A Multi-Objective Mathematical Model for Designing Energy Solar Power Plants' Location and Applicants' Allocation under Uncertainties

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Abstract

Inadequate conditions of energy production and consumption in Iran compared to its population, make the country's position in the energy dimension more critical. One solid way to address these issues is to exploit renewable energy resources efficiently. Hence, The extant study aimed at providing a multi-objective mathematical model for designing a green energy generation grid considering solar power plants' location and applicants' allocation under uncertainties. In the first step, a decision-making method under fuzzy uncertainties was used to assess and evaluate potential locations for solar power plants in South Khorasan Province. In the first step, a decision-making method under fuzzy uncertainties was used to assess and evaluate potential locations for solar power plants in South Khorasan Province. The method included two parts of determining the weight of criteria and sub-criteria using the Fuzzy SWARA Technique, and ranking alternatives using Fuzzy-EDAS. In the second step, a mathematical programming technique was employed to solve the solar plants' location problem and allocate demographic sites to power plants based on the location-zoning model. After final weights of criteria and sub-criteria were determined, six favorable regions (Ferdows, Birjand, Boshrouyeh, Tabas, Khusf, Nehbandan) in South Khorasan Province were selected based on the EDAS method. Finally, Birjand was selected as the prior region, while Tabas was chosen as the lowest prior region. There are not enough studies on the use of renewable energy to solve various problems in Iran. Comparing the values obtained from the analysis of the location of solar power plants and allocation to applicants under conditions of uncertainty can be an effective step in reducing electricity shortages and widespread blackouts, especially in summer and environmental pollution.

Keywords:*Solar Power Plants, Location-Zoning Model, Fuzzy Uncertainty*.

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Introduction

Energy supply has been one of the substantial concerns of humans over recent years. The critical point of the case indicates that many environmental problems stem from the overuse of fossil fuels, that are not renewable and alternative energies must be replaced (Kryukova et al., 2021). Solar energy generated from solar panels is one of the best energy supply resources. In this respect, most of developed countries are putting remarkable funding to motivate the industrial sectors for transition to less carbon-intensive and more sustainable renewable energy technologies (Kubanov et al., 2019). According to IEA's statistics, share of renewables in global electricity production was 26% (Sedghiyan, D 2021). As a deniable truth, energy generation and consumption are the most important goals of sustainable development.

In this lieu, scientific means must be used to solve the relevant problems optimally. As an application, the considered problems can be solved at strategic levels. According to available information, it is highly substantial to determine the suitable location for the construction of energy generation power plants, and allocate customers to each center to received energy since the needs of society, which comprises customers should be met.

Yanik et al. (2016) stated that there are few zoning studies on energy planning (Yanik et al., 2016). Yanik and colleagues used a heuristic method based on the location-allocation approach to determine energy sustainable zones. Activity measurement was assessed as balanced energy consumption and the green energy potential in each zone (Yanık et al., 2016). Aguayo et al. (2019) studied a problem for designing a sustainable energy generation system, which comprised multi-period location, parallel-facilities capacitated lot-sizing, and network flow problems. This problem was solved as a mixed-integer programming model and a branch-and-price-based method that relies on effective implementation strategies. Their computational investigation revealed the efficacy of the proposed method in obtaining near-optimal solutions for large-sized problem instances. Finally, several managerial insights were analyzed (Aguayo et al., 2019).

Thongpun et al. (2017) studied site selection for solar power plant location based on the DEA method in Thailand. They aimed to determine the efficiencies of plant site candidates, which are based on 77 provinces of Thailand. The analysis provided practical results that could be used for determining solar plant location (Thongpun et al., 2017). Saracoglu et al. (2018) proposed a framework for selecting the location of very large photovoltaic solar power plants on a global/super grid (Saracoglu et al., 2018). Yousefi et al. (2018) applied a fuzzy logic model to carry out spatial site selection for solar power plants in the Markazi Province of Iran. The results identified some areas near Mahalat and Zarandineh cities as suitable for solar energy utilization (Yousefi et al., 2018). Amjad and Ali Shah identified and assessed sites for solar farms development by providing a list of potential clusters, with their different sizes located in the Baluchistan province of Pakistan (Amjad and Shah, 2020). Dhunny et al. (2019) applied fuzzy logic modeling to identify optimal wind, solar and hybrid wind-solar farming sites. This methodological framework analyzes climatological, topographic, and human factors. According to the obtained results, Le Morne and La Laura-Malenga were the best optimum sites for wind, solar and hybrid wind-solar farm construction. According to case studies, annual power generation in this method could cover 281.28GWh at La Laura-Malenga (Dhunny et al., 2019).

