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DOI
10.1142/S0219622020500157

Publication date
2020

Document Version
Final published version

Published in
International Journal of Information Technology and Decision Making

International Journal of Information Technology & Decision Making
Vol. 19, No. 3 (2020) 741–773

DOI: 10.1142/S0219622020500157

Sustainable Location Selection of Data Centers: Developing a Multi-Criteria Set-Covering Decision-Making Methodology

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Received 25 October 2019
Revised 24 March 2020
Accepted 26 March 2020
Published 24 June 2020

In this paper, a multi-criteria set-covering methodology is proposed to select suitable locations for a set of data centers. First, a framework of criteria, with social, economic and environmental dimensions, is presented. The framework is used to calculate the suitability of potential data center locations in Iran. To that end, a sample of specialists in Iran was asked to take part in an online questionnaire, based on best–worst method (BWM), to determine the weight of the criteria included in the proposed framework, after which a number of potential locations are evaluated on the basis of the criteria. The proposed model is evaluated under a number of settings. Using the proposed multi-criteria set-covering model, not only the utility of candidate places is evaluated by sustainability criteria but also all service applicants are covered by at least one data center with a specific coverage radius.

Keywords: Data center; location selection; best–worst method (BWM); sustainability framework; linear set-covering model; conditional performance.

1. Introduction

At the start of the third millennium, most researchers and practitioners have acknowledged the crucial role information technology plays in the economic, political

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and cultural development of today's societies. In recent years, computer networks have evolved considerably, for instance, when it comes to data processing and storage centers. A data center consists of a set of servers, communication infrastructures and electronic devices that are used to store, provide and support network services.[1,2] The primary functions of such centers are connecting large numbers of servers at low cost, analyzing data and indexing information in a safe space.[3,4] For most countries, choosing a suitable location for their data centers is important, because (i) outsourcing the national data and information to data centers located abroad poses a potential threat to national security[5,6]; (ii) using these centers facilitates the sharing of data and information among people and organizations and (iii) individuals and organizations can access data, information, analysis and meta-analysis more quickly.

Selecting a suitable location is one of the main steps in this process. Although multi-criteria decision making (MCDM) methods are popular when it comes to selection of a suitable location of data centers, on their own, MCDM methods are not effective enough, mainly due to their inability to handle the distribution of the clients of the data centers. That is to say, there is a chance that some customers are not covered by a given data center, even if the distance between the data centers and the applicants is included as a criterion. To address this crucial deficiency, a multi-criteria methodology is proposed in this paper that directly takes the distance into account. Using the proposed methodology, the selected locations not only have the proper qualifications with respect to the decision-making criteria (used in MCDM methods), but they are also guaranteed to cover all the applicants of the data centers, which guarantee acceptable speed and support services for all.

To develop the proposed methodology, first a sustainability framework is proposed to identify the criteria that affect the location of the data center, divided into economic, social and environmental dimensions. Using the proposed framework, which is the first contribution of this paper, the suitability of the various candidate locations is assessed, after which a linear set-covering model is proposed to select a certain number of data centers. That model, which is the second contribution of this paper, guarantees both the suitability of the selected location and the coverage radius for high-quality services. Applying the proposed method on a large scale, in this case an entire country, is the third contribution of this study. The multi-criteria set-covering model was used to determine the best location(s) for data centers in Iran. At the moment, more than 30 servers are rented by Iranian companies in western countries, with the corresponding expenses for hosting and transmitting the data. Establishing data centers not only reduces the waiting time for Iranian users, but also it increases service reliability and security of information sharing on social networks. As such, setting up data centers is a logical step in expanding information technology in Iran.

The remainder of this paper is organized as follows. Section 2 contains a literature review involving data center location, followed by a discussion of the framework and the relevant criteria. In Sec. 3, the methodology being used is discussed, whereas Sec. 4 contains a description of the data collection process. In Sec. 5, the results of this study are addressed, and the most suitable data center locations in Iran are selected. In Sec. 6, finally, the conclusion of this study and suggestions for future research are discussed.

2. Literature Review

Since few studies have focussed specifically on selecting suitable locations for data centers, we examined papers about different topics related to data centers to identify relevant criteria. The results are presented in Table 1. References and definitions of criteria were used to divide them into economic, social and environmental categories (Table 1). The papers related to the location of data centers are discussed below.

Chang *et al.*[7] solved a capacitated p-median problem to select the optimal location of army data centers in the USA. The mathematical model they proposed was based on two types of decision drivers, namely, facility capacity and application performance. It minimizes both the total demand-weighted distance and the load on any area processing centers. Abbasov *et al.*[8] suggested a linear integer programming model to determine the location of data centers. The proposed model determines the optimal locations based on possible natural, political and economic risk factors. Floods, earthquakes, pollution, magnetic radiation, government laws and regulations, inter-state relations, political and social events, tax policies, economics and dependence on the national economy are among the main criteria. Yang and Ye[9] used the Delphi method to select the location for data centers of industrial agencies in China. Physical data security, sufficient resources and costs, environmental factors, government policies, manpower and level of economic are among the main criteria. The results indicate that natural geography is the most important criterion.

Goiri *et al.*[10] assessed the locations of data centers in seven regions in the USA, using a nonlinear cost optimization model that minimizes the costs of network latency, consistency delay and availability constraints. The potential data center locations were identified based on (i) the distance to power plants, population centers and network backbones, (ii) the origin of electricity in the location, (iii) the price of water, land and electricity in the region and (iv) the temperature conditions in the region. They solved the suggested model using five different approaches. Larumbe and Sanso[11] proposed a convex integer programming to solve the cloud location and routing problem for global content providers, including Google, Akamai, Amazon and Facebook. The objective function in the proposed model minimizes the average network delay, subject to system and budget constraints. Based on the results, 11 locations in Africa, Asia, Europe, Latin America and North America were selected for data centers from among 24 potential locations. Covas *et al.*[12] applied Elimination and Choice Expressing Reality III (ELECTRE III) in a group decision-making environment for locating data centers in Portugal. They examined possible alternatives using 35 criteria, divided into risk-related, social, economic and environmental categories. Covas *et al.*[13] used geographic information system (GIS) to determine the best location from among 62 potential locations in Portugal.

Table 1. Sustainable framework for locating data center's location.

