
\tag{2}
$$

$$
\text{Max}\, Z_2 = \sum_{f=1}^{F} \sum_{s=1}^{S} \sum_{k=1}^{K_{fs}} \sum_{t=1}^{LST_n - LT_{fs}+1} \eta_{fs} \cdot \sum_{j=1}^{n} u_{jf} z_{fksjt} \tag{3}
$$

Table 2
Environmental and social indicators.

Criteria	Sub-criteria	Effective indicator
Environmental	Pollution	Noise pollution (3)
	Emission	Total CO2 emission (3), Green house emission (11), Total NOx emission (1), Total SOx emission (1)
	Total resource consumption	Total energy consumption (9), Use of natural light (1), Water consumption (12), Use of renewable resources (8), Efficiency of energy consumed (5), Paper used (2)
	Waste	Waste generated (10), Waste reduction (4), Chemical waste (2), Waste water (6), Hazardous waste (6)
	Recycling or reuse	Water recycling (3), Waste recycling (5), Reuse (water or other resources) (5)
	Environmental Management System (EMS)	Environmental management authentication (3), Internal control process (3), Environmental policies (2), Quality of EMS (1), Expenditure on environmental protection (2)
	Materials	Use of environmental friendly materials (8), Use of durable materials (3), Use of recycled materials (4), Product waste (2), Packaging waste (1), Green packaging (3), Use of hazardous materials (5), Regional (local) materials (1)
	Green competencies	Recycling capability (3), Compliance with environmental regulations (5), Energy consumption control (1), Eco-design for reuse and recycling (2), Product durability (2)
Social	Investing	Percent of net profit for community investment (3), Infrastructure improvement (3), Influence on the local economy (2)
	Female	Percent of females in senior position (1), Employment gender ratio (3)
	Training	Job training hours (9), Health and safety training (4)
	Job	Employee turnover (5), Average number of hours worked (1), Average of labor's overtime work hour (1), Full-time workers (1), Salary (4)
	Safety and suitability of workplace	Ventilation efficiency (2), Thermal comfort (2), Lighting comfort (1), Noise complaints (3), Odor complaints (1), Complaints of dust (2), Health and safety incidents (9), Hazardous materials for workers health (1)
	Injury and Illness Prevention Program (IIPP)	Level of OHSAS 18,001 (1), Personnel engagement in health and safety committee (1), Health and safety policies (7), Emergency preparedness and response (1), Employee health evaluation (2)
	Job convenience	The interests and rights of employee (1), Employee contracts (1), Grants and donations (1), Average distance travelled by employees to the company (2)
	Domestic employment policies	Number of created job opportunities (7), Local suppliers (1), Local workers (1)
	Dissatisfactions	Claims (product quality and responsibility) (6), Lay-offs (1), Employee satisfaction (6), Involving stakeholders in decision making (2), Public discomfort (2)
	Business ethics and human rights	Corruption and/or bribery (2), Charities and donations (1), Child labor (4), Compliance with human rights standards and regulations (1), Confidentiality of data (2)

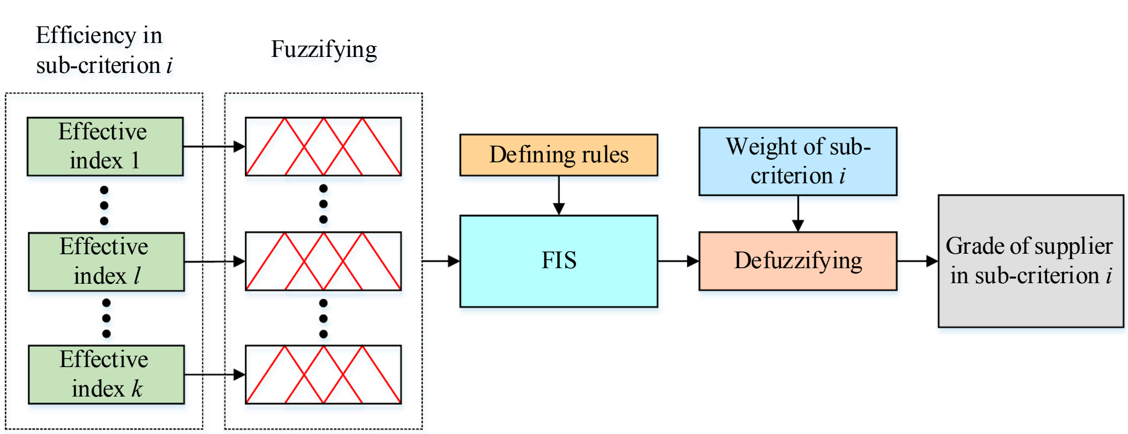


Fig. 3. Fuzzy evaluation process for a supplier.

$$\text{Max } Z_3 = \sum_{f=1}^{F}\sum_{s=1}^{S}\sum_{k=1}^{K_{fs}}\sum_{t=1}^{LST_n-LT_{fs}+1}\rho_{fs}\cdot\sum_{j=1}^{n}u_{jf}\,z_{fksjt} \tag{4}$$

S.t.

$$\sum_{t=EST_j}^{LST_j} t\,x_{jt} - \sum_{t=EST_i}^{LST_i} t\,x_{it} \geqslant d_i \quad \forall\ j=1,2,\dots,n;\ \forall\ i\in Pr(j) \tag{5}$$

$$\sum_{j=1}^{n}\sum_{t'=\max(t-d_j+1,EST_j)}^{\min(t,LST_j)} r_{jl}\,x_{jt'} \leqslant R_l^{\max} \quad \forall\ t=1,2,\dots,LST_n;\ \forall\ l\in L \tag{6}$$

$$I_{ft} = I_{f(t-1)} + \sum_{j=1}^{n}\sum_{s=1}^{S}\sum_{k=1}^{K_{fs}} u_{jf}\,z_{fksj(t-LT_{fs})} - \sum_{j=1}^{n}\sum_{t'=\max(t-d_j+1,EST_j)}^{\min(t,LST_j)}\frac{u_{jf}}{d_j}x_{jt'} \quad \forall\ f\in F;\ \forall\ t=1,2,\dots,LST_n \tag{7}$$

$$I_{f0} = I_{f\,LST_n+d_n} = 0 \quad \forall\ f\in F \tag{8}$$

$$\sum_{t=EST_j}^{LST_j} x_{jt} = 1 \quad \forall\ j=1,2,\dots,n \tag{9}$$

$$\gamma_{f(k-1)s}\,y_{fkst} \leqslant \sum_{j=1}^{n} u_{jf}\,z_{fksjt} \leqslant \gamma_{fks}\,y_{fkst} \quad \forall\ f\in F;\ \forall\ s\in S;\forall\ k\in K_{fs};\ \forall\ t=1,2,\dots,LST_n \tag{10}$$

$$\sum_{k=1}^{K_{fs}} y_{fkst} \leqslant 1 \quad \forall\ f\in F;\ \forall\ t=1,2,\dots,LST_n;\ \forall\ s\in S \tag{11}$$

$$\sum_{s=1}^{S}\sum_{k=1}^{K_{fs}}\sum_{t=1}^{T-1} z_{fksjt} = 1 \quad \forall\ j=1,2,\dots,n;\ \forall\ f\in F \tag{12}$$

$$\sum_{s=1}^{S}\sum_{k=1}^{K_{fs}}\sum_{t=1}^{T-1}(t+LT_{fs})z_{fksjt} \leqslant \sum_{t=EST_j}^{LST_j} t\,x_{jt} \quad \forall\ j=1,2,\dots,n;\ \forall\ f\in F \tag{13}$$

$$\begin{matrix} x_{jt},\ y_{fkst},\ z_{fksjt}\in[0,1] \\ I_{ft}\geqslant 0 \end{matrix} \quad \forall\ j=1,2,\dots,n;\ \forall\ f\in F;\ \forall\ s\in S;\ \forall\ k\in K_{fs};\ \forall\ t=1,2,\dots,LST_n \tag{14}$$

Eq. (2) or the first objective function maximizes the project NPV. The first term of this equation is related to cash inflows or payments from activities, the next term expresses the project costs, including the activities cost, ordering cost, holding inventory cost, and purchasing cost, and the last term calculates the bonus/penalty for early/delayed project completion.

Eq. (3) or the second objective function of the model maximizes the overall environmental grade due to the purchase of materials from suppliers. In this equation, the environmental grade of each supplier, which is determined by the proposed fuzzy approach, is used as a multiplier for the $\sum_{j=1}^{n} u_{jf}\,z_{fksjt}$.

Eq. (4) or the third objective function maximizes the total social grade resulting from the purchase of materials from suppliers.

Eq. (5) is a constraint defining the precedence relationships between project activities. According to this constraint, an activity cannot begin if its preceding activities are not completed. Constraint (6) prevent the start of activities without sufficient renewable resources. Constraint (7) maintains the balance of non-renewable resources (materials). Constraint (8) states that the level of inventory at the beginning of the first period and the end of the final period is zero for all of materials. Eq. (9) states that an activity can start only once between its earliest and latest starting times. Eqs. (10)–(12) are the constraints related to purchasing and discounts. Eq. (10) limits the amount of material to be purchased to the range between the lower and upper limits of the applying discount. Eq. (11) states that the quantity of material to be purchased can fall in at most one discount range. Constraint (12) states that for each activity and each type of material needs one purchase. Constraint (13) states that each activity can begin only after the needed materials are acquired. Also, Eq. (14) defines the domains of decision variables.

3. Solution approaches

3.1. Introduction of solution methods

Sajadieh et al. (2009) proved that the PSMO problem falls within the NP-Hard problems class, and since the presented model is an extension of the PSMO problem, it also will be an NP-Hard problem. Hence, the model is solved using two metaheuristic algorithms, namely the Multi-Objective Particle Swarm Optimization (MOPSO) and the Non-dominated Sorting Genetic Algorithm II (NSGA-II). The reason for choosing these algorithms to solve large instances of the proposed problem is their good track record in successfully solving project scheduling problems (see Habibi, Barzinpour, & Sadjadi, 2017). To evaluate the performance of these two methods in solving small-sized problems, their results are compared with that of second version of the augmented ε-constraint method (AUGMECON2) but for larger problems, where the exact method was unable to produce a solution within a reasonable time, these two algorithms were compared with each other. Introduced by Mavrotas and Florios (2013), AUGMECON2 is a modified version of the original augmented ε-constraint method (AUGMECON) developed by Mavrotas (2009) and provides a better solution speed (especially for MOIP problems). The MOPSO algorithm was first introduced by Coello, Pulido, and Lechuga (2004) as an extension of the PSO algorithm to solve multi-objective problems. NSGA-II was developed by Deb, Pratap, Agarwal, and Meyarivan (2002) by improving upon its original version called NSGA. Further information about each method can be found in the related articles. In this study, NSGA-II and MOPSO were subjected to following modifications to enhance their ability to solve the presented model.