Nguyen and Pearce (2010) presented a complete algorithm covering the steps of data acquisition and preprocessing to post-simulation to evaluate solar power plants' designs (Nguyen and Pearce, 2010). Janke used a multi-criteria GIS modeling for wind and solar power plants in Colorado (Janke, 2010). Sozen et al. (2015) presented an approach for the location of solar plants by data envelopment analysis (DEA) applied to 30 different cities in different regions of Turkey by using the TOPSIS method (Sozen et al., 2015). Wu et al. (2019) designed a decision-making framework to select sites for the large commercial photovoltaic system based on sustainability prospects by using the fuzzy ANP-VIKOR method (Wu et al., 2019). Fang et al. (2018) solved the sustainable site section problem for photovoltaic power plants. To do so, a novel integrated method based on the variable precision rough number, TOPSIS technique, and prospect theory were developed (Fang et al., 2018).

According to conducted studies, there is only one study carried out by Yanik et al. (2016) that used the location-zoning method. Therefore, the present study has applied a novel problem-solving method, including location-zoning hybrid models. According to the aforementioned points, the present paper was conducted to provide a multi-objective mathematical model for designing a green energy generation grid considering the location of power plants and the allocation of applicants under uncertainties.

Method

This study was analytical-correlational research in terms of nature and method, applied research in terms of objective, and survey study in terms of data collecting. The data were collected from interviews with experts in different industrial and academic contexts. Accordingly, opinions of three categories of experts were asked through semi-structured free interviews. The interviewed experts comprised 1) university professors who have theoretical and practical information about assessment methods of sites for construction of clean energy power plants; 2) Energy management experts, supervisors, and managers whose ideas are used to achieve more pragmatic results and methods for clean energy management; 3) consultants, instructors, and scholars of teaching and consultation who are familiar with different industries.

A researcher-made questionnaire was used to assess constructions sites for solar power plants, determine weights, and rank the key factors. The questionnaire was scored on a scale of 1-9 to examine the opinions of experts. The collected data were analyzed within three steps. In the first step, bibliographic literature was reviewed to identify important criteria and sub-criteria, confirm and select the final criteria by using the Lawshe validation method. In the second step, weights of criteria and sub-criteria were determined using multi-criteria decision making. In the third step, the prioritization method was used to rank potential sites for the construction of solar power plants.

[Table I]

Potential sites are assessed based on the aforementioned criteria and sub-criteria and multi-criteria decision-making method. The mathematical structure of the model can be described as follows:

Sets

V set of base units

K set of first-level zones

P set of second-level zones

C set of potential sites for construction of power plants, $C \subseteq V$,

A set of base units' pairs adjacent to the first level

B Set of base units' pairs adjacent to the second level

Input Parameters

α_i Demand for energy in node i

L_{ij} The distance between sites i and j

T_{max} Maximum allowed distance between sites located in each zone

β_i Coefficient of social utility (job creation) to select site i as the power plant in the first-level zone

$Ucost_i$ Cost of construction of power plant in site i in the first-level zone

$Lcost_i$ Cost of construction of energy distribution center in site i in second-level zone

Budget Maximum budget for construction of energy generation power plants

Decision Variables

X_{ip} The binary variable, which equals 1 if node i is allocated to zone P

W_{ip} The binary variable, which equals 1 if node i is selected as the center of zone P; in other words, if (i=P)

Y_{ijp} The amount of current from node i to node j in zone p

μ Workload differences in energy generation between power plants

U_{ik} The binary variable, which equals 1 if node i is allocated to the first-level zone k

$$\text{Max } Z_1 = \sum_{i \in C}\left(\beta_i \sum_{k \in K} U_{ik}\right) \quad (1)$$

$$\text{Min } Z_2 = \mu \quad (2)$$

$$\text{Min } Z_3 = \sum_{i \in C}\left(\text{Ucost}_i \sum_{k \in K} U_{ik}\right) + \sum_{i \in C}\left(\text{Lcost}_i \sum_{p \in P} W_{ip}\right) \quad (3)$$

s.t

$$\sum_{i \in V} \alpha_i X_{ip} - \sum_{i \in V} \alpha_i X_{ip'} \le \mu \qquad p \neq p' \in P \quad (4)$$

$$L_{ij} \le T_{max} + |M|(2 - X_{ip} + X_{jp}) \qquad i,j \in V \quad (5)$$

$$\sum_{p \in P} X_{ip} = 1 \qquad i \in V \quad (6)$$

$$\sum_{i \in V} W_{ip} = 1 \qquad p \in P \quad (7)$$

$$\sum_{j:(i,j) \in B} Y_{ijp} - \sum_{j:(i,j) \in B} Y_{jip} = X_{ip} - |V|\, W_{ip} \qquad p \in P, i \in C \quad (8)$$

$$\sum_{j:(i,j) \in B} Y_{ijp} \le (|V| - 1) X_{ip} \qquad p \in P, i \in V \quad (9)$$

$$\sum_{k \in K} W'_{ik} = 1 \qquad i \in C \quad (10)$$

$$\sum_{i \in C} U_{ik} = 1 \qquad k \in K \quad (11)$$

$$\sum_{j:(i,j) \in A} Y'_{ijk} - \sum_{j:(i,j) \in A} Y'_{jik} \ge W'_{ik} - |V|\, U_{ik} - |V| \sum_{p \in P} W_{ip} \qquad k \in K, i \in C \quad (12)$$