Category	Criteria	Sub-criteria	References
Social	Life quality (attractiveness to employees)		13
		Availability of public transportation and accessibilities	13
		• Rail stations	
		• Main roads	
		• Access to airport	
		Life cost (municipalities tax discounts-IRS)	13
		Life security	9, 12, 14
		• Crime against property (crime against persons)	9, 12–14
		• Police	12
		• Fireman	12
	Level of expansion of society		9, 12
	Availability of skilled labor in the region		12, 13, 16
	Political risks		8
		Change in the general policies and laws of the country	8, 12
		Inefficient and incomplete laws	8
		Existence of restrictive laws	8
		Government failure to comply with obligations	8
		Weakness of international relations	8
	Attractiveness to costumer (distance to data center)		12
		Distance to main road access	12
		Distance to rail stations	12
		Distance to airports	12
	Information security		9
	High-tech talent resources		9

Table 1. (*Continued*)

Category	Criteria	Sub-criteria	References
Economical	Investment costs		12, 20
		Electric grid connection cost	12, 14, 19
		Local incentives	8, 13
		• Easier licensing	14
		• Tax reduction	
		• Access to subsidies	
		• Competitive prices	
		• Land for free	
		Network communications connection costs	7, 12–14, 18, 19
		Land acquisition and construction cost	12, 14, 16, 19
		Synchronization costs	12
		Natural gas grid connection costs	12
	Operational costs		12, 16, 19
		Taxes	8, 9, 12, 14
		Energy costs	12
		Human resources costs	9, 12, 13
		Climate condition costs	
		• Humidity	11–13
		• Temperature	
	Economic risks		8
		Effective communication between investors and the market	8
		Dependence of the national economy	8
		Availability of qualified support vendor in the region	12
		Physical security	9
		Military regional security	8, 9, 12
		• Active defensive	
		• Nonactive defensive	
		• Frontier threats	

Table 1. (*Continued*)

Category	Criteria	Sub-criteria	References
		Natural and ecological risks	8, 12
		• Seismic activity	8, 12, 13
		• Earthquake	8
		• Other natural disasters (storms, floods and landslides)	8
		• Electromagnetic radiation	8
		• Pollution	8
		• Interruption of earth	8
Environmental	Local pollution		8, 9, 12, 21
		Noise	9
		Residues	
		Temperature	11–13
		Air pollution	9, 12
	Energy savings		9, 12, 22–24
		Renewable energy sources (solar and wind)	12
		Areas where waste heat data center can be reused (office building, swimming pools, greenhouses)	12
		Potential for free cooling by water	14, 16
		Potential for free cooling by air	12, 16
	Interference with protected areas		13

Alternatives were evaluated based on eight criteria, divided into environmental, economic and risk-related categories. Daim *et al.*[14] proposed hierarchical decision model (HDM) to select the best location of a data center in California. To assess the alternatives, 12 criteria were used, divided into five categories, including financial, environmental, social, political and geographic. Based on the results, telecom network availability, land cost, tax structure, incentives and subsidies and safety and security crime were identified as the main criteria in selecting the best location for the data center.

Klinkowski *et al.*[15] focussed on the optimization algorithms that minimize the required spectrum in the location selection problem of the data center. To this end, they first proposed a mathematical model to minimize the required spectrum based on demand constraints, after which they used several algorithms to solve the proposed model. The results indicated that the column generation technique presents good results within a reasonable time frame. Ounifi *et al.*[16] used a mixed integer linear programming (MILP) model to select the optimal location of the data center from five areas in Quebec. The objective function in the proposed model minimizes different costs, such as fixed and variable, server and switch and energy costs. To solve the MILP model, nine parameters were applied, including costs of maintenance, server, administration, energy, land and bandwidth. Based on the results, energy cost, accounting for 21% of the total costs, was determined to be the main factor in determining the best location for the data center. Depoorter *et al.*[17] conducted a study to illustrate the efficiency of the data center location in different regions of Europe. To that end, they analyzed the data center's energy efficiency with both direct air free cooling strategy and photovoltaic system integration to identify candidate locations, using energy consumption, electricity generation, renewable energy supply, primary energy consumption, carbon emissions and energy cost as the main indicators. The results show that in comparison with photovoltaic system integration, the direct free air-cooling strategy significantly reduces the energy consumption of the data center. Mustafa *et al.*[18] used GIS and analytic hierarchy process (AHP) to determine the most suitable locations for landslide monitoring in Cameron Highland, identifying tower distance, elevation, communication service coverage and slope as the main criteria. The results indicated that communication service coverage has the greatest impact on the data center location selection problem. Liu *et al.*[19] proposed a hybrid methodology, including the Lagrangian multiplier method and particle swarm optimization algorithm, to determine the optimal location of railway data centers in China. Minimizing the transmission distance between different railway data centers is the main aim of their proposed method. They evaluated the locations based on factors like construction costs, availability of specialists in the region, existing communication networks and electricity efficiency (maintenance).

As the literature review shows, both MCDM methods and mathematical programming are popular when it comes to determining the optimal location of data centers. The review reveals that (i) although many criteria have been identified in literature as affecting the location of data centers, there is no comprehensive framework bringing those criteria altogether, (ii) the geographical distribution of the selected locations has been ignored in most MCDM studies and (iii) the mathematical models suggested in literature may not cover all criteria (especially the qualitative ones) that affect the location of data center. This may have to do with the fact that, by increasing the number of constraints and variables, not only does the complexity of creating a mathematical model increase,[25] but the feasibility of the mathematical model in question is also reduced dramatically. Therefore, it turns out that the application of MCDM or a mathematical model, as a single solution to the problem of finding the best location for data centers, may not be sufficiently effective.

To remedy that state of affairs, a multi-criteria set-covering method is proposed in this paper, consisting of two parts, an MCDM method, namely BWM, to calculate the utility of potential locations and a set-covering model to determine the optimal location of data centers. We used the performance of each alternative in the criteria presented in Table 1 to calculate the utility of each alternative presented. The results of the multi-criteria part are then used as parameters of the objective function in the model suggested in the second part of the proposed methodology. Using the set-covering model not only addresses the problem of the geographical distribution of selected locations but also means that a wide range of criteria, presented in Table 1, is considered in the selection process.

3. Research Methodology

As shown in Fig. 1, the methodology used in this paper consists of two parts and five steps. In the first part called MCDM, the utility of alternatives (in this case the provinces of Iran) is calculated through three steps. To this end, in the first step a sustainable framework of criteria is created through literature review (Table 1) and then using the best–worst method (BWM) and additive value function the weight of the criteria and the utility of each alternative are computed in Steps 2 and 3, respectively.

In the second part of the methodology applied in this research, first using the result of additive value function, a linear set-covering model is proposed in Step 4 and then through the brute-force and genetic algorithm the developed model is evaluated in Step 5.