- In the NSGA-II algorithm, new populations are generated using the arithmetic crossover and Gaussian mutation operators. The use of these operators will lead to a more efficient search of the solution space.
- In the MOPSO algorithm, the Boltzmann distribution is used to enhance the leader selection process as well as the replacement of repository members with new non-dominated solutions. The use of this approach improves the chances of roulette wheel choosing the desired solutions.

3.2. Solution representation

Efficient searching of the solution space requires the use of an efficient solution representation. In this study, the matrix ∇ (Fig. 4) is designed to represent the set of solutions. The columns of this matrix demonstrate the activities of project, and its rows represent the results of the presented model. The first row of this matrix shows an sequence of activities (AS_j^{∇}) that represents the order in which activities are performed and must be feasible in term of their precedence relationships. The second row of this matrix shows the start times of these activities (ST_j^{∇}). The rows 3 to $m+2$ show the time of order to be made for each activity and material (OT_{mj}). The rows $m+3$ to $2m+2$ of matrix ∇ show the suppliers from whom each material for each activity will be purchased (S_{mj}^{∇}).

3.3. Standard problems

The performance of the solution methods for the proposed model is

$$\nabla = \begin{bmatrix} AS_1^\nabla & AS_2^\nabla & \cdots & AS_n^\nabla \\ ST_1^\nabla & ST_2^\nabla & \cdots & ST_n^\nabla \\ OT_{11}^\nabla & OT_{12}^\nabla & \cdots & OT_{1n}^\nabla \\ OT_{21}^\nabla & OT_{22}^\nabla & \cdots & OT_{2n}^\nabla \\ \vdots & \vdots & & \vdots \\ OT_{m1}^\nabla & OT_{m2}^\nabla & \cdots & OT_{mn}^\nabla \\ S_{11}^\nabla & S_{12}^\nabla & \cdots & S_{1n}^\nabla \\ S_{21}^\nabla & S_{22}^\nabla & \cdots & S_{2n}^\nabla \\ \vdots & \vdots & & \vdots \\ S_{m1}^\nabla & S_{m2}^\nabla & \cdots & S_{mn}^\nabla \end{bmatrix}$$

Fig. 4. Representation matrix for the proposed model.

evaluated by problem instances of different sizes, which are derived from the Project Scheduling Problem Library (PSPLIB). The size of the proposed model depends on various parameters; these parameters and their values in the selected test problems are listed in Table 3. It should be noted that these problem sizes have been originally proposed and studied in Tabrizi and Ghaderi (2015c).

Those parameters that are absent from the standard library data are generated randomly with a uniform distribution. This distribution function is chosen either because of the existence of random data generated with the same distribution in other articles or because of the nature of parameter itself. The values of the problem parameters in the evaluation of the solving methods are shown in Table 4.

3.4. Evaluation criteria

The comparison between the solution methods is made based on a set of basic measures for comparing multi-objective solution methods, which have been reviewed in Mohammadi, Jolai, and Tavakkoli-Moghaddam (2013).

- **Number of Pareto Solutions (NPS):** The NPS is one of the criteria commonly used for the evaluation of multi-objective solving methods. Naturally, access to a higher number of Pareto solutions can improve the quality of decision-making. Thus, those algorithms that have a higher NPS are more preferable (Habibi et al., 2017).
- **Quality Metric (QM):** To evaluate the quality of algorithms outputs, all of Pareto solutions of all algorithms must be subjected to pairwise comparison to determine and remove the dominated solutions. The Quality Metric, defined as the ratio of the number of achieved non-dominated solutions of each algorithm to the total number of its solutions at the beginning is used as a measure of the quality of solutions. Naturally, a higher QM reflects a better algorithm performance (Habibi et al., 2017).
- **Mean Ideal Distance (MID):** The MID measures the proximity of non-dominated solutions to the ideal solution ($f_1^{best}, f_2^{best}, f_3^{best}$). This metric is calculated by Eq. (15):

Table 4
Value of parameters used in standard problems.

Parameter	Value	Reference
K_{fs}	~ U[1, 3]	Tabrizi and Ghaderi (2015c)
$Pr(j)$	Standard data	PSPLIB
d_j	Standard data	PSPLIB
DD	Standard data	PSPLIB
T	Standard data	PSPLIB
r_{jl}	Standard data	PSPLIB
u_{jf}	~ U[1, 4]	Tabrizi and Ghaderi (2015c)
R_l^{max}	Standard data	PSPLIB
A_{fs}	~ U[5, 10]	Tabrizi and Ghaderi (2015c)
H_f	~ U[1, 5]	Tabrizi and Ghaderi (2015c)
P	Standard data	PSPLIB
B	Standard data	PSPLIB
CF_j^+	~ U[250, 350]	Tabrizi and Ghaderi (2015c)
CF_j^-	~ U[60, 100]	Tabrizi and Ghaderi (2015c)
C_{fks}	~ U[3, 8]	Tabrizi and Ghaderi (2015c)
LT_{fs}	~ U[1, 15]	Tabrizi and Ghaderi (2015c)
γ_{fks}	~ U[5, 15]	Tabrizi and Ghaderi (2015c)
Ir	~ U[0.04, 0.1]	Tabrizi and Ghaderi (2015c)
η_{fs}	~ U[0, 1]	Parameter nature
ρ_{fs}	~ U[0, 1]	Parameter nature

Table 5
Parameter levels of NSGA-II algorithm.

Row	Parameters	Levels		
		Low	Medium	High
1	Max iterations	100*	200	300
2	Population size	50	100	150*
3	Crossover Percentage	0.5*	0.7	0.9
4	Mutation Percentage	0.1*	0.2	0.3
5	Mutation rate	0.02	0.1	0.18*
6	Mutation step size	0.05	0.1	0.15*

* Chosen levels for running the algorithm.

Table 6
Parameter levels of MOPSO algorithm.

Row	Parameters	Levels		
		Low	Medium	High
1	Max iterations	50	100*	150
2	Population size	50	100*	150
3	Repository size	100	150*	200
4	Inertia weight	0.5	1*	1.5
5	Inertia weight damping rate	0.85*	0.9	0.95
6	Personal experience weight	1*	2	3
7	Leader weight	2*	3	4
8	Number of grids	3	5	7*
9	Inflation rate for grids	0.1	0.15	0.2*
10	Leader selection pressure	2	4	6*
11	Deletion selection pressure	2	4	6*
12	Mutation rate	0.02	0.1*	0.18

* Chosen levels for running the algorithm.

Table 3
Size of selected standard problems.

Parameter	Number of activities	Number of Suppliers	Number of non-renewable resources	Number of renewable resources
Considered values	4, 5, 6, 7 30, 60, 90, 120	1, 2, 3	2, 3, 4	2, 3, 4

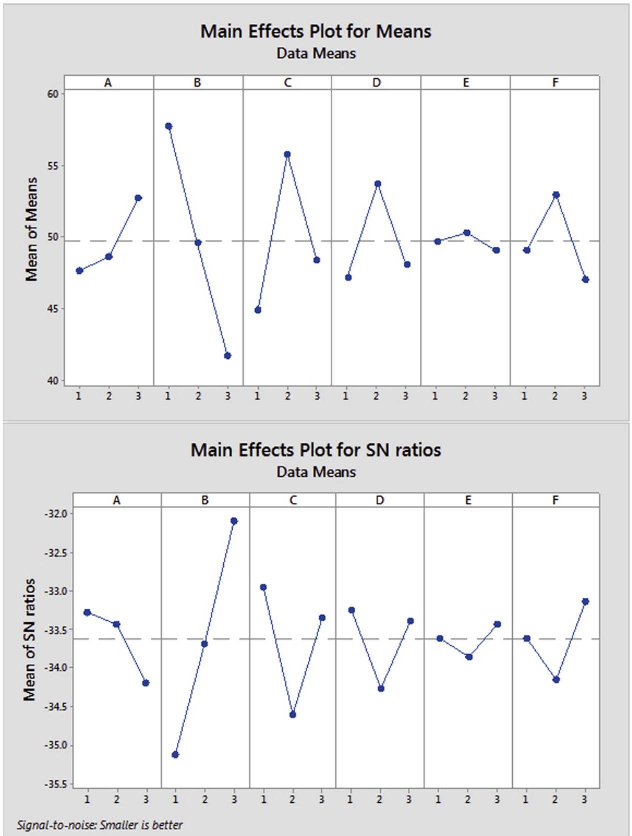


Fig. 5. Minitab software output for determining the parameters of NSGA-II algorithm.

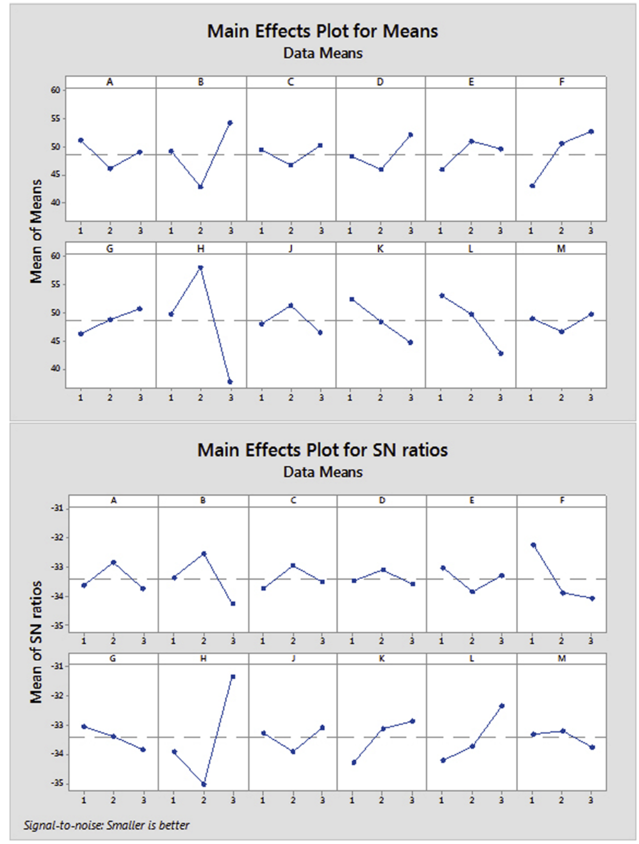


Fig. 6. Minitab software output for determining the parameters of MOPSO algorithm.

$$MID = \frac{\sum_{i=1}^{n}\sqrt{\left(\frac{f_{1i}-f_1^{best}}{f_{1,total}^{\max}-f_{1,total}^{\min}}\right)^2+\left(\frac{f_{2i}-f_2^{best}}{f_{2,total}^{\max}-f_{2,total}^{\min}}\right)^2+\left(\frac{f_{3i}-f_3^{best}}{f_{3,total}^{\max}-f_{3,total}^{\min}}\right)^2}}{n} \tag{15}$$

where n expresses the NPS, $f_{i,\,total}^{\min}$ and $f_{i,\,total}^{\max}$ indicate the minimum and maximum values of the objective function i among all solution methods. By definition, a lower MID is indicative of a better algorithm performance.