$$\sum_{j:(i,j) \in A} Y'_{ijk} \le (|V| - 1) W'_{ik} + |V| \sum_{p \in P} W_{ip} \qquad k \in K, i \in C \quad (13)$$

$$U_{ik} \le |V| \sum_{p \in P} W_{ip} \qquad k \in K, i \in C \quad (14)$$

$$W_{ip}, W'_{ik}, X_{ip}, U_{ik} \in \{0,1\} \qquad p \in P, k \in K, i \in V$$
$$Y_{ijp}, Y'_{ijk} \ge 0 \qquad p \in P, (i,j) \in B \quad (15)$$
$$k \in K, (i,j) \in A$$

$$W_{ip}, W'_{ik}, X_{ip}, U_{ik} \in \{0,1\} \qquad p \in P, k \in K, i \in V$$
$$Y_{ijp}, Y'_{ijk} \ge 0 \qquad p \in P, (i,j) \in B \quad (16)$$
$$k \in K, (i,j) \in A$$

The first objective function maximizes utility (the employment rate) if the first-level zone is selected. The second objective function minimizes the maximum workload difference in energy generation between power plants. The third objective function minimizes the total cost of construction of electricity distribution centers and power plants.

However, it can be stated about the third objective function that energy location-zoning problem is an organizational strategic issue followed by cost in next ranks. In other words, the public and private sectors should provide the maximum budget for energy supply. Hence, it is preferred to enter the cost minimization function as a constraint to the model limiting it to the predetermined available maximum amount. Accordingly, the objective aims to maximize social utility (the employment rate), while considering other objective functions as constraints. Therefore, the modified form of the mathematical model will be provided.

$$\text{Max } Z_1 = \sum_{i\in C}\left(\beta_i \sum_{k\in K} U_{ik}\right) \quad (17)$$

s.t

$$\sum_{i\in V}\alpha_i X_{ip} - \sum_{i\in V}\alpha_i X_{ip'} \le \mu \sum_{i\in V}\alpha_i \qquad p \ne p' \in P \quad (18)$$

$$\sum_{i\in C}\left(\text{Ucost}_i \sum_{k\in K} U_{ik}\right) + \sum_{i\in C}\left(\text{Lcost}_i \sum_{p\in P} W_{ip}\right) \le \text{Budget} \quad (19)$$

$$L_{ij} \le T_{max} + |M|\left(2 - X_{ip} + X_{jp}\right) \qquad i,j \in V \quad (20)$$

$$\sum_{p\in P} X_{ip} = 1 \qquad i \in V \quad (21)$$

$$\sum_{i\in V} W_{ip} = 1 \qquad p \in P \quad (22)$$

$$\sum_{j:(i,j)\in B} Y_{ijp} - \sum_{j:(i,j)\in B} Y_{jip} = X_{ip} - |V|\, W_{ip} \qquad p \in P, i \in C \quad (23)$$

$$\sum_{j:(i,j)\in B} Y_{ijp} \le (|V| - 1) X_{ip} \qquad p \in P, i \in V \quad (24)$$

$$\sum_{k\in K} W'_{ik} = 1 \qquad i \in C \quad (25)$$

$$\sum_{i\in C} U_{ik} = 1 \qquad k \in K \quad (26)$$

$$\sum_{j:(i,j)\in A} Y'_{ijk} - \sum_{j:(i,j)\in A} Y'_{jik} \ge W'_{ik} - |V|\, U_{ik} - |V| \sum_{p\in P} W_{ip} \qquad k \in K, i \in C \quad (27)$$

$$\sum_{j:(i,j)\in A} Y'_{ijk} \le (|V| - 1) W'_{ik} + |V| \sum_{p\in P} W_{ip} \qquad k \in K, i \in C \quad (28)$$

$$U_{ik} \le |V| \sum_{p\in P} W_{ip} \qquad k \in K, i \in C \quad (29)$$

$$W_{ip}, W'_{ik}, X_{ip}, U_{ik} \in \{0,1\} \qquad p \in P, k \in K, i \in V$$
$$Y_{ijp}, Y'_{ijk} \ge 0 \qquad p \in P, (i,j) \in B \quad (30)$$
$$k \in K, (i,j) \in A$$

Regarding the NP-hard nature of the zoning problem, Cplex 12.1 solver was used to solve small dimensions of the problem.

Findings

Computational results of the extant study have been proposed to solve solar power plants' location problems using hybrid multi-criteria decision-making techniques and multi-objective optimization. It must be noted that computations of multi-criteria decision-making techniques were done through Excel Software, while computations of mathematical model solving algorithms were run through MATLAB R2017b.

In the first step, a decision-making method was used under fuzzy uncertainties to assess and evaluate potential sites for the construction of solar power plants in South Khorasan Province. The mentioned method included two parts of determining weights of criteria and sub-criteria using fuzzy SWARA Technique, and ranking alternatives using Fuzzy-EDAS. In the second step, a mathematical programming technique was employed to solve the solar plants' location problem and allocate demographic places to power plants based on the location-zoning model. It is worth noting that the model was tested and evaluated within two single-level and hierarchical zoning modes. Since the location-zoning problem is an NP-hard problem, the numerical results have been analyzed using metaheuristic algorithms to select the best algorithm to solve real-world problems.