3.1. *BWM*

As presented in Fig. 1, to calculate the weight of criteria, presented in Table 1, BWM is employed in this research. BWM, which is a pairwise comparison-based method, has many advantages compared to weighting methods.[26–28] The number of pairwise comparisons in the BWM is efficient,[26] which increases the number of respondents.

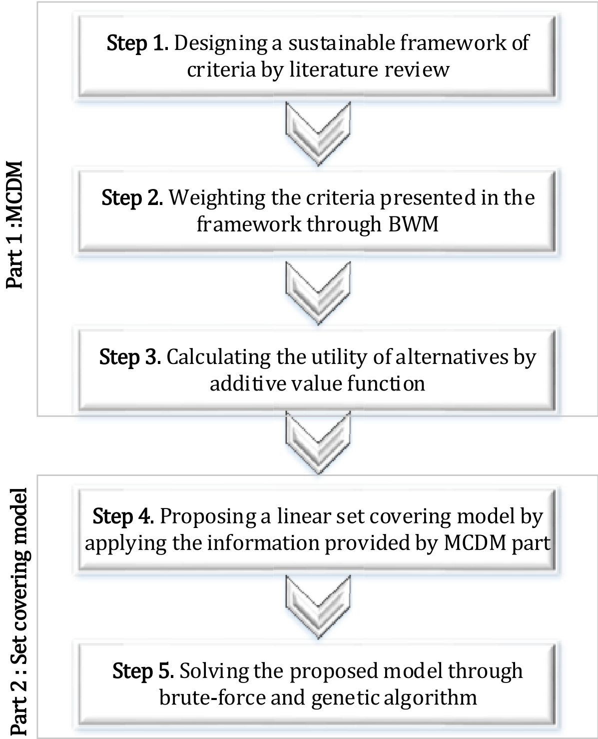

Fig. 1. The methodology applied in this research.

The high consistency rate provided by BWM makes its results more reliable than similar methods.[26,29,30] BWM has been successfully used in several real-world problems, including location selection problems,[31–33] sustainability,[34–36] technology selection,[37,38] emergency decision-making,[39] reliability engineering,[40] customer requirements.[41] and supply chain management.[42–44] The process of weighting using BWM is divided into five steps, as follows.[26,27]

(1) Determine a set of decision criteria $\{c_1, c_2, \ldots, c_n\}$. This step is done by decision-makers and/or experts.
(2) Determine the best (B) and the worst (W) criteria by the decision-makers and/or experts.
(3) Determine the preference of the best criterion (B) over all the other criteria by the decision-makers and/or experts using a number from 1 to 9 (where 1 is equally important and 9 is extremely more important). The result of "Best-to-Others" comparisons is the vector $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bj}, \ldots, a_{Bn})$, where a_{Bj} indicates the preference of criterion B over criterion j
(4) Determine the preference of all the criteria over the worst by the decision-makers and/or experts using a number from 1 to 9. The result of "Others-to-Worst"

comparisons is the vector $A_w = (a_{1W}, a_{2W}, \ldots, a_{jW}, \ldots, a_{nW})$, where a_{jW} denotes the preference of criterion j over criterion W.

(5) Calculate the optimal weights $(w_1*, w_2*, \ldots, w_n*)$ by an optimization model.

The optimal weights are calculated by minimizing the maximum of $\{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\}$ for all j, which is translated into the following optimization model:

$$\min \max_j \{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\}$$

$$\text{subject to:}$$

$$\sum_{j=1}^{n} w_j = 1$$

$$w_j \geq 0, \quad \text{for all } j. \tag{1}$$

Model (1) is transferred into:

$$\begin{gathered} \min \xi \\ \text{subject to:} \\ |w_B - a_{Bj}w_j| \leq \xi, \text{ for all } j \\ |w_j - a_{jW}w_W| \leq \xi, \text{ for all } j \\ \sum_{j=1}^{n} w_j = 1 \\ w_j \geq 0, \quad \text{for all } j. \end{gathered} \tag{2}$$

Model (2) is used to determine the local weight of the criteria $(w_1*, w_2*, \ldots, w_n*)$ and the consistency indicator $(\xi*)$. When there is more than one level in the decision-making hierarchy, the local weights are first calculated using Model (2), after which the global weights of criteria are computed by multiplying the local weights at the different levels. After determining the global weight of the criteria, by using Eq. (3), the additive value function presented by Keeney and Raiffa,[45] the utility of alternatives with regard to different criteria, is calculated[46,47]:

$$V_i = \sum_j w_j u_{ij} \quad \text{for all } i, \tag{3}$$

where w_j and u_{ij} are the global weight of criterion j and the normalized value of alternative i in criterion j, respectively using Eqs. (4) and (5), the amount of u_{ij} for monotonic increasing (e.g. quality of life) and monotonic decreasing (e.g. cost) criteria can be calculated.

$$u_{ij} = \frac{x_{ij}}{\max_i(x_{ij})} \quad \text{for all } i \text{ and } j, \tag{4}$$

$$u_{ij} = \frac{\min_i(x_{ij})}{x_{ij}} \quad \text{for all } i \text{ and } j. \tag{5}$$

3.2. *Linear set-covering model*

In the second part of the methodology, the most suitable locations for data centers are identified using the linear set-covering model. The utility of the potential candidates calculated in the first part, the number of data centers and the coverage radius of each data center are included as parameters in the proposed model. We used the following notations for developing the mathematical model.

Notations

$P = \{p_1, p_2, \ldots, p_n\}$	A set of n provinces
$\text{Dis} : P \times P \to R^{>0}$	A distance function between each pair of provinces
$\text{Per} : P \to [0, 1]$	Normalized performance function which assigns a proper performance showing how much a province deserves to be a center without considering utility or distance of other provinces
T	A distance threshold (i.e., the cover radius for each data center)
k	Maximum number of provinces which can be selected as a data center (this can also be replaced by budget constraints)
x_i	A binary decision variable: if a province p_i is selected as a data center place $x_i = 1$, otherwise $x_i = 0$
$X = \{x_1, x_2, \ldots, x_n\}$	Solution set
$D[i, j]$,	A Boolean $n \times n$ matrix shows the distance between each pair of provinces is less than T or not. $D[i, j] = 1$ shows $D(p_i, p_j) \leq T$, otherwise $D[i, j] = 0$.
V_j	The utility of province p_i resulted by MCDM (Eq. (3))

Conditional objective function

The proposed linear set-covering model, including conditional performance function and constraints, is described below.