- **Diversification Metric (DM):** The DM measures the diameter of the cube encompassing the space created by the boundaries of objective functions for the set of Pareto solutions. This metric is calculated by Eq. (16):

$$DM = \sqrt{\left(\frac{\max\{f_{1i}\}-\min\{f_{1i}\}}{f_{1,\,total}^{\max}-f_{1,\,total}^{\min}}\right)^2+\left(\frac{\max\{f_{2i}\}-\min\{f_{2i}\}}{f_{2,\,total}^{\max}-f_{2,\,total}^{\min}}\right)^2+\left(\frac{\max\{f_{3i}\}-\min\{f_{3i}\}}{f_{3,\,total}^{\max}-f_{3,\,total}^{\min}}\right)^2} \tag{16}$$

With this definition, the higher is the DM of algorithm solutions, the better is the algorithm performance.

- **Spacing Metric (SM):** This indicator shows how uniformly spread is the set of non-dominated solutions and is calculated by Eq. (17):

$$SM = \frac{\sum_{i=1}^{n-1}|d_i-\bar{d}|}{(n-1)\bar{d}} \tag{17}$$

where n expresses the NPS, d_i is the distance (Euclidean) between adjacent solutions given by the algorithm, and $\bar{d}$ indicates the mean of these distances. Lower values of this metric represent a more uniform dispersion of solutions on the Pareto front.

3.5. Parameter tuning

One of the fundamental steps required for implementation and performance evaluation of metaheuristic algorithms is parameters tuning. In this study, algorithm parameters are tune using the Taguchi's design of experiments method. Taguchi method as a robust design method can decline the number of required experiments in a full factorial experiment so as to determine the significant factors (here the parameters of an algorithm) which affect the response (here the solution). Two types of factors, namely noise (N) and controllable factors (S), exist in this method. In addition, Taguchi proposed a process for N to decrease the variation around the target. Hence, this method can determine the design impressed less by N as the robust one through considering orthogonal arrays (Sadeghi & Niaki, 2015). For tuning, the parameters of MOPSO and NSGA-II are divided into three different levels, and then adjusted for a medium-sized problem consisting of 60 activities, 2 suppliers, 2 non-renewable resources, and 2 renewable resources. The defined parameter levels for NSGA-II and MOPSO are presented in Tables 5 and 6, respectively. Also, Figs. 5 and 6 shows the results of parameter tuning for NSGA-II and MOPSO. These results are obtained using the Minitab software.

4. Computational results

4.1. Evaluating solution methods

To evaluate the performance of NSGA-II and MOPSO for the proposed model, their performance in solving small-sized standard problems is compared with that of AUGMECON 2; but for large-sized problems, they are compared against each other. Hence, the proposed

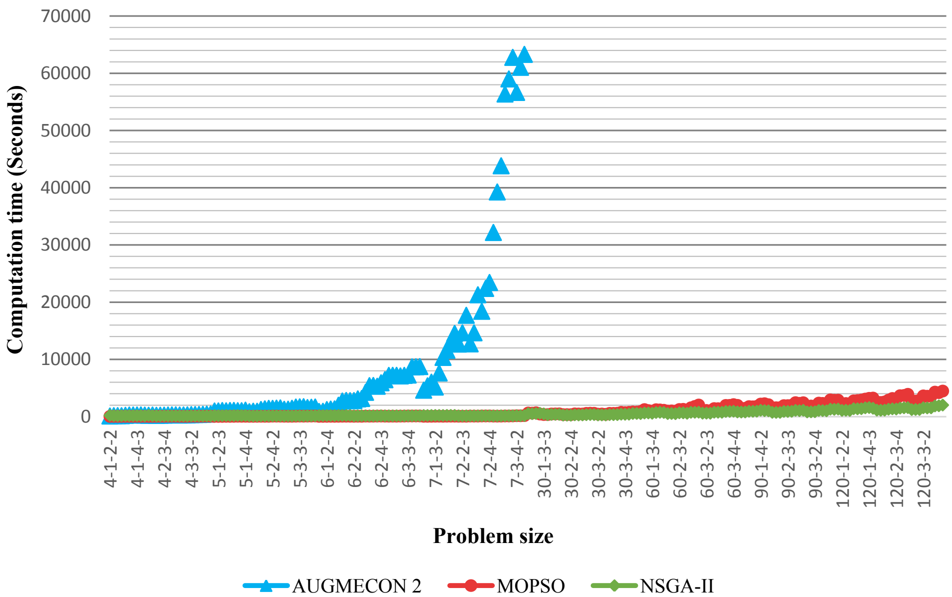


Fig. 7. The result of comparing solution methods in terms of computational time.

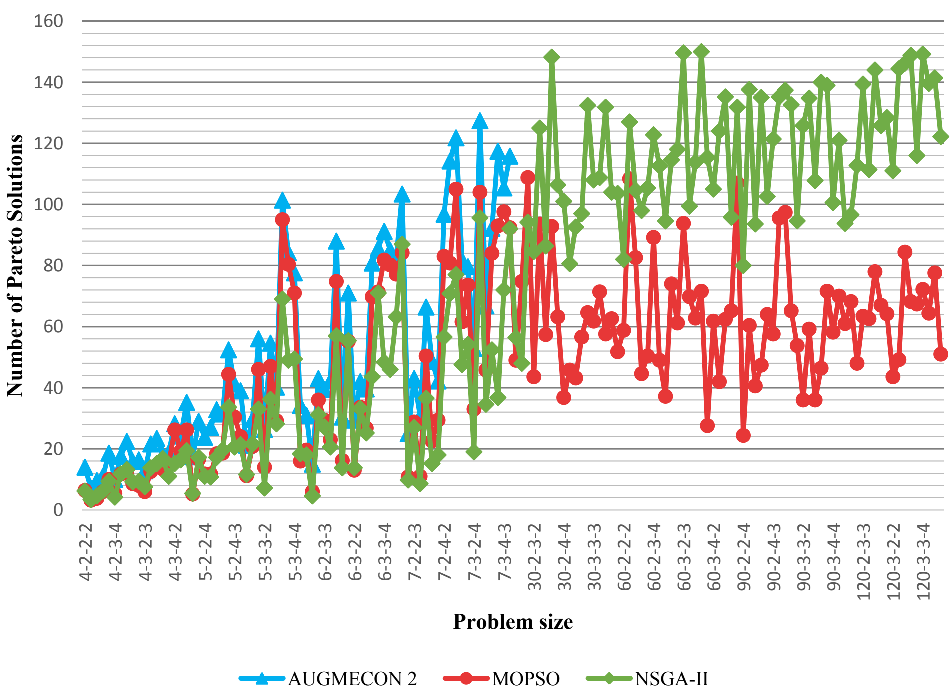


Fig. 8. The result of comparing solution methods in terms of NPS.

model was coded in MATLAB R2015a software, and was run on a PC with corei7@ 2.0 GHz processor, 8 GB Ram and Windows 7-64-bit OS. Since some of the problem parameters are created using a uniform distribution function, to reduce the impact of random data and errors on the results, problem of each size is solved five times and the mean of results is considered as the final result for that particular problem size.

- **Computational time:** The solution time of AUGMECON 2, NSGA-II, and MOPSO for different problem sizes are shown in Fig. 7. Here, the size of the problem is expressed as n-S-F-L, which represent the number of project activities, suppliers, and non-renewable and renewable resources, respectively.
  Fig. 7 shows that the solution time of all three methods increases with the problem size. For AUGMECON 2, this increase in solution time is exponential, but for MOSPO and NSGA-II, it is linear with a slight slope. In AUGMECON 2, there is a significant prolongation of the solution time when the number of project activities goes above 7. It is therefore evident that this method is not suitable for large-sized problems. In it can also be seen that for large-sized problems, MOPSO has a significantly longer solution time than NSGA-II.
- **Number of Pareto Solutions (NPS):** Fig. 8 shows the NPS obtained by the solving methods for the different problem sizes.
  As shown in Fig. 8, in general, NPS of all three methods almost increases with the problem size. In small-sized standard problems, AUGMECON 2 yields a greater NPS than MOPSO and NSGA-II. The difference between the NPS of AUGMECON 2 and that of MOPSO and NSGA-II gradually widens as the problem size increases. Regarding MOPSO and NSGA-II methods, for smaller problems,

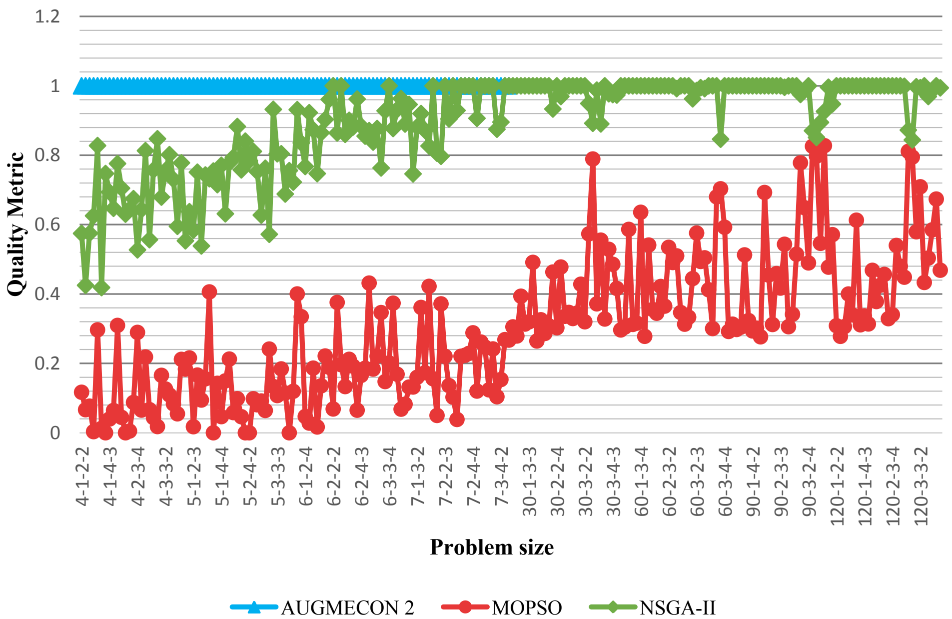


Fig. 9. The result of comparing solution methods in terms of QM.