First, the final list of criteria and sub-criteria related to the evaluation of potential sites for the construction of solar power plants was presented to the decision-making board (experts). Second, experts determined relative weights of main criteria and sub-criteria by using the SWARA technique.

The fuzzy and definite global optimal weight of sub-criteria associated with potential sites for the construction of solar power plants have been reported in Table II. For instance, the local weight of sub-criterion (C11) in its groups equals (0.067, 0.084, 0.101), and weight of criterion (C1) equals (0.358, 0.377, 0.404); therefore, the global weight of sub-criterion C11 is measured by multiplying the weights mentioned above, and the final weight will be (0.024, 0.032, 0.041). Global optimal weights of other sub-criteria are calculated similarly. According to the obtained results, sub-criteria (C12) (0.135), (C13) (0.102), and (C32) (0.101) are the most substantial indicators used to assess potential sites for the construction of solar power plants. Moreover, (C48) had the lower importance among the considered indicators. In the next step, relative weights have been employed in the fuzzy EDAS model.

[Table II]

The results of implemented fuzzy EDAS method have been presented herein. Firstly, decision-makers proposed their preferences for evaluation of options in for of defined expressions concerning each criterion. As mentioned, this paper includes six options for potential sites:

Option 1: Ferdows

Option 2: Birjand

Option 3: Boshrouyeh

Option 4: Tabas

Option 5: Khusf

Option 6: Nehbandan

Secondly, the fuzzy mean matrix was calculated as shown in the table below, and then the fuzzy matrix of the mean solution was created using the equation presented in section 3. According to the obtained results, option A2 had the highest score, so it was ranked as the first option. The final ranking of the option was as follows: $A_2 \succ A_5 \succ A_6 \succ A_1 \succ A_3 \succ A_4$.

[Table III]

Sensitivity analysis was done to monitor the robustness of results based on the guidelines presented by Kahraman (2002). It was aimed at analyzing the suggested decision fuzzy SWARA-fuzzy EDAS model by generating new weighted vectors and assessing their impacts on ranking variations. As explained, the weighted coefficient of elasticity was estimated for C12, and variation in the weighted coefficient of this criterion was measured. The threshold value of C12 was calculated with the interval of [-0.135, 0.878]. After threshold values were defined for criterion C12, the new vectors of weighted coefficients were obtained for 15 scenarios reported in Table IV.

[Table IV]

According to data analysis in Table IV, variation in weight of Criterion C12 did not lead to any considerable change in the final rank of option A2, and this option was the dominant option in all scenarios.

Sensitivity Analysis of Problem

Location and zoning process was done for demographic regions of power plants concerning the results obtained from multi-criteria decision-making to determine importance weights of different criteria and sub-criteria within the assessment of potential locations for construction of solar power plants. In other words, it is aimed at developing an optimization approach to optimal allocation of regions asking for solar energy with respect to demand rate and ranking of potential locations in the first phase of the study.

Input parameters, number of zones, and maximum allowed distance between two sites in different modes of a zone were changed, and numerical results were described to assess problem conduct in achieving different solutions. To do so, the number of zones is assumed to vary between 2 and 5, and the maximum distance changed within 5 different modes. Overall, 20 modes were assessed. Solution time and objective function values were reported per mode.

[Table V]

Analysis of model variations trend was logical for input parameters; hence, the model provides an appropriate performance in solving real-world numerical cases.

According to the results mentioned in previous sections, the problem model could present acceptable numerical results, and sensitivity analysis confirmed the case. In this step, extensive numerical analyses were applied to the results to find the best solution method. To do so, three metaheuristic algorithms of genetic algorithm (GA), gray wolf (GWO), and Salp swarm (SSA) were compared based on numerical results. To this end, 30 numerical samples were generated randomly, and then the results of solved algorithms were proposed in Table VI.

[Table VI]

As can be seen in Table 6, an increase in dimension of numerical examples leads to an increase in solution time although as a non-exponential rise. In other words, the larger the dimension of numerical problems, the longer the solution time of the large-dimensional problems will be. Accordingly, the case study can be solved in large dimensions.

Solving Case Study at Single-Level Mode

This part of the study assesses the problem of allocating demand sites to solar energy power plants in South Khorasan Province as the first case study. To do so, 1921 demographic sites were considered in the province, and demand rates of selected sites for energy were taken into account in the input data based on the statistical data published by Iran's New Energy Organization. Moreover, the energy generation difference between power plants was considered at 20%, the maximum distance between sites located in each zone equaled 150km. According to available data, it was planned to construct five power plants in Khorasan Province. Therefore, the problem was solved for five zones. It is worth noting that potential sites for zones were considered based on the ranking proposed by the multi-criteria decision-making method. After the problem was solved, using GA that was the prior algorithm compared to other ones, the convergence of solutions was found,

the algorithm achieved the optimal solution around iteration 50 after which tried to find a better solution. There is the least improvement in the algorithm in iterations 400 onwards, and solutions remain almost unchanged. Finally, the zoning structure of demographic points can be considered, as illustrated in Figure 1.