Conditional performance function$Per(p_i|X)$

According to the objective function (Eq. (6)), the provinces selected for a data center not only cover the service applicants in a specific radius but also have a high performance in the various criteria, divided into economic, social and environmental categories. Since choosing a province for a data center affects the utility of the other provinces, we need an approach to handle such interactions. In this regard, we introduce a simple and efficient method, called *conditional performance function*. The idea is to gradually reduce the utility of a province with regard to the distance and utility value of the surrounding data centers. To this end, we define $\alpha(i, j)$ as the distance interaction function, where $\alpha(i, j) = 0$ shows the distance of provinces p_i and p_j is far from the distance threshold T, which means that there is no interaction between the two. Otherwise $0 < \alpha(i, j) < 1$ shows the amount of such interaction, such that by reducing the distance between provinces p_i and p_j, the value of $\alpha(i,j)$ is gradually increased. $\beta(i)$ is an aggregative utility function for the province p_i. It denotes the aggregative impact of surrounding provinces of p_i and reduces the utility of a province p_i up to half of its independent utility. If, in a solution vector X, there is no data center near p_i, $\alpha(i,j) = 0$ and consequently it results in $\beta(i) = 0$, that is, the conditional performance function $Per(p_i \,|\, X) = V_j$. Otherwise, $Per(p_i \,|\, X) = \frac{V_j}{1+}\beta(i)$ is a reduced or conditional utility value of p_i. The method is formulated as follows.

$$\text{Maximize}\,\text{Per}(X) = \sum_{i=1}^{n} x_i \text{Per}(p_i \,|\, X). \tag{6}$$

In the conditional performance function $\text{Per}(p_i|X)$:

$$\alpha(i,j) = \begin{cases} 0, & \text{if Dis}[i,j] > T, \\ \dfrac{T - \text{Dis}[i,j]}{T}, & \text{otherwise,} \end{cases}$$

$$\beta(i) = \frac{\sum\limits_{\substack{j=1 \\ j\neq i}}^{n} x_j \alpha(i,j)\, V_j}{\sum\limits_{j=i}^{n} x_j D[i,j]\, V_j},$$

$$\text{Per}(p_i \,|\, X) = \frac{V_j}{1+\beta(i)}. \tag{7}$$

Constraints

As indicated in constraint (8), the number of selected provinces should be equal to or less than k:

$$\sum_{i=1}^{n} x_i \leq k. \tag{8}$$

According to constraint (9), for each province p_i, there is at least one province p_j such that $x_j = 1$ and $\text{Dis}(p_i, p_j) \leq T$:

$$\sum_{j=1}^{n} x_j D[i,j] > 0, \quad \forall i = 1, 2, \ldots, n \tag{9}$$

4. Data Collection

In this section, we discuss the procedure we used to collect data to evaluate the various provinces of Iran as possible data center locations. The data collection process for this study consisted of two steps, with data being collected to weight the criteria and calculate alternatives scores. The steps are discussed in greater detail below.

4.1. *Data for the criteria*

In the first data collection step, first the criteria included in Table 1 were screened. When the number of criteria is reduced, which is the result of screening, the

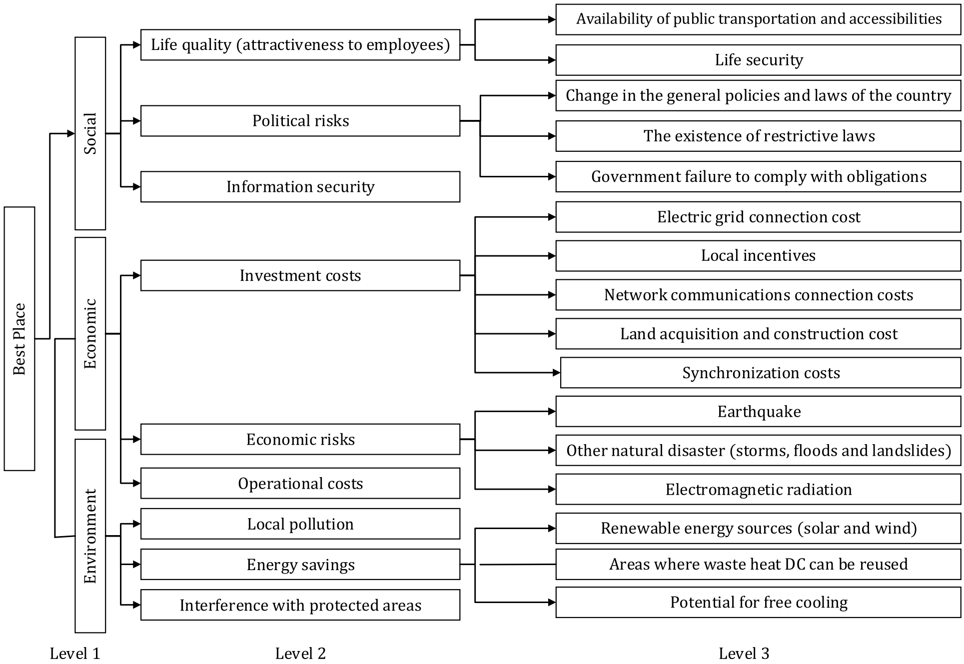

Fig. 2. The hierarchical tree for criteria.

discriminant power of decision maker(s)/experts[48] and the inconsistency in the pairwise comparisons[49] are decreased. To screen the criteria, 11 experts were invited to fill in an online questionnaire based on a five-point Likert scale. After aggregating the experts' opinion, the number of 3 (out of 5) was selected as a threshold, which leads to appropriate balance among the three dimensions of hierarchical tree. The results are presented in Fig. 2.

Then, BWM was used to design an online questionnaire for weighting the criteria listed above, in which 35 experts were asked to provide their opinions. All respondents in both stages have academic knowledge about and work experience with data centres. They were identified by their online profile. Since Iran is a large country with different economic, social and environmental conditions, we have tried to select the experts from different parts of Iran. So that, of 35 experts invited in this research, 11 (31%) worked in east provinces of Iran and the remaining experts were employed as specialist members of server room in center (23%), west (17%), north (15%) and south (14%) of Iran. Table 2 shows the specific backgrounds of the respondents used in both steps. For aggregating the experts' opinion in the weighting step, geometric mean is applied.

4.2. *Data for the alternatives*

In the second step of data collection, based on the type of criteria (i.e., qualitative or quantitative), data were collected to evaluate the utility of provinces of Iran as

Table 2. Specifications of experts.