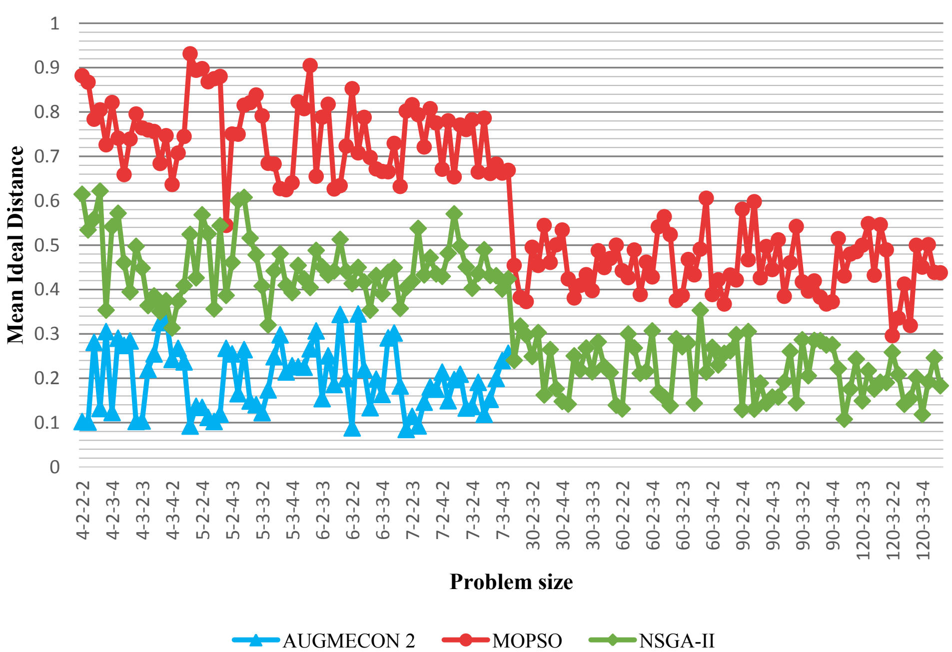


Fig. 10. The result of comparing solution methods in terms of MID.

MOPSO has a generally greater NPS than NSGA-II, but as the problem size grows, NSGA-II strongly outperforms MOPSO in this respect.

- **Quality Metric (QM):** Fig. 9 shows the QM values obtained for the solving methods in the different problem sizes.
  As shown in Fig. 9, none of the solutions of AUGMECON 2 are dominated by those of MOPSO and NSGA-II. Also, for the all problem sizes, NSGA-II yields higher quality solutions than MOPSO. In fact, as the problem size increases, the QM of NSGA-II converges to 1. Although the QM of MOPSO also increases with problem size, it never reaches the same level as NSGA-II.
- **Mean Ideal Distance (MID):** The MID values obtained for the solving methods are presented in Fig. 10.
  As Fig. 10 shows, the solutions of AUGMECON 2 are generally closer to the ideal solution than those of NSGA-II and MOPSO. The comparison between MOPSO and NSGA-II in this respect shows that NSGA-II achieves a lower MID in both small-sized and large-size problems.
- **Diversification Metric (DM):** The results of the evaluation of three methods in terms of DM are presented and compared in Fig. 11.
  Fig. 11 shows that as the problem size increases, the solutions become more diversified. For small-sized problems, the solutions of AUGMECON 2 have more diversification than those of other methods. For smaller problems, the results of NSGA-II and MOPSO have almost the same degree of spread, but for larger problems, MOPSO has a superiority over NSGA-II in this respect.
- **Spacing Metric (SM):** The SM values of the solution methods are compared in Fig. 12.
  As shown in Fig. 12, for small-sized problems, AUGMECON 2 has the best performance among the solution methods in terms of SM. Also,

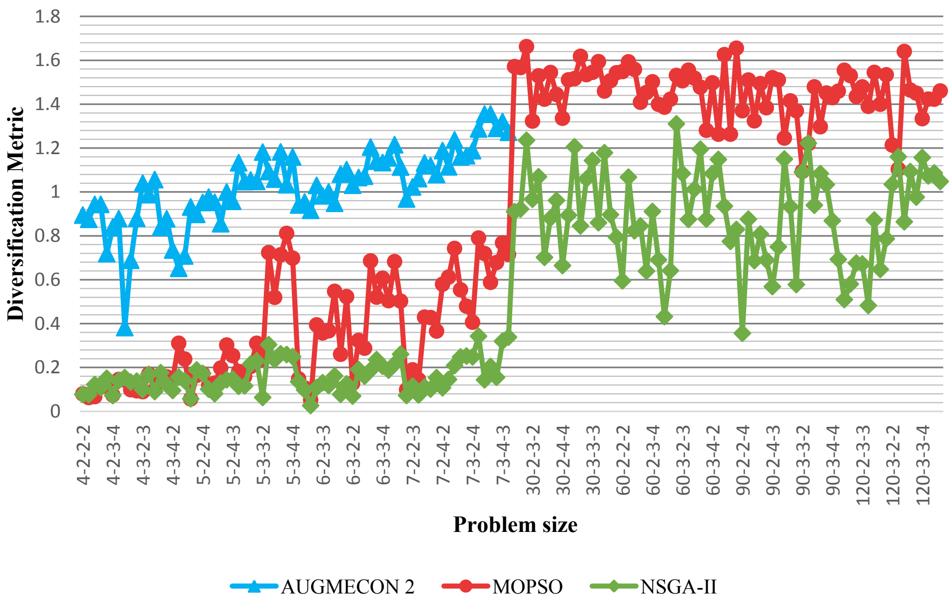


Fig. 11. The result of comparing solution methods in terms of DM.

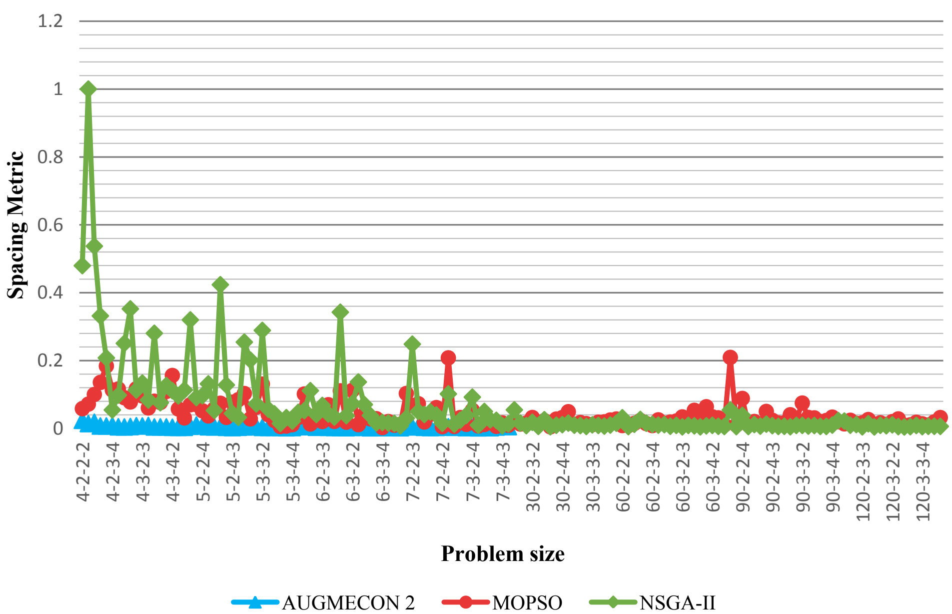


Fig. 12. The result of comparing solution methods in terms of SM.

Table 7
The results of the ANOVA test for small-sized problems.

ANOVA	Algorithm	Average	Variance	P-value	Superior algorithm	Significant difference
Computational time	MOPSO	77.92	689.06	7.165E-61	MOPSO	Yes
	NSGA-II	161.94	704.83			
NPS	MOPSO	37.85	958.92	8.697E-2	MOPSO	No
	NSGA-II	29.95	554.79			
QM	MOPSO	0.152	0.0116	5.241E-98	NSGA-II	Yes
	NSGA-II	0.807	0.0198			
MID	MOPSO	0.750	0.0070	1.219E-49	NSGA-II	Yes
	NSGA-II	0.452	0.0051			
DM	MOPSO	0.342	0.0552	2.278E-9	MOPSO	Yes
	NSGA-II	0.157	0.0050			
SM	MOPSO	0.057	0.0021	1.135E-3	MOPSO	Yes
	NSGA-II	0.122	0.0251			

Table 8
The results of the ANOVA test for large-sized problems.