[Figure 1]

According to the proposed optimal structure, Tabas, Ferdows, Birjand, Khusf, and Nehbandan counties were selected as sites for the construction of power plants. Figure 2 indicates the structure of allocating demographic regions to power plants.

Conclusion

The main problem of the extant study was the location of solar power plants and zoning demographic regions to allocate them to constructed power plants; hence, mathematical programming was the best means could achieve optimal solutions. Therefore, mathematical modeling was used as the main pillar of this study to propose optimal solutions, which are applicable for real-world cases. This study examined uncertainties of input parameters to develop research dimensions. Therefore, a part of the study was related to programming model development in the definite mode, while the other part solved the problem under uncertainties. The NP-hard attribute of proposed models must also be taken into account.

The present study was conducted to assess and evaluate potential sites for the construction of solar power plants in South Khorasan Province by using a decision-making method under fuzzy uncertainties. The applied technique included two parts of determining weights of criteria and sub-criteria using fuzzy SWARA Technique, and ranking alternatives using Fuzzy-EDAS. After final weights of criteria and sub-criteria were determined, six favorable regions (Ferdows, Birjand, Boshrouyeh, Tabas, Khusf, Nehbandan) in South Khorasan Province were selected based on the EDAS method. Finally, Birjand was selected as the prior region, while Tabas was chosen as the lowest prior region.

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Figure 1. Optimal location-zoning structure of Case Study (South Khorasan)

Tables

Table I. The most important factors affecting the selection of sites for the construction of photovoltaic power plants

Criteria	Sub-criteria	Reference
Economic (C1)	Return of capital (C11)	(Uyan, 2013),(Tahri, Hakdaoui, & Maanan, 2015),(Suh & Brownson, 2016), (Noorollahi, Fadai, Akbarpour Shirazi, & Ghodsipour, 2016),(Lee et al., 2017) ،(Anwarzai & Nagasaka, 2017), (Sabo, Mariun, Hizam, Radzi, & Zakaria, 2017), (Gherboudj & Ghedira, 2016), (Bouhal et al., 2018)
	Cost of repair and maintenance (C12)	(Sánchez-Lozano, Teruel-Solano, Soto-Elvira, & García-Cascales, 2013), (Sánchez-Lozano, Antunes, García-Cascales, & Dias, 2014), (Lee et al., 2017), (Khanjarpanah, Jabbarzadeh, & Seyedhosseini, 2018), (Simsek, Watts, & Escobar, 2018), (Y. Wu et al., 2018)
	Initial investment cost (C13)	(Simsek et al., 2018), (Rathore, Chauhan, & Singh, 2018), (Manju & Sagar, 2017), (Liu, Xu, & Lin, 2017), (Y. Wu et al., 2018)
	Cost of efficient R&D (C14)	(Lee, Kang, Lin, & Shen, 2015), (Niblick & Landis, 2016), (Kengpol, Rontlaong, & Tuominen, 2012), (Saha & Eckelman, 2018), (Fritsche et al., 2017), (Al Garni & Awasthi, 2017), (Zoghi et al., 2017), (J. Liu et al., 2017)
	Cost of technical equipment (C15)	(J. Liu et al., 2017), (Lee et al., 2015), (Jun, Tian-tian, Yi-sheng, & Yu, 2014), (J. Liu et al., 2017), (Yun-na et al., 2013), (Vafaeipour, Zolfani, Varzandeh, Derakhti, & Eshkalag, 2014), (Simsek et al., 2018)
	Distance to pastures and	(J. Liu et al., 2017), (Bendato, Cassettari, Mosca, Williams, & Mosca,

Environmental and Social (C2)	catchments (C21)	2017), (Chang & Starcher, 2018), (Ogunmodimu & Okoroigwe, 2018), (Minaeian, Sedaghat, Mostafaeipour, & Alemrajabi, 2017)
	Distance to preserved areas (C22)	(Sabo et al., 2017), (Gherboudj & Ghedira, 2016),(Bouhal et al., 2018), (Buffat, Grassi, & Raubal, 2018), (Sultan, Kuznetsov, & Diab, 2018b)
	Social acceptability and welfare (C23)	(León-Vargas, García-Jaramillo, & Krejci, 2019), (J. Fan et al., 2018), (Bouhal et al., 2018)
	Job creation rate (C24)	(León-Vargas et al., 2019), (J. Fan et al., 2018), (Bouhal et al., 2018), (Sultan et al., 2018b), (Khanjarpanah et al., 2018), (Simsek et al., 2018), (Y. Wu et al., 2018)
	The average level of society income (C25)	(León-Vargas et al., 2019), (J. Fan et al., 2018), (Bouhal et al., 2018), (Sultan et al., 2018b), (Khanjarpanah et al., 2018), (Simsek et al., 2018), (Y. Wu et al., 2018)
Managerial and Technical (C3)	Utility of sunlight angle and rate (C31)	(Yunna & Geng, 2014), (Sindhu et al., 2017), (Jun et al., 2014), (Alkhalidi, Qoaider, Khashman, Al-Alami, & Jiryes, 2018), (Anwar, Shafei, & Ibrahim, 2017), (Y. Wu et al., 2018)
	Number of sunny days (C32)	(Alkhalidi et al., 2018), (Anwar et al., 2017), (Y. Wu et al., 2018)
	Average temperature (C33)	(Alkhalidi et al., 2018), (Anwar et al., 2017)
	Geographical and climate position (C34)	(Al Garni & Awasthi, 2017), (Zoghi et al., 2017), (J. Liu et al., 2017), (Y. Wu et al., 2018)
	Skilled manpower (C35)	(Doljak & Stanojević, 2017), (Sindhu et al., 2017), (Nematollahi & Kim, 2017), (Firozjaei et al., 2018)
	Political risk (C41)	(Doljak & Stanojević, 2017), (Doorga, Rughooputh, & Boojhawon, 2018)
	Investment risk (C42)	(Suh & Brownson, 2016),(Noorollahi, Fadai, Akbarpour Shirazi, & Ghodsipour, 2016)
	Labor risk (C43)	(Sánchez-Lozano, Antunes, García-Cascales, & Dias, 2014), (Lee et al., 2017), (Khanjarpanah, Jabbarzadeh, &