Respondents	For screening criteria	Average years of work experience	For weighting criteria	Average years of work experience
Information and Communication Center of Ferdowsi University	—	—	11	8.5
Research Center of Information Technology of Iran University of Science and Technology	—	—	6	10.6
Information and Communication Center of Vali-E-Asr University of Rafsanjan	—	—	4	8.4
Tehran Municipality ICT Organization	—	—	2	5
Specialists in different server rooms	11	3.81	12	5.5

alternatives. From among the criteria presented in Fig. 2, *local incentives* have been considered as qualitative criteria. The score of provinces of Iran, in this criterion, was determined based on the experts' opinion through an online questionnaire. To this end, we used a 10-point Likert scale to determine the score of provinces of Iran for *local incentives criterion.* For collecting data in other criteria, both web sites and internal database of Iran Meteorological Organization, the Law Enforcement Force of Iran, the Ministry of Science Research and Technology, the Ministry of Culture and Islamic Guidance, the Ministry of Health and Medical Education, the Statistical Centre of Iran, the Ministry of Housing and Urban Development and the Institute for Research and Planning in Higher Education were used in this research.

5. Results and Discussion

In this section, first the local weight of the criteria shown in Fig. 2 is analyzed. Secondly, the global weights and data collected from different sources are used to determine the suitability of the different provinces of Iran for the location of a data center. Finally, the performance of the linear set-covering model is evaluated based on a number of examples.

5.1. *Local weight of criteria*

A sustainable framework of criteria is applied that includes social, economic and environmental dimensions to determine the optimal location for a data center in Iran. The mean values of criteria for the three levels are presented in Tables 3–5. According to the findings, which are based on expert opinions, the economic criteria are more important than either social or environmental criteria (Table 3). A lack of transparency when it comes to supporting investors in a developing country like Iran, the general instability in the Middle East, which limits investments into sensitive facilities like data centers, and the unstable economic conditions of Iran as a result of the sanctions in particular[50,51] could explain the distribution of the weights.

Table 3. Weigh of the main criteria.

Criteria	Weight	Rank
Economic	0.416	1
Environmental	0.324	2
Social	0.260	3

Table 4. Weigh of sub-criteria in level 2.

Category	Sub-criteria	Weight	Rank
Economic	Investment costs	0.380	1
	Operational costs	0.316	2
	Economic risks	0.304	3
Social	Life quality	0.317	2
	Political risks	0.259	3
	Information security	0.424	1
Environmental	Local pollution	0.374	2
	Energy saving	0.388	1
	Interference with protected areas	0.238	3

Economic dimension

Of the indicators in the economic category, *investment costs* were weighted as the most important criterion by the experts (Table 4). The cost of equipment, problems with regard to importing the equipment to Iran because of the sanctions,[52,53] the high exchange rate in Iran[54] and the lack of transparency facing investors in Iran[55] are some of the reasons for that. *Operational costs* and *economic risks* were ranked second and third, with not much difference between them (Table 4).

Since the problems mentioned in the investment section can be remedied by providing incentives like free land, taxes and subsidies,[55] the experts considered *local incentives*as the most important sub-criterion in the category of *investment costs* (Table 5). *Land acquisition* and *construction costs*, *network connectivity costs*, *electric grid connection cost* and *synchronization costs* are other important factors in this category (Table 5). *The earthquake* has been selected as the most important indicator of the *economic risk* category by experts (Table 5). The geographical location of Iran, in an earthquake zone, justifies that selection. *Electromagnetic radiation* and *other natural disasters* were also considered to be important sub-criteria in this category (Table 5).

Social dimension

Of the three criteria included in the social category, *information security* is selected as the main factor (Table 4). The role of Iran in the political, economic and military constellation in the Middle East[56] combined with high levels of insecurity in neighboring countries[57] are reasons to select *information security* as an important factor in this regard. *Life quality* and *political risks* are two other important criteria in this

Table 5. Weigh of sub-criteria in level 3.

Category	Sub-criteria	Weight	Rank
Investment costs	Electric grid connection cost	0.198	4
	Local incentives	0.247	1
	Network communications connection costs	0.199	3
	Land acquisition and construction cost	0.205	2
	Synchronization costs	0.152	5
Economic risks	Earthquake	0.400	1
	Other natural disasters (storms, floods and landslides)	0.265	3
	Electromagnetic radiation	0.334	2
Life quality	Availability of public transportation and accessibilities	0.281	2
	Life security	0.719	1
Political risks	Change in the general policies and laws of the country	0.364	1
	The existence of restrictive laws	0.363	2
	Government failure to comply with obligations	0.273	3
Energy saving	Renewable energy source (solar, wind)	0.386	2
	Areas where waste heat data center can be reused	0.224	3
	Potential for free cooling	0.391	1

category (Table 4). The results of the analysis in the weight of criteria categorized into *political risks* indicate that *changes in the general policies and laws of the country,* with very little difference between them, are more important than *the existence of restrictive laws* and *government failure to comply with obligations* (Table 5). The unstable economic condition in Iran can be mentioned to justify the high weight of the first two criteria. In an economic crisis, different restrictive laws and policies could be implemented and cause social upheaval, like a reduction in the workforce,[58] which would affect society directly. Based on the expert opinions, of the criteria included in *life quality, life security* is more important with regard to the location of a data center than the *availability of public transport and accessibilities* (Table 5). The size of the country, which can lead to a reduction in security in some areas, combined with the high levels of insecurity in neighboring countries[57] are among the reasons why the experts considered *life security* to be that important.

Environmental dimension

Of the criteria included in the first level of the environmental category, *energy saving*, *local pollution* and *interference with the protected area* were identified by the experts as being the most important criteria (Table 4). This may have been affected by air pollution levels in Iran. Due to the heat generated by data centers, there may be some areas of the country that would be unable to meet the energy demand involved,[59] while the use of fossil fuels, the main source of air pollution in Iran, is reduced. According to the experts, the *potential for free cooling* is the most important sub-criterion of *energy saving* (Table 5). The high cost of cooling the equipment[60] and differences in climate condition in various parts of Iran are among the reasons for assigning the high weight to the *potential for free cooling. Renewable*

Table 6. Global weight of sub-criteria.