ANOVA	Algorithm	Average	Variance	P-value	Superior algorithm	Significant difference
Computational time	MOPSO	1751.76	1,130,562	3.416E-14	NSGA-II	Yes
	NSGA-II	857.46	175,978			
NPS	MOPSO	62.90	340.32	3.100E-32	NSGA-II	Yes
	NSGA-II	115.54	494.24			
QM	MOPSO	0.446	0.0222	7.017E-94	NSGA-II	Yes
	NSGA-II	0.985	0.0013			
MID	MOPSO	0.453	0.0042	7.086E-49	NSGA-II	Yes
	NSGA-II	0.218	0.0036			
DM	MOPSO	1.453	0.0144	6.758E-42	MOPSO	Yes
	NSGA-II	0.889	0.0462			
SM	MOPSO	0.026	0.0007	2.594E-5	NSGA-II	Yes
	NSGA-II	0.011	0.0001			

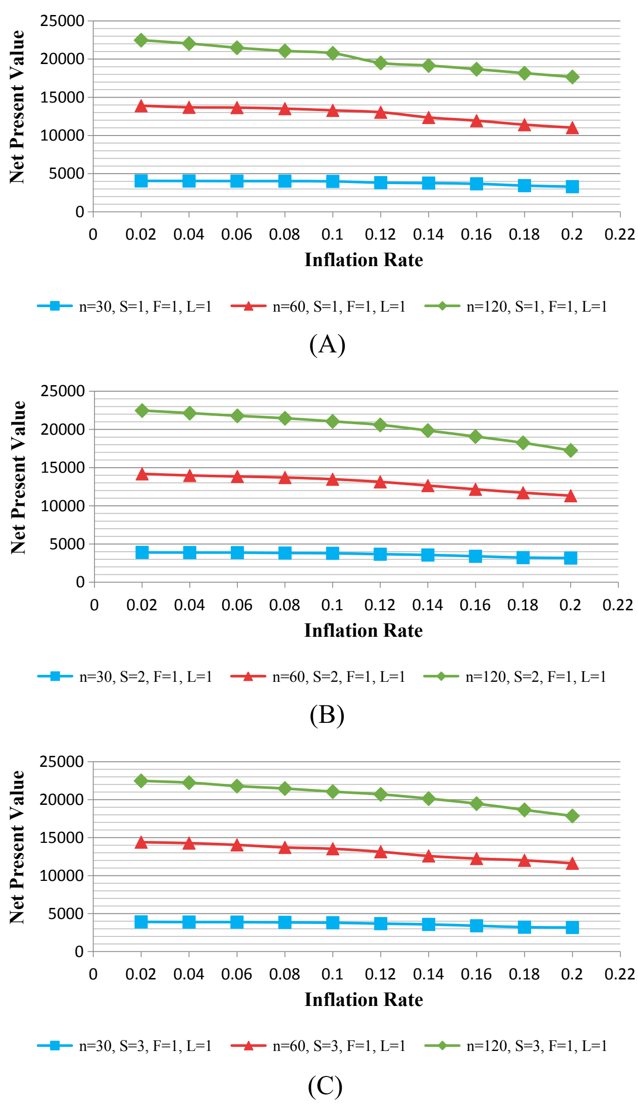


Fig. 13. The sensitivity of NPV to the inflation rate in different problem sizes.

for the problems of this size, MOPSO has a lower SM than NSGA-II, indicating the greater uniformity of its solutions. However, as the problem size increases, NSGA-II achieves lower (better) SM values, and eventually outperforms MOPSO by producing more uniform solutions for large-sized problems.

In this stage, single factor ANOVA is used to determine whether there is a significant difference between the performance of MOPSO and NSGA-II or not (Khalilpourazari & Pasandideh, 2018).Tables 7 and 8 give information on the results of this test for small-sized and large-sized problems, respectively. It is worth mentioning that ninety-five percent confidence level is considered for this test.

The results of the ANOVA test show that NSGA-II has a significantly better performance for solving real-world issues. This algorithm is able to provide much more efficient solutions for large-sized problems in terms of computational time, NPS, QM, MID, and SM metrics. However, the MOPSO algorithm provides more diverse solutions. In general, the NSGA-II algorithm performs better to solve real-world problems.

4.2. Sensitivity analysis

To verify the presented model and study the effect of inflation on the NPV of the project, a sensitivity analysis was conducted on the inflation parameter. This analysis was conducted by the use of standard problems with 30, 60, and 120 activities and 1, 2 and 3 suppliers, 1 renewable source, and 1 non-renewable source. In this analysis, project NPV was considered as the only objective function. Assuming that the inflation rate β applies to the problem, the present value of the payment F in the period t with the interest rate $Ir\%$ can be obtained by Eq. (18).

$$P = \frac{F(1+\beta)^t}{(1+Ir+\beta)^t} \tag{18}$$

The above equation was used to calculate the NPV term in the first objective function for the inflation rates of between 0.02 and 0.20. Since the NPV term was the only objective function and these single-objective problems could not be solved by the exact methods, they were solved by a Genetic Algorithm (GA). Fig. 13 shows the impact of inflation rate on the project NPV for the different problem sizes.

Fig. 13 shows that as the inflation increase, NPV decreases. Also, inflation has a greater impact on bigger projects. Thus, the impact of inflation rate on project implementation needs to be regarded as a critical factor. Moreover, as can be seen, the NPV curve exhibits a steeper slope as the inflation rate increases. Therefore, under unstable economic conditions, neglecting the inflation can confront the project implementation with more serious threats.

5. Case study

5.1. Introduction

Railways are known to be one of the safest methods of transportation and account for a major portion of total land transit in developed countries. One of the major rail transport development projects currently underway in Iran is the Mianeh-Bostanabad-Tabriz railway. In fact, this project can be considered as the most important railway development project in the northwestern region of this country. The Mianeh-Bostanabad-Tabriz railway is a 183 km long double-track railroad that is under construction in 10 separate sections (still unfinished

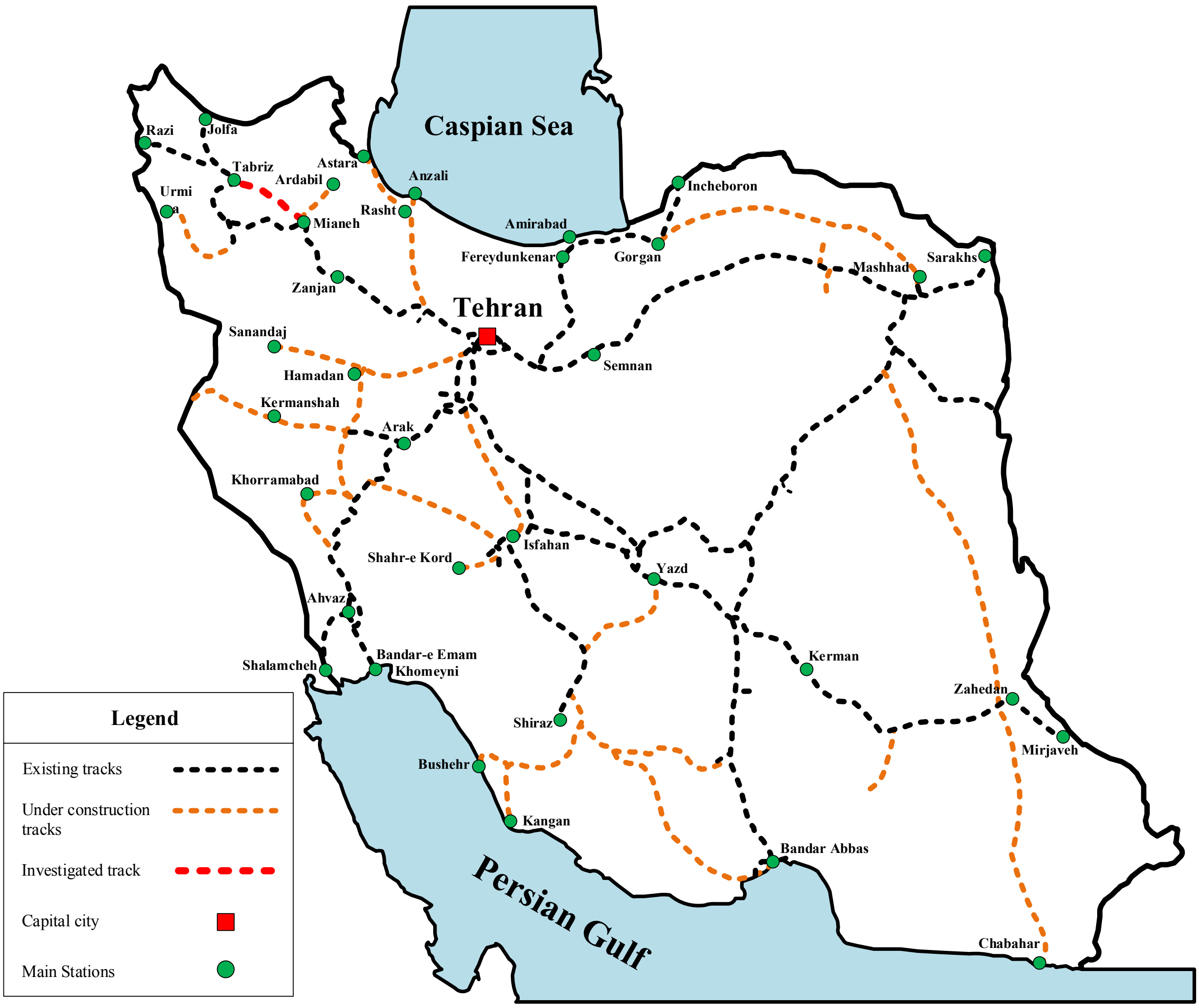


Fig. 14. Iran Railway network and location of investigated project.

Table 9
Resources of the investigated project.

Renewable resources	Dump truck, Excavator, Loader, Bulldozer, Batching plant, Concrete mixer truck, Grader, Road roller, Water sprinkler truck, Concrete pump, Concrete workers, Reinforcement workers, Formwork workers
Non-renewable resources	Aggregates, Cement, Steel bars

Table 10
Potential distributers in investigated project.

Distributer	Organization tasks
YNZ ETP BMT	Consultation and supply of materials and construction equipment used by contractors in construction projects

Table 11
Sub-criteria and effective indicators identified for the investigated project.

Criteria	Sub-criteria	Effective indicators
Environmental	Greenhouse gas emission	CH_4 emission CO_2 emission NO_2 emission
	Resource consumption	Water consumption Power consumption
	Environmental Management System (EMS)	Attempt to EMS fulfillment Quality of EMS
Social	Injury and Illness Prevention Program (IIPP) Job policies	IIPP fulfillment stage Employee health assessment Number of created job opportunities Employment gender ratio

at the time of research). This project also requires 11 relatively large tunnels, 10 galleries with a total length of 14.34 km, 21 long bridges with a total length of about 8 km, and 515 canals with a total length of about 10 km to be constructed along the route. This railway will reduce the transport distance between Tehran (Iran's capital) and Tabriz by 114 km or 5.5 h. Fig. 14 displays the location of this project.