Risk (C4)		Seyedhosseini, 2018), (Simsek, Watts, & Escobar, 2018)
	Risk of equipment use (C44)	(Manju & Sagar, 2017), (Liu, Xu, & Lin, 2017), (Y. Wu et al., 2018)
	Risk of governmental support (C45)	(Lee, Kang, Lin, & Shen, 2015), (Fritsche et al., 2017), (Al Garni & Awasthi, 2017), (Zoghi et al., 2017), (J. Liu et al., 2017)
	Environmental risk (C46)	(J. Liu et al., 2017), (Yun-na et al., 2013), (Vafaeipour, Zolfani, Varzandeh, Derakhti, & Eshkalag, 2014), (Simsek et al., 2018)
	Technical risk (C47)	(J. Liu et al., 2017), (Bendato, Cassettari, Mosca, Williams, & Mosca, 2017), (Chang & Starcher, 2018)
	Foreign investors (C48)	(Sabo et al., 2017) (Bouhal et al., 2018), (Buffat, Grassi, & Raubal, 2018), (Sultan, Kuznetsov, & Diab, 2018b)
	Competitiveness in the market (C49)	(León-Vargas, García-Jaramillo, & Krejci, 2019), (J. Fan et al., 2018), (Bouhal et al., 2018)

Table II. Final weights of criteria and sub-criteria

Criteria	Criteria fuzzy local weight	Sub-criteria	Sub-criteria fuzzy local weights	Global fuzzy weights	Global crisp weights	Rank
C_1	(0.358, 0.377, 0.404)	C_{11}	(0.067, 0.084, 0.101)	(0.024, 0.032, 0.041)	0.032	13
		C_{12}	(0.342, 0.356, 0.375)	(0.122, 0.134, 0.151)	0.135	1
		C_{13}	(0.247, 0.270, 0.295)	(0.088, 0.102, 0.119)	0.102	2
		C_{14}	(0.104, 0.119, 0.135)	(0.037, 0.045, 0.055)	0.045	9
		C_{15}	(0.153, 0.171, 0.189)	(0.055, 0.064, 0.076)	0.065	5
C_2	(0.158, 0.193, 0.229)	C_{21}	(0.314, 0.334, 0.363)	(0.049, 0.064, 0.083)	0.065	6
		C_{22}	(0.153, 0.183, 0.216)	(0.024, 0.035, 0.049)	0.036	11
		C_{23}	(0.103, 0.133, 0.164)	(0.016, 0.026, 0.037)	0.026	16
		C_{24}	(0.073, 0.099, 0.128)	(0.012, 0.019, 0.029)	0.020	18
		C_{25}	(0.223, 0.251, 0.283)	(0.035, 0.048, 0.065)	0.049	8
C_3	(0.254, 0.283, 0.315)	C_{31}	(0.224, 0.255, 0.290)	(0.057, 0.072, 0.091)	0.073	4
		C_{32}	(0.333, 0.353, 0.383)	(0.085, 0.100, 0.121)	0.101	3
		C_{33}	(0.097, 0.124, 0.153)	(0.025, 0.035, 0.048)	0.035	12
		C_{34}	(0.147, 0.174, 0.203)	(0.037, 0.049, 0.064)	0.050	7
		C_{35}	(0.069, 0.093, 0.119)	(0.018, 0.026, 0.037)	0.027	15
C_4	(0.116, 0.148, 0.181)	C_{41}	(0.261, 0.290, 0.332)	(0.030, 0.043, 0.060)	0.044	10
		C_{42}	(0.170, 0.204, 0.247)	(0.020, 0.030, 0.045)	0.031	14
		C_{43}	(0.082, 0.111, 0.146)	(0.010, 0.016, 0.026)	0.017	19
		C_{44}	(0.119, 0.151, 0.191)	(0.014, 0.022, 0.035)	0.023	17
		C_{45}	(0.055, 0.080, 0.111)	(0.006, 0.012, 0.020)	0.012	20
		C_{46}	(0.039, 0.060, 0.086)	(0.005, 0.009, 0.016)	0.009	21
		C_{47}	(0.018, 0.032, 0.050)	(0.002, 0.005, 0.009)	0.005	23
		C_{48}	(0.014, 0.025, 0.041)	(0.002, 0.004, 0.007)	0.004	24
		C_{49}	(0.029, 0.046, 0.068)	(0.003, 0.007, 0.012)	0.007	22