Criteria	Global weight (w_j)	Rank
Operational costs	0.132	1
Local pollution	0.121	2
Information security	0.110	3
Interference with protected areas	0.077	4
Life security	0.059	5
Earthquake	0.051	6
Potential for free cooling	0.049	7
Renewable energy source (solar and wind)	0.048	8
Electromagnetic radiation	0.042	9
Local incentives	0.039	10
Other natural disasters (storms, floods and landslides)	0.034	11
Land acquisition and construction	0.033	12
Network communications connection costs	0.032	13
Electric grid connection cost	0.031	14
Areas where waste heat data center can be reused	0.028	15
Change in the general policies and laws of the country	0.025	16
The existence of restrictive laws	0.0241	17
Synchronization costs	0.024	18
Availability of public transportation and accessibilities	0.023	19
Government failure to comply with obligation	0.018	20

energy sources (*solar*, *wind*) and *areas where waste heat data center can be reused* were considered to be the other two important factors in this category (Table 5).

5.2. *Alternatives' utility*

To determine the utility of provinces of Iran for establishing a data center, first the global weight of criteria, w_j, is calculated (Table 6). Based on w_j in Table 6, *operational costs*, *local pollution* and *information security,* respectively, are the first three criteria that play a significant role in deciding the suitability of alternatives.

By using w_j (mean values) and u_{ij} as shown in Table A.1 in Appendix A, the suitability of candidate locations is computed by Eq. (3) for the various provinces of Iran (Table 7). The results indicate that, of the 31 provinces in Iran, Qom, Semnan and Zanjan offer the best alternatives. However, as shown in Fig. 3, the three alternatives are located near each other, which may affect the service for clients further afield (i.e., customers located in the southern and south eastern provinces of Iran).

5.3. *Results of the multi-criteria set-covering model*

As discussed earlier, to ensure an appropriate geographical distribution in the selected location of data centers, something that is not addressed by MCDM methods, we use a multi-criteria set-covering method, using the results of the MCDM part as parameters in the objective function of the linear set-covering model. By using the proposed model, the selected centers guarantee both a good performance on the criteria in the economic, social and environmental categories and an appropriate

Table 7. The utility of Iran's provinces for data center location.

Provinces of Iran	Utility of candidate places	Rank
Qom	0.4645	1
Semnan	0.4603	2
Zanjan	0.4542	3
Markazi	0.4444	4
South Khorasan	0.4416	5
Bushehr	0.4320	6
Qazvin	0.4272	7
Ardabil	0.4197	8
North Khorasan	0.4081	9
Hormozgan	0.4050	10
Yazd	0.3991	11
Alborz	0.3985	12
Tehran	0.3984	13
Kohgeluyeh and Boyer-Ahmad	0.3954	14
Ilam	0.3945	15
Razavi Khorasan	0.3821	16
Isfahan	0.3617	17
Kordestan	0.3434	18
Chaharmahal and Bakhtiari	0.3419	19
Kerman	0.3416	20
Hamadan	0.3375	21
East Azarbaijan	0.3341	22
Mazandaran	0.3304	23
Sistan and Baluchestan	0.3289	24
Gilan	0.3232	25
Kermanshah	0.3150	26
Golestan	0.3017	27
Fars	0.2973	28
Lorestan	0.2741	29
West Azarbaijan	0.2735	30
Khuzestan	0.2714	31

geographical distribution, which guarantees high-quality services for potential clients. To demonstrate the performance of the proposed model, we analyze the problem under different conditions (Table 8). To analyze the problem, two methods, Brute-Force and a genetic algorithm, were applied. Although the Brute-Force method provides optimal solutions, it is not a practical method for the large instances that exist in a country like Iran. In this regard, we used Brute-Force method to solve problems with small number of centers (i.e., $k \leq 8$), solving the rest using a genetic algorithm (Table 8). Note that the parameter $D[i, j]$, which shows the distance between alternatives, is presented in Table A.2 in Appendix A.

As Table 8 indicates, there is a connection between the number of the data center (s), the coverage radius of data centers in a specific area and the geographical distribution of selected locations. In other words, when there is a limitation on the number of data centers, for instance, due to a limited budget, the suggested model tries to select locations that have a high geographical dispersion for a small coverage

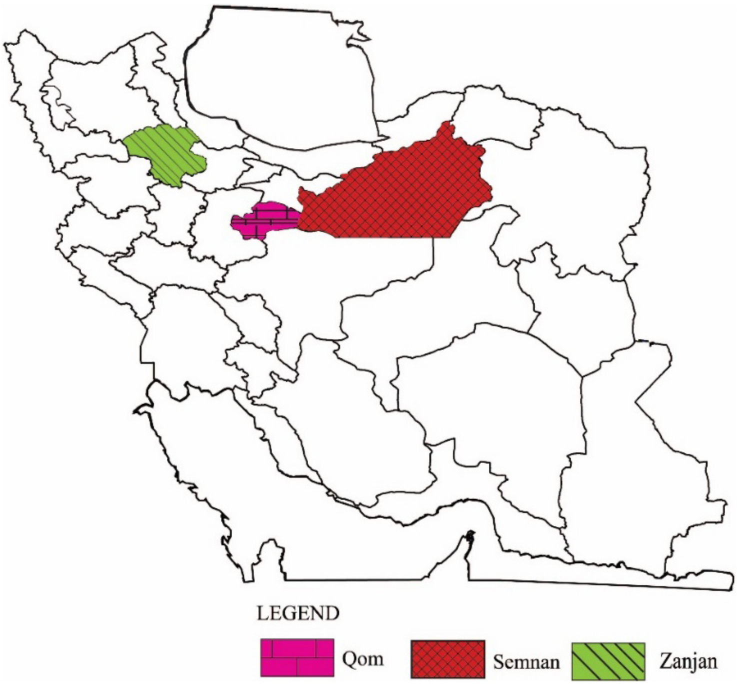

Fig. 3. The location of the first three provinces resulted in MCDM.

radius. Otherwise, the suitability of the selected places is the first priority through the proposed model for a large coverage radius. Figure 4 clarifies the case mentioned for three data centers. As indicated in Fig. 4, for $T = 800$ km and 1000 km, only Zanjan, which is a province in the north-west of Iran, is selected as a highly suitable location. However, when the coverage radius of each data center increases (i.e., $T = 1200$ km and 1500 km) and taking into account that not all potential clients may receive high-quality services, the most suitable locations (i.e., Qom, Semnan and Zanjn) are selected (Fig. 4).

In contrast, when there is no limitation on the number of the selected locations, the results provided by the set-covering model yield about the same results as the MCDM, even for small coverage radius, which means that the role of the utility in the selection becomes far more important than the distribution of data centers. In other words, by increasing the number of data centers, all potential clients can be serviced by at least one data center within a reasonable distance, so the objective function in the proposed model attempts to select the most suitable locations even for small coverage radius. For instance, as shown in Table 8, when $T = 500$ km, when we increase the number of data centers, the most suitable locations (i.e., Qom, Semnan and Zanjan) are selected as alternatives, which means that based on the opinion of decision-maker(s)/experts who want to know the suitable locations of data center, if the suitability of the selected locations is more important than the coverage radius of data centers, or vice versa, the linear set-covering model performs well.