5.2. Framework implementation

In this study, the trackbed construction project for the Section 5 of this railway (from km 86 to km 92) was investigated as an illustrative example. This subsection describes how the framework was implemented for this project:

Table 12
Fuzzy numbers and verbal variables.

Fuzzy numbers	Verbal variable
(1, 1, 1)	Equal importance
(1/2, 1, 3/2)	Very weak importance
(1, 3/2, 2)	Weak importance
(3/2, 2, 5/2)	Moderate importance
(2, 5/2, 3)	Strong importance
(5/2, 3, 7/2)	Very strong importance

- **Project definition:** All information related to the project under study (trackbed construction project for the Section 5 of the Mianeh-Bostanabad-Tabriz railway) was extracted and checked to ensure full compatibility with the model assumptions. The project has 57 main activities, 13 types of renewable resources, 3 types of non-renewable resources, and 3 main distributers. The information about resources and identified distributers are presented in Table 9. The general information about the project is provided in the Appendix A.
- **Recognition of candidate distributers:** The non-renewable resources utilized in this project (aggregates, cement and steel bars) are standard construction materials with many potential distributers. The candidate distributers that were capable of providing these materials in needed quantities at the site of the project are listed in Table 10.
- **Determining the costs:** After identifying the candidate distributers, the material costs were calculated accordingly.
- **Defining the corresponding sub-criteria and effective indicators:** Since the environmental and social sub-criteria and effective indicators may vary with the organization, the framework requires a standard mechanism for selecting the most relevant evaluation measures. For this particular project, the list of effective indicators shown in Table 2 was shared with a panel of experts, who were asked to select the most relevant measures with the yes/no operator, add any sub-criteria or effective indicator that might be neglected, and then modify the list accordingly. After redrafting the list according to modifications, the experts were asked to give the listed sub-criteria and effective indicators a score of zero or one based on their opinion regarding whether the indicator should be included in the list. The effective indicators that achieved 51% of expert votes were included in the secondary list. This list was again returned to the experts, who after several meetings developed a final list of criteria, sub-criteria, and effective indicators for this particular project. Table 11 shows the results of this process.
- **Evaluating environmental and social aspects:** The experts were asked to specify the weights of environmental and social sub-criteria through pairwise comparisons based on the Chang's FAHP approach (Chang, 1996). Table 12 shows the used fuzzy scale. The final weights are listed in Table 13.

In the following, the data related to the criteria, sub-criteria, and effective indicators shown in Table 11 were calculated. The first sub-criterion in the environment category was the greenhouse gas emission represented by the emissions of CH_4, CO_2, and NO_2. In this study, the distributers deliver the materials to the project site. Given the differences between the distributers' locations and means of transportation, the amount of CH_4, CO_2, and NO_2 to be produced by each distributer was calculated based on its distance from the project site and the type of vehicle. It is clear that for a constant amount of purchased material (constant weight), the distance and means of transport are the most important factors influencing the amount of CH_4, CO_2 and NO_2 emissions. Table 14 shows the amount of pollution to be produced upon the selection of each distributer. The amounts of pollution to be produced per kilometer travel were derived from Xing et al. (2016) and truck standards.

The second sub-criterion considered for the environmental criterion was the resource consumption. The indicators of this sub-criterion, namely water consumption and power consumption, were determined based on consumption of suppliers. In other words, for each distributer, after identifying the suppliers separated by the material type (aggregates, cement, and steel bars), the water and power consumptions at the original source of each product were estimated according to production capacity, technology, and process. Having the contribution of each supplier to the stock of each distributer, the resource consumption corresponding to each distributer was estimated. Tables 15 and 16 show the water and power consumption corresponding to each distributer.

For the Environmental Management System (EMS) sub-criterion, the effective indicators were considered as the attempt to EMS fulfillment and quality of EMS. Table 17 presents the ranking considered for the assessment of distributers according to these effective indicators. As represented in this table, three stages for attempting to EMS fulfillment were considered: not fulfilled, fulfilled without authentication, and fulfilled with authentication. In the resulting classification, distributers that lack any documentation for EMS fulfillment (such as ISO 14000) are categorized as Stage 1; distributers that have the necessary documentation for EMS fulfillment but have not been able to obtain an authentication are categorized as Stage 2; and the distributers that have fulfilled the EMS and acquired the corresponding authentication are categorized as Stage 3. The grades of distributers based on these stages are represented in Table 18.

The two effective indicators considered for the Injury and Illness Prevention Program (IIPP) sub-criterion (a subset of social criterion) were the IIPP fulfillment stage and employee health assessment. For the first indicator, distributers were evaluated based on the IIPP fulfilled in their work environment. For this purpose, three IIPP fulfillment stages is defined. The ranking of these stages are shown in the upper part of Table 19. In this classification, distributers that lack any documentation for IIPP fulfillment are categorized as Stage 1; distributers that have the necessary documentation for IIPP fulfillment but have not acquired an authentication are categorized as Stage 2; and the distributers that have fulfilled the IIPP and acquired an authentication (such as OHSAS 18000) are categorized as Stage 3. Similarly, three stages were defined for the employee health assessment (the lower part of Table 19). In this classification, distributers that do not perform any employee health assessment are categorized as Stage 1; distributers that conduct health assessments only for senior staff are categorized as Stage 2; and the distributers that conduct regular periodic employee health assessments are categorized as Stage 3. The final results regarding these evaluations are presented in Table 20.

Another social sub-criterion was the job policies with the number of created job opportunities and the employment gender ratio considered as its effective indicators. Here, the number of people employed in the

Table 13
Weights of sub-criteria.

Criteria	Sub-criteria	Weight	Criteria	Sub-criteria	Weight
Environmental	Greenhouse gas emission	0.304	Social	Injury and Illness Prevention Program	0.432
	Resource consumption	0.256			
	Environmental Management System	0.440		Job policies	0.568

Table 14
Greenhouse gas emission.

Distributer	Used truck	Pollution per unit distance (g/km)			Distance from construction site (km)	Total emission (g)		
		CH_4	CO_2	NO_2		CH_4	CO_2	NO_2
YNZ	Volvo-FH500	0.1	884	0.01	525.7	52.57	464718.8	5.257
ETP	Iveco- Eurocargo	0.05	791	0.005	506.9	25.345	400957.9	2.534
BMT	Mercedes Benz-L series	0.18	1025	0.02	531.6	95.688	544,890	10.632

Table 15
Indirect water consumption by distributors.

Distributor	Material	Supplier	Capacity (ton)	Water consumption per ton of production (L)	Total water consumed by the supplier (L)	The amount of share in supplying	Total water consumed by the distributor (L)
YNZ	Aggregates	DY	600,000	560	336,000,000	100%	561,236,064,615
	Cement	GHN	811,200	315	255,528,000	90%	
		Others	1,431,410*		450,894,150	10%	
	Steel bars	ZAE	2,800,000	230,000	644,000,000,000	80%	
		FY	1,200,000		276,000,000,000	15%	
		FK	350,000		80,500,000,000	5%	
ETP	Aggregates	SCO	650,000	560	364,000,000	65%	645,029,168,739
		SHC	600,000		336,000,000	35%	
	Cement	SGH	2,184,000	315	687,960,000	95%	
		Others	1,359,158*		428,134,770	5%	
	Steel bars	ZAE	2,800,000	230,000	644,000,000,000	100%	
BMT	Aggregates	TSH	500,000	560	280,000,000	100%	143,469,680,000
	Cement	SGH	2,184,000	315	687,960,000	75%	
		SD	936,000		294,840,000	25%	
	Steel bars	FAI	700,000	230,000	161,000,000,000	80%	
		AZ	300,000		69,000,000,000	20%	

* It is calculated as an average of other suppliers' capacities.

Table 16
Indirect power consumption by distributors.

Distributor	Material	Supplier	Capacity (ton)	Power consumption per ton of production (kwh)	Total power consumed by the supplier (kwh)	The amount of share in supplying	Total power consumed by the distributor (kwh)
YNZ	Aggregates	DY	600,000	100	60,000,000	100%	1,197,413,299
	Cement	GHN	811,200	119	96,532,800	90%	
		Others	1,431,410*		170,337,790	10%	
	Steel bars	ZAE	2,800,000	424	1,187,200,000	80%	
		FY	1,200,000		508,800,000	15%	
		FK	350,000		148,400,000	5%	
ETP	Aggregates	SCO	650,000	100	65,000,000	65%	1,505,438,190
		SHC	600,000		60,000,000	35%	
	Cement	SGH	2,184,000	119	259,896,000	95%	
		Others	1,359,158*		161,739,802	5%	
	Steel bars	ZAE	2,800,000	424	1,187,200,000	100%	
BMT	Aggregates	TSH	500,000	100	50,000,000	100%	535,648,000
	Cement	SGH	2,184,000	119	259,896,000	75%	
		SD	936,000		111,384,000	25%	
	Steel bars	FAI	700,000	424	296,800,000	80%	
		AZ	300,000		127,200,000	20%	

* It is calculated as an average of other suppliers' capacities.

Table 17
Ranking for EMS.

Effective indicator	Stage	Grade
Attempt to EMS fulfillment	Not fulfilled	1
	fulfilled without authentication	2
	fulfilled with authentication	3
Quality of EMS	Weak	1
	Moderate	2
	Good	3

Table 18
Grades of distributers in EMS.

Effective indicator	distributer		
	YNZ	ETP	BMT
Attempt to EMS fulfillment	2	3	3
Quality of EMS	1	2	2

Table 19
Ranking for IIPP.

Effective indicator	Stage	Grade
IIPP fulfillment stage	Not fulfilled	1
	fulfilled without authentication	2
	fulfilled with authentication	3
Employee health assessment	Not assessed	1
	Assessed only for senior staff	2
	Assessed for all employees	3

Table 20
Grades of distributers in IIPP.

Effective indicator	Distributer		
	YNZ	ETP	BMT
IIPP fulfillment stage	2	1	1
Employee health assessment	2	3	1

Table 21
Grades of distributers in job policies.

Effective indicator	Distributer		
	YNZ	ETP	BMT
Number of created job opportunities	216	98	137
Employment gender ratio	0.176	0.204	0.102

business was considered as the number of created job opportunities. The second effective indicator was adopted to encourage gender balance in the created job opportunities. This indicator is represented by the Gender Ratio Index (GRI), which is given by Eq. (19).

$$GRI = 1 - 2\left(\left|\frac{\text{Number of male employees}}{\text{Total number of employees}} - \frac{1}{2}\right|\right) \tag{19}$$

A GRI value that is closer to 1 represents greater gender balance among employees. Table 21 shows the values of these indicators for the evaluated distributers.