Table III. The weighted sum of final distance and weight

	$\widetilde{sp}_i$	$\widetilde{sn}_i$	$\widetilde{nsp}_i$	$\widetilde{nsn}_i$	$\widetilde{as}_i$	$k(\widetilde{as}_i)$	Rank
A_1	(-0.103,0.043,0.19)	(-0.093,0.063,0.223)	(-0.541,0.225,1.003)	(-0.797,0.491,1.748)	(-0.669,0.358,1.375)	0.357	4
A_2	(-0.094,0.192,0.463)	(0.007,0.015,0.022)	(-0.493,1.013,2.439)	(0.821,0.882,0.943)	(0.164,0.948,1.691)	0.941	1
A_3	(-0.071,0.057,0.186)	(-0.064,0.11,0.28)	(-0.374,0.299,0.98)	(-1.26,0.114,1.516)	(-0.817,0.207,1.248)	0.210	5
A_4	(-0.067,0.047,0.161)	(-0.03,0.125,0.273)	(-0.353,0.246,0.846)	(-1.206,-0.008,1.239)	(-0.779,0.119,1.043)	0.123	6
A_5	(-0.07,0.051,0.172)	(-0.118,0.065,0.245)	(-0.369,0.269,0.905)	(-0.975,0.478,1.952)	(-0.672,0.373,1.429)	0.375	2
A_6	(-0.066,0.061,0.187)	(-0.114,0.073,0.256)	(-0.348,0.321,0.988)	(-1.07,0.41,1.918)	(-0.709,0.366,1.453)	0.368	3

Table IV. Weights of criteria based per scenario

	w_{S_1}	w_{S_2}	w_{S_3}	w_{S_4}	w_{S_5}	w_{S_6}	w_{S_7}	w_{S_8}	w_{S_9}	$w_{S_{10}}$	$w_{S_{11}}$	$w_{S_{12}}$	$w_{S_{13}}$	$w_{S_{14}}$	$w_{S_{15}}$
C_{11}	0.037	0.035	0.033	0.032	0.030	0.028	0.026	0.024	0.022	0.021	0.019	0.017	0.015	0.013	0.012
C_{12}	0.000	0.050	0.099	0.149	0.198	0.248	0.297	0.347	0.396	0.446	0.495	0.545	0.594	0.644	0.693
C_{13}	0.118	0.112	0.106	0.100	0.095	0.089	0.083	0.077	0.072	0.066	0.060	0.054	0.049	0.043	0.037
C_{14}	0.052	0.049	0.047	0.044	0.042	0.039	0.037	0.034	0.032	0.029	0.027	0.024	0.021	0.019	0.016
C_{15}	0.075	0.071	0.068	0.064	0.060	0.057	0.053	0.049	0.046	0.042	0.038	0.035	0.031	0.027	0.024
C_{21}	0.075	0.071	0.068	0.064	0.060	0.057	0.053	0.049	0.046	0.042	0.038	0.035	0.031	0.027	0.024
C_{22}	0.042	0.040	0.037	0.035	0.033	0.031	0.029	0.027	0.025	0.023	0.021	0.019	0.017	0.015	0.013
C_{23}	0.030	0.029	0.027	0.026	0.024	0.023	0.021	0.020	0.018	0.017	0.015	0.014	0.012	0.011	0.009
C_{24}	0.023	0.022	0.021	0.020	0.019	0.017	0.016	0.015	0.014	0.013	0.012	0.011	0.010	0.008	0.007
C_{25}	0.057	0.054	0.051	0.048	0.045	0.043	0.040	0.037	0.034	0.032	0.029	0.026	0.023	0.021	0.018
C_{31}	0.084	0.080	0.076	0.072	0.068	0.064	0.060	0.055	0.051	0.047	0.043	0.039	0.035	0.031	0.027
C_{32}	0.117	0.111	0.105	0.099	0.094	0.088	0.082	0.077	0.071	0.065	0.060	0.054	0.048	0.042	0.037
C_{33}	0.040	0.038	0.036	0.034	0.032	0.031	0.029	0.027	0.025	0.023	0.021	0.019	0.017	0.015	0.013
C_{34}	0.058	0.055	0.052	0.049	0.046	0.044	0.041	0.038	0.035	0.032	0.029	0.027	0.024	0.021	0.018
C_{35}	0.031	0.030	0.028	0.027	0.025	0.024	0.022	0.020	0.019	0.017	0.016	0.014	0.013	0.011	0.010
C_{41}	0.051	0.048	0.046	0.043	0.041	0.038	0.036	0.033	0.031	0.028	0.026	0.023	0.021	0.018	0.016
C_{42}	0.036	0.034	0.032	0.031	0.029	0.027	0.025	0.024	0.022	0.020	0.018	0.017	0.015	0.013	0.011
C_{43}	0.020	0.019	0.018	0.017	0.016	0.015	0.014	0.013	0.012	0.011	0.010	0.009	0.008	0.007	0.006
C_{44}	0.027	0.025	0.024	0.023	0.021	0.020	0.019	0.017	0.016	0.015	0.014	0.012	0.011	0.010	0.008
C_{45}	0.014	0.013	0.012	0.012	0.011	0.010	0.010	0.009	0.008	0.008	0.007	0.006	0.006	0.005	0.004
C_{46}	0.010	0.010	0.009	0.009	0.008	0.008	0.007	0.007	0.006	0.006	0.005	0.005	0.004	0.004	0.003
C_{47}	0.006	0.005	0.005	0.005	0.005	0.004	0.004	0.004	0.004	0.003	0.003	0.003	0.002	0.002	0.002
C_{48}	0.005	0.004	0.004	0.004	0.004	0.003	0.003	0.003	0.003	0.003	0.002	0.002	0.002	0.002	0.001
C_{49}	0.008	0.008	0.007	0.007	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.003	0.003	0.003