Table 8. Analyzing the problem under different settings.

Solved by		Selected places for (T is distance in km)				
		$T = 500$	$T = 800$	$T = 1000$	$T = 1200$	$T = 1500$
Brute-Force	$k = 1$	No feasible solution	No feasible solution	No feasible solution	No feasible solution	Qom Objective function: 0.4645
	$k = 3$	No feasible solution	Zanjan South Khorasan Kohgeluyeh and Boyer-Ahmad Objective function: 1.2912	Zanjan South Khorasan Bushehr Objective function: 1.3278	Qom Semnan South Khorasan Objective function: 1.3664	Qom Semnan Zanjan Objective function: 1.3790
	$k = 5$	No feasible solution	Qom Semnan Zanjan South Khorasan Yazd Objective function: 2.2197	Qom Semnan Zanjan Bushehr South Khorasan Objective function: 22526	Qom Semnan Zanjan Markazi South Khorasan Objective function: 2.2650	Qom Semnan Zanjan Markazi South Khorasan Objective function: 2.2650
	$k = 8$	Qom Semnan Zanjan South Khorasan Bushehr North Khorasan Hormozgan Kordestan	Qom Semnan Zanjan Markazi South Khorasan Bushehr Qazvin Hormozgan	Qom Semnan Zanjan Markazi South Khorasan Bushehr Qazvin Ardabil	Qom Semnan Zanjan Markazi South Khorasan Bushehr Qazvin Ardabil	Qom Semnan Zanjan Markazi South Khorasan Qazvin Ardabil

Table 8. (*Continued*)

Solved by		Selected places for (T is distance in km)				
		$T = 500$	$T = 800$	$T = 1000$	$T = 1200$	$T = 1500$
		Objective function: 3.4091	Objective function: 3.5292	Objective function: 3.5439	Objective function: 3.5439	Objective function: 3.5439
Genetic algorithm	$k = 10$	Qom	Qom	Qom	Qom	Qom
		Semnan	Semnan	Semnan	Semnan	Semnan
		Zanjan	Zanjan	Zanjan	Zanjan	Zanjan
		Markazi	Markazi	Markazi	Markazi	Markazi
		South Khorasan	South Khorasan	South Khorasan	South Khorasan	South Khorasan
		Bushehr	Bushehr	Bushehr	Bushehr	Bushehr
		North Khorasan	Qazvin	Qazvin	Qazvin	Qazvin
		Hormozgan	Ardabil	Ardabil	Ardabil	Ardabil
		Yazd	North Khorasan	North Khorasan	North Khorasan	North Khorasan
		Objective function: 4.2526	Objective function: 4.3511	Objective function: 4.3570	Objective function: 4.3570	Objective function: 4.3570
	$k = 12$	Qom	Qom	Qom	Qom	Qom
		Semnan	Semnan	Semnan	Semnan	Semnan
		Zanjan	Zanjan	Zanjan	Zanjan	Zanjan
		Markazi	Markazi	Markazi	Markazi	Markazi
		South Khorasan	South Khorasan	South Khorasan	South Khorasan	South Khorasan
		Bushehr	Bushehr	Bushehr	Bushehr	Bushehr
		Qazvin	Qazvin	Qazvin	Qazvin	Qazvin
		Ardabil	Ardabil	Ardabil	Ardabil	Ardabil
		North Khorasan	North Khorasan	North Khorasan	North Khorasan	North Khorasan
		Hormozgan	Hormozgan	Hormozgan	Hormozgan	Hormozgan
		Ilam	Alborz	Yazd	Yazd	Yazd
		Kordestan	Tehran	Alborz	Alborz	Alborz
		Objective function: 5.0949	Objective function: 5.1539	Objective function: 5.1546	Objective function: 5.1546	Objective function: 5.1546

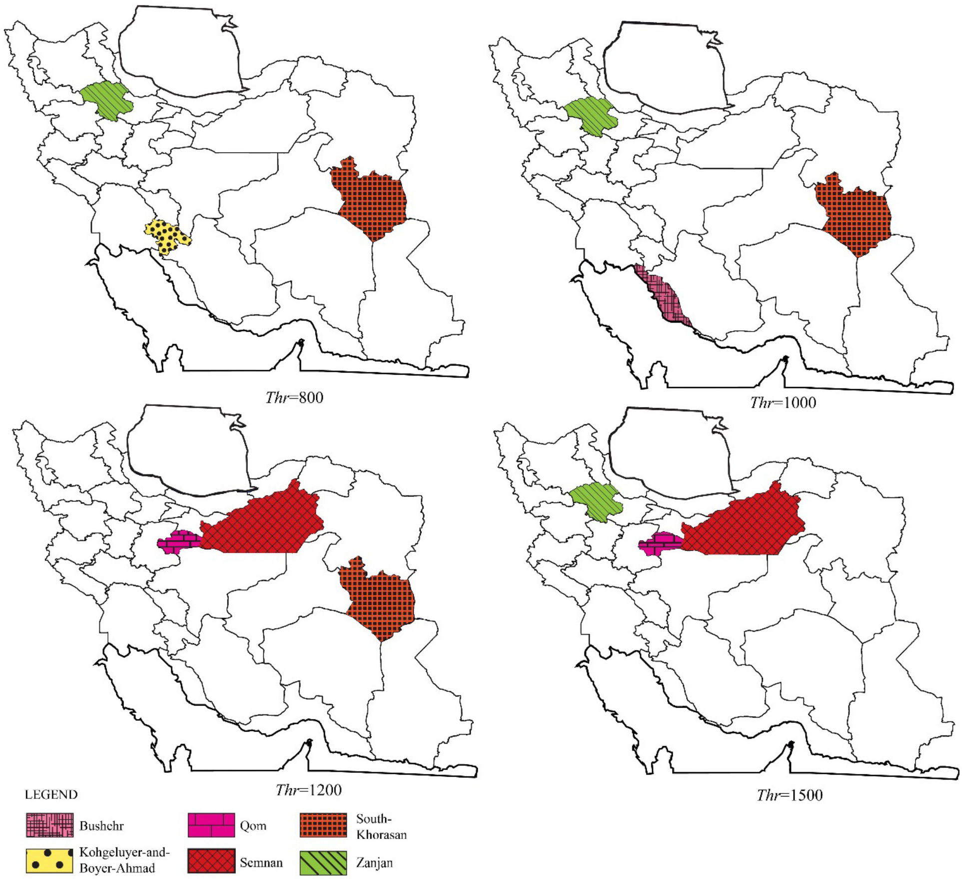

Fig. 4. Geographical place of three provinces of Iran for data center with different distance thresholds.