After calculating data, the FIS was used to evaluate the distributers and determine their environmental and social grades. After consultation with experts, it was decided to define three levels (weak, moderate and good) and five levels (very weak, weak, moderate, good and very good) for the membership grades of input and output variables respectively. Table 22 represents the fuzzy input variables. The fuzzy logic toolbox of MATLAB software was utilized to conduct a fuzzy evaluation of the distributers. Table 23 shows some examples of the defined rules and Table 24 presents the environmental and social grades of distributers. It should be noted that the total grade of each distributer was calculated by weighted averaging based on the weights of Table 13.

The results show that ETP and YNZ are the best distributers from the environmental and social points of view respectively. To encourage performance betterment, the weaknesses of distributers were identified and reported to them as feedback. With this approach, distributers may be encouraged to take further steps toward sustainability goals.

- **Building the optimization model and solving it:** The extracted information and parameters were used to construct and solve the optimization model of the investigated project. Since this was a large-sized problem, AUGMECON 2 could not provide a solution in a reasonable time, and therefore, MOPSO and NSGA-II were used for this purpose. In Fig. 15, the results of these algorithms are shown from two different views.

6. Discussion

In this section, we examined the tradeoff between the objectives and the impact of environmental and social objectives on the results. For this purpose, the model of the case study was solved by NSGA-II for different combinations of objective functions. Figs. 17–19 illustrate the tradeoff between the NPV-environmental, NPV-social, and environmental-social objectives, respectively.

As shown in Fig. 16, as the value of NPV grows larger, the value of the environmental performance exhibits a stepwise reduction. In other words, the environmental performance grows with the project cost. It can be easily concluded that the decision maker can achieve a better environmental performance by accepting to incur a higher cost. The observed tradeoff between the NPV and environmental objective functions allows the decision-makers to make a decision according to their priorities. For example, in Area A of Fig. 16 between the first and second decision points, a 517046010-unit decrease in the project NPV leads to a 47-unit increase in environmental grade. But in Area B, a

Table 22
Fuzzy input variables.

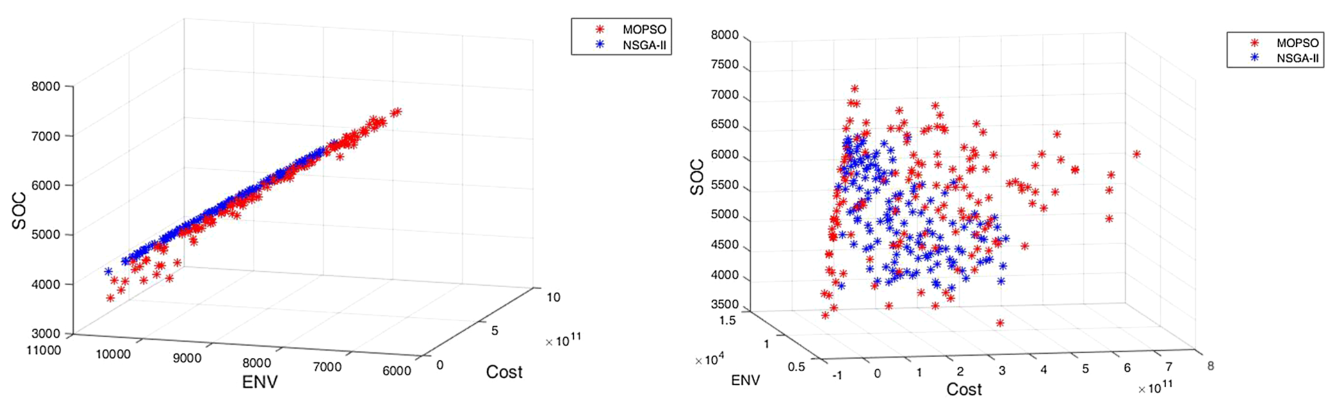
Effective indicator	Verbal variable	Fuzzy number	Effective indicator	Verbal variable	Fuzzy number
CH_4 emission	Weak	[70 105 inf *inf*]	CO_2 emission	Weak	[4.5E + 05 5.0E + 05 inf *inf*]
	Moderate	[35 70 105]		Moderate	[4.0E + 05 4.5E + 05 5.0E + 05]
	Good	[−inf −inf 35 70]		Good	[−inf −inf 4.0E + 05 4.5E + 05]
NO_2 emission	Weak	[6 9 inf *inf*]	Water consumption	Weak	[4.0E + 11 6.0E + 11 inf *inf*]
	Moderate	[3 6 9]		Moderate	[2.0E + 11 4.0E + 11 6.0E + 11]
	Good	[−inf −inf 3 6]		Good	[−inf −inf 2.0*E* + 11 4.0*E* + 11]
Power consumption	Weak	[1.0E + 09 1.5E + 09 inf *inf*]	Attempt to EMS fulfillment	Weak	[−inf −inf 1 2]
	Moderate	[5.0E + 08 1.0E + 09 1.5E + 09]		Moderate	[1 2 3]
	Good	[−inf −inf 5.0E + 08 1.0E + 09]		Good	[2 3 inf *inf*]
Quality of EMS	Weak	[−inf −inf 1 2]	IIPP fulfillment stage	Weak	[−inf −inf 1 2]
	Moderate	[1 2 3]		Moderate	[1 2 3]
	Good	[2 3 inf *inf*]		Good	[2 3 inf *inf*]
Employee health assessment	Weak	[−inf −inf 1 2]	Number of created job opportunities	Weak	[−inf −inf 100 150]
	Moderate	[1 2 3]		Moderate	[100 150 200]
	Good	[2 3 inf *inf*]		Good	[150 200 inf *inf*]
Employment gender ratio	Weak	[−inf −inf 2.5E - 01 5.0E - 01]			
	Moderate	[2.5E - 01 5.0E - 01 7.5E - 01]			
	Good	[5.0E - 01 7.5E - 01 inf *inf*]			

Table 23
Examples of the defined rules.

Row	Rule
1	If [Water consumption is weak] and [Power consumption is weak] then [Resource consumption is very weak]
2	If [Water consumption is moderate] and [Power consumption is moderate] then [Resource consumption is moderate]
3	If [Water consumption is good] and [Power consumption is good] then [Resource consumption is very good]
4	If [Water consumption is good] and [Power consumption is weak] then [Resource consumption is moderate]
5	If [Water consumption is good] and [Power consumption is moderate] then [Resource consumption is good]

Table 24
Grades of distributers in aspects of environmental and social.

Criteria	Sub-criteria	Weight of sub-criteria	Grades of distributes		
			YNZ	ETP	BMT
Environmental	Greenhouse gas emission	0.304	0.558	0.937	0.162
	Resource consumption	0.256	0.278	0.0633	0.899
	Environmental Management System (EMS)	0.440	0.25	0.75	0.75
Total grade			0.3508	0.631	0.6094
Social	Injury and Illness Prevention Program (IIPP)	0.432	0.5	0.5	0.0633
	Job policies	0.568	0.5	0.0633	0.228
Total grade			0.5	0.252	0.1568



(A) (B)

Fig. 15. Pareto optima front resulting from solving the model in two views A and B.

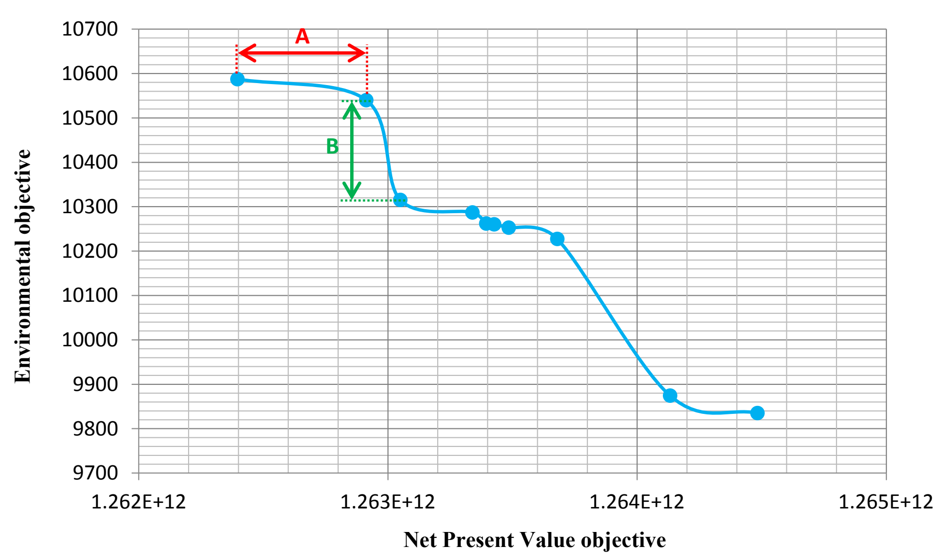


Fig. 16. Tradeoff between the NPV and environmental objectives.

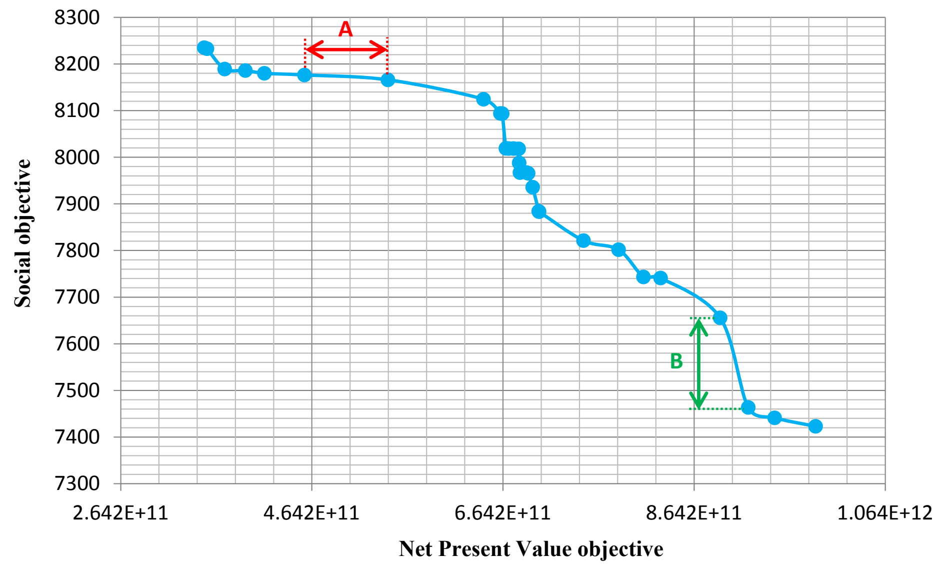


Fig. 17. Tradeoff between the NPV and social objectives.