Table V. Results of sensitivity analysis of the problem

	$\|P\| = 5$		$\|P\| = 4$		$\|P\| = 3$		$\|P\| = 2$	
	Objective function	**Solution time**	**Objective function**	**Solution time**	**Objective function**	**Solution time**	**Objective function**	**Solution time**
$T_{max} = \frac{6}{\|P\|}\max_{(i,j)}\{L_{i,j}\}$	45	21.3	37	19.23	30	22.41	26	21.44

$T_{max} = \frac{5}{\|P\|} \max_{(i,j)}\{L_{i,j}\}$	41	17.84	32	18.74	29	23.17	25	23.98
$T_{max} = \frac{4}{\|P\|} \max_{(i,j)}\{L_{i,j}\}$	39	18.44	29	15.66	24	21.66	25	22.73
$T_{max} = \frac{3}{\|P\|} \max_{(i,j)}\{L_{i,j}\}$	36	17.65	26	15.49	24	20.23	25	20.19
$T_{max} = \frac{2}{\|P\|} \max_{(i,j)}\{L_{i,j}\}$	36	17.91	25	16.1	24	21.07	25	19.66

Table VI. Numerical results of numerical samples using different algorithms

SSA		GWO		GA			
Solution time	Objective function	Solution time	Objective function	Solution time	Objective function	Number of zones	Number of vertices
181	310	160	344	148	400	10	80
159	456	135	480	117	510		90
156	361	145	383	130	440		100
150	481	128	534	129	600	12	110
147	523	123	568	120	660		120
135	576	129	619	119	672		130
169	485	142	527	139	612		140
143	560	136	602	116	684		150
191	545	141	592	143	696		160
216	590	156	648	149	728	14	170
220	672	190	707	161	812		180
147	700	146	744	138	826		190
188	612	174	657	174	714		200
221	521	178	572	169	672		210
159	472	164	518	156	588		220
256	640	214	695	205	798		230
264	676	190	719	182	798		240
210	539	180	567	147	630		250
314	669	213	719	219	816	16	260
261	742	238	789	211	848		270
240	764	204	830	197	912		280

273	628	203	682	205	774		290
250	750	218	824	208	936	18	300
242	715	206	777	187	882		310
244	918	248	1020	214	1200		320
257	761	221	818	198	940		330
250	729	226	792	227	920		340
297	720	268	782	244	840		350
314	657	279	730	238	820		360
243	976	217	1038	213	1140		370
299	1027	254	1128	243	1200	20	380
312	792	295	870	259	1000		390
2858	762	248	828	217	880		400
337	948	253	1030	263	1144		410
322	856	278	910	264	968		420
282	1076	263	1156	263	1298		430
329	857	295	911	273	990		440
320	1001	235	1076	227	1144		450
314	1113	290	1171	264	1232		460
264	800	283	879	234	1034		470
333	1025	277	1126	248	1210		480
291	976	278	10725	229	1232	22	490
336	857	272	931	259	1034		500
308	806	243	848	248	902		510
313	960	284	1010	272	1122		520
312	769	246	845	250	960		530
389	1127	262	1186	272	1248		540
293	1109	291	1167	240	1296		550
324	923	271	981	268	1032		560
334	1026	302	1139	249	1224		570
277	942	309	1035	283	1176	24	580
259	961	286	1056	246	1200		590

290	837	253	919	234	1032		600
322	1003	282	1102	285	1296		610
278	911	275	1001	245	1150		620
330	801	252	890	227	1000		630
340	1017	307	1105	258	1175		640
314	1184	274	1259	248	1325		650
295	1143	253	1215	238	1350	25	660
310	897	326	964	262	1025		670