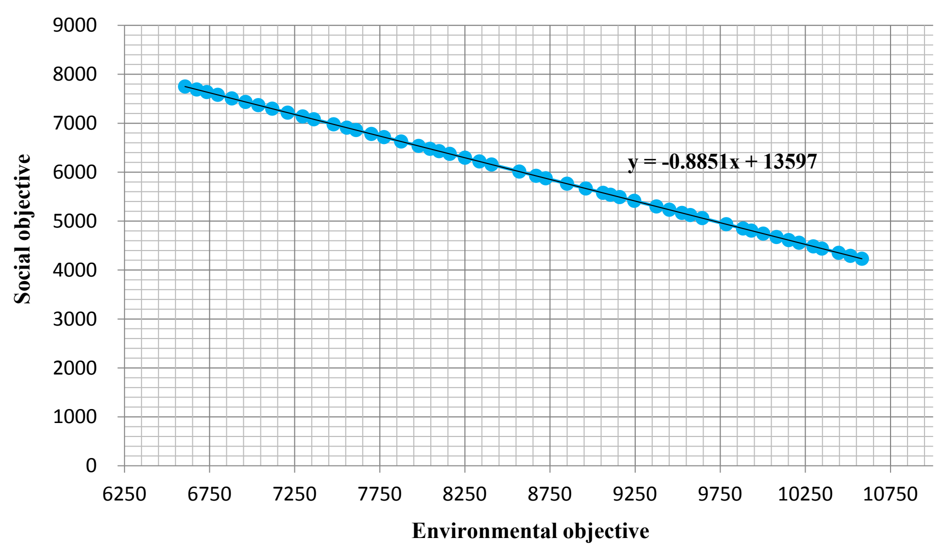


Fig. 18. Tradeoff between the environmental and social objectives.

smaller decrease in NPV (136531369 units) will result in a greater increase in the environmental grade (225 units).

Similarly, Fig. 17 shows that as the value of the NPV increases, that of the social performance function decreases. In other words, the social performance grows with the project cost. Hence, decision-maker can achieve a better social performance by accepting a higher project cost. As before, this tradeoff between the NPV and social objective functions enables the decision-makers to make a decision according to their preferences. For example, in Area A of Fig. 17 between the sixth and seventh decision points, an 87350846579-unit decrease in the project NPV results in a 10-unit increase in social grade. But in Area B, a greater increase in the social grade (192 units) can be achieved by incurring a smaller decrease in NPV (29441058632 units). Overall, it can be argued that the environmental and social objectives are considered as motivational factors so that decision makers will improve their performance from environmental and social perspectives only through motivation.

Fig. 18 shows that there is an inverse relationship between the values of the environmental and social objective functions, and unlike in Figs. 17 and 18, the relationship between these objective functions is linear. Therefore, the decision-maker can easily decrease one of these objective functions in favor of the other. However, since this curve has a slope of -0.8851 (> -1), decreasing the social objective function value by $\times$ units will result in a more than $\times$ units increase in the value of the environmental performance (for example, a 0.8851-unit decrease in the social objective function leads to a 1-unit increase in the environmental objective function). This relationship enables the decision makers to decide based on their social or environmental preferences.

7. Conclusion and future research

PSMO problem is a special type of RCPSP in which, unlike the traditional approach, a tradeoff can be established between scheduling and material ordering costs so as to make a better decision with lower total cost. On the other hand, today, organizations are encouraged to procure their resources from the suppliers with environmentally and socially sound attitude and track record, and this trend has been researched under the label of sustainable supplier selection problem. This approach encourages the suppliers to improve their social and environmental performance in line with sustainability objectives and compete not only economically but in these areas as well. In this study, the PSMO problem was formulated with sustainability considerations. The paper first provided an introduction to the PSMO discussion and reviewed the related literature. It then explained its innovations and the proposed framework for the implementation of this problem with sustainability considerations, as well as the proposed mathematical optimization model. Given the inability of exact solution methods to solve the real-world instances of the discussed problem within a reasonable time, MOPSO and NSGA-II metaheuristics methods were modified to be used for this purpose. After tuning the parameters of these algorithms by Taguchi method, the small-sized problems derived from PSPLIB were used to compare the performance of MOPSO and NSGA-II with AUGMECON2, and the large problems derived from the same library were used to compare performance of metaheuristic algorithms with each other. These evaluations showed the ability of NSGA-II to outperform MOPSO in most of the considered evaluation criteria. To show the applicability of the presented model and provide an illustrative example of its implementation, a case study was conducted on the trackbed construction project in Section 5 of Mianeh-Bostanabad-Tabriz railway in Iran, and the decision options provided to the decision maker were discussed. Future studies in this area are recommended to use uncertainty handling approaches such as robust and fuzzy methods to examine the model under uncertainty conditions. They are also suggested to consider the use of other newer meta-bureaucratic methods (such as Symbiotic Organism Search (SOS) algorithm proposed by Cheng and Prayogo (2014) and Grey Wolf Optimizer (GWO) algorithm provided by Mirjalili, Mirjalili, and Lewis (2014)) to solve the PSMO problem and compare the results with those of similar papers.

Appendix A

The general information about the investigated project is provided in Table 25.

Table 25
Data of investigated project.

Title	Number	Activity	Duration (days)	Prerequisite
Initial Operations	1	Starting the project	0	–
Equipping the workshop	2	Providing ground for equipping workshop	10	1
	3	Delivery of bench mark by consultant and employer	1	2
	4	Create coordinate grid and surveying operations	20	2
	5	Performing executive works of buildings, premises and camp facilities	60	2
	6	Transferring machinery and equipment to the workshop	30	2
	7	Preparing and installing aggregates sieving and washing machinery	60	2
	8	Prepare and install batching plant	60	2
	9	Approving and reporting route maps by consulting engineers from km 86 to 92	1	2
	10	Setting out and surveying the route and analyzing the transverse and longitudinal profiles from km 86 to 92	30	9
Land preparation	11	Delivery of land from km 86 to 92 by the employer	1	2
	12	Delivery of land related to access route by the employer	1	11
	13	Constructing the access route	10	6, 12
Earthworks	14	Determining the location of improper soil depot from excavations by consulting engineers from km 86 to 92	1	9, 11
	15	Determining the location of borrow pit for embanking by consulting engineers from km 86 to 92	1	9, 11
	16	Land clearance from km 86 to 92	150	6, 14
	17	Excavating the route from km 86 to 92	274	14
	18	Embanking the route from km 86 to 92	150	15, 16, 17
	19	Sprinkling and consolidating the subgrade of route from km 86 to 92	150	18
Completion of Shahriar station in km 88	20	Delivery of Shahriar station land by employer	1	9, 17, 19
	21	Approving and reporting Shahriar station maps by consulting engineers	1	20
	22	Setting out and surveying the land and analyzing the transverse and longitudinal profiles in Shahriar station	5	21
	23	Delivery of land related to access route to the Shahriar station by the employer	1	22
	24	Constructing the access route to Shahriar station	5	23
	25	Construction of signs and communications building in Shahriar station	180	24
	26	Construction of emergency generator building in Shahriar station	180	24
	27	Construction of ferrocement water storage tank in Shahriar station	180	24
	28	Construction of elevated steel water tank in Shahriar station	180	24
	29	Landscaping the signs and communications Building in Shahriar station	30	25
Completion of Bridge No. 1 (km 87-4 m span)	30	Completion of Bridge No. 1	30	9, 17, 19
Completion of Bridge No. 2 (km 87-7 m span)	31	Completion of Bridge No. 2	50	9, 17, 19, 30
Completion of Bridge No. 3 (km 87-7 m span)	32	Approving and reporting bridge No. 3 maps by consulting engineers	1	9, 17, 19, 31
	33	Setting out the bridge and surveying the land and controlling the map and verifying by bridge No. 3 monitoring system	1	32
	34	Digging up and pouring lean concrete for bridge No. 3	5	33
	35	Rebar binding for bridge No. 3	46	34
	36	Concrete shuttering for bridge No. 3	46	35
	37	Pouring concrete for bridge No. 3	46	36
	38	Backfilling for bridge No. 3	1	37

(*continued on next page*)

Table 25 (*continued*)

Title	Number	Activity	Duration (days)	Prerequisite
Completion of Bridge No. 4 (km 89-2 m span)	39	Completion of Bridge No. 4	30	9, 17, 19, 38
Completion of Bridge No. 5 (km 89-7 m span)	40	Approving and reporting bridge No. 5 maps by consulting engineers	1	9, 17, 19, 39
	41	Setting out the bridge and surveying the land and controlling the map and verifying by bridge No. 5 monitoring system	1	40
	42	Digging up and pouring lean concrete for bridge No. 5	5	41
	43	Rebar binding for bridge No. 5	46	42
	44	Concrete shuttering for bridge No. 5	46	43
	45	Pouring concrete for bridge No. 5	46	44
	46	Backfilling for bridge No. 5	1	45
Completion of Bridge No. 6 (km 89-5 m span)	47	Completion of Bridge No. 6	50	9, 17, 19, 46
Completion of Bridge No. 7 (km 89-5 m span)	48	Approving and reporting bridge No. 7 maps by consulting engineers	1	9, 17, 19, 47
	49	Setting out the bridge and surveying the land and controlling the map and verifying by bridge No. 7 monitoring system	1	48
	50	Digging up and pouring lean concrete for bridge No. 7	5	49
	51	Rebar binding for bridge No. 7	46	50
	52	Concrete shuttering for bridge No. 7	46	51
	53	Pouring concrete for bridge No. 7	46	52
	54	Backfilling for bridge No. 7	1	53
Completion of Bridge No. 8 (km 90-5 m span)	55	Completion of Bridge No. 8	50	9, 17, 19, 54
Final Operations	56	Construction site cleanup	3	3, 4, 5, 6, 7, 8, 10, 13, 17, 19, 26, 27, 28, 29, 55
	57	Finishing the project	0	56

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