6. Conclusion and Future Research

In this paper, a multi-criteria set-covering method was used to determine the location of data centers. In the proposed method, first the utility of candidate places was calculated, using the BWM, after which a linear set-covering model was used to select the optimal number of locations for data centers that cover a specific radius. To evaluate the suitability of candidate locations, sustainable framework of criteria was created on the basis of a comprehensive literature review. The proposed methodology was applied to Iran. To weighting the criteria included in the proposed framework, a group of specialists from Iran was asked to fill in an online questionnaire designed based on the BWM, the results indicating that *operational costs*, *local pollution* and *information security* are the most important criteria, respectively. The weight of the criteria was then used to determine the suitability of the various provinces of Iran.

In addition to the criteria included in the proposed framework, the layout of data centers plays an important role in the quality of the services provided by the various data centers, because the speed of accessing to information in cyberspace is affected by the radius covered by the data centers. In this regard, by applying the suitability of the alternative locations and the coverage radius of each data center as parameters, a linear set-covering model was used to select a certain number of data centers in the second part of the proposed methodology, using a brute-force algorithm and a genetic algorithm to solve the proposed model. The performance of the proposed model was tested under different settings.

The sustainable framework proposed in this paper has a number of advantages. Using the list of the criteria presented in the framework, public policymakers can produce better laws to increase the level of satisfaction regarding Internet services, while decision-makers can improve the quality of the selected locations.

Since the evaluation of candidate places should satisfy two major requirements: sustainability perspective and geographical distribution, which could apply to many other similar location selection problems (e.g., telecommunication or biofuel distribution center selection), the use of the proposed multi-criteria set-covering methodology in those similar problems could be considered as one possible avenue for future research.

We also suggest including other features of data centers, such as workload/traffic exchanged within a data center network, as well as using other optimization algorithms such as simulated annealing, particle swarm optimization and tabu search to solve the suggested model.

Appendix A

Table A.1. Normalized value of alternatives in different criteria.

	Criteria										
Alternatives	Operational cost	Local pollution	Information security	Interference with protected areas	Life security	Earthquake	Potential for free cooling	Renewable energy source (solar, wind)	Electromagnetic radiation	Local incentives (obtaining of construction license)	Other natural disaster (storms, floods and landslides)
East Azarbaijan (A_1)	0.3258	0.1484	0.2448	0.4366	0.3631	0.0950	0.7686	0.1369	0.8184	1.0000	0.0714
West Azarbaijan (A_2)	0.2537	0.1777	0.2615	0.1047	0.3462	0.1275	0.8304	0.0995	0.7585	0.4941	0.0435
Ardabil (A_3)	0.4559	0.4567	0.7333	0.1163	0.1247	0.5135	1.0000	0.3831	0.9426	0.4941	0.1176
Isfahan (A_4)	0.5841	0.1133	0.2285	0.2707	0.3972	0.2159	0.5706	0.9119	0.7226	0.3216	0.0606
Alborz (A_5)	0.8240	0.2139	0.5220	0.0654	0.1753	0.6129	0.6039	0.1358	0.7870	0.5059	0.2000
Ilam (A_6)	0.3077	1.0000	0.7700	0.1321	0.0521	0.0603	0.5439	0.0630	0.7631	0.4941	0.1538
Bushehr (A_7)	0.2173	0.4987	0.8415	0.1365	0.0952	0.0417	0.3750	0.1170	0.7072	1.0000	0.0417
Tehran (A_8)	0.7156	0.0437	0.0917	0.3377	1.0000	0.3455	0.5376	0.0177	0.7870	0.3216	0.1111
Chaharmahal and Bakhtiari (A_9)	0.3133	0.6121	0.6364	0.1379	0.1444	0.1387	0.7623	0.0409	0.7623	0.3216	0.1111
South Khorasan (A_{10})	0.3773	0.7545	1.0000	0.0849	0.0910	0.3167	0.5536	0.5897	0.7267	0.5059	0.0303
Razavi Khorasan (A_{11})	0.4546	0.0902	0.1548	0.7089	0.5719	0.2676	0.6596	0.6657	0.7834	0.5059	0.0426
North Khorasan (A_{12})	0.4517	0.6722	0.6968	0.2439	0.1310	0.4872	0.7045	0.1273	0.8380	0.3216	0.1667
Khuzestan (A_{13})	0.0632	0.1232	0.1812	0.3111	0.2693	0.0285	0.3563	0.2054	0.7372	1.0000	0.0171
Zanjan (A_{14})	0.9185	0.5486	0.2388	0.1935	0.3707	1.0000	0.8087	0.1559	0.8121	0.3216	0.2857
Semnan (A_{15})	0.3648	0.8260	0.7333	1.0000	0.1251	0.0950	0.5110	0.3469	0.8053	0.3216	0.0833
Sistan and Baluchestan (A_{16})	0.1776	0.2091	0.5404	0.5339	0.1698	0.0826	0.5000	0.7315	0.6982	0.4941	0.0364
Fars (A_{17})	0.1151	0.1196	0.1990	0.6889	0.4570	0.0138	0.5167	0.2442	0.7032	0.5059	0.0339
Qazvin (A_{18})	0.9639	0.4555	0.4968	0.0228	0.1571	0.4222	0.6549	0.3141	0.8878	0.3216	0.2500
Qom (A_{19})	0.7361	0.4489	0.7778	0.0279	0.1182	0.8636	0.5082	0.3425	0.7641	0.5059	1.0000
Kordestan (A_{20})	0.4176	0.3619	0.1265	0.1587	0.5778	0.5135	0.6503	0.2593	0.7769	0.4941	0.3333

Table A.1. (*Continued*)

Alternatives	Criteria										
	Operational cost	Local pollution	Information security	Interference with protected areas	Life security	Earthquake	Potential for free cooling	Renewable energy source (solar, wind)	Electromagnetic radiation	Local incentives (obtaining of construction license)	Other natural disaster (storms, floods and landslides)
Kerman (A_{21})	0.1212	0.1833	0.2862	0.7424	0.3097	0.0205	0.5471	1.0000	0.7066	0.5059	0.0278
Kermanshah (A_{22})	0.3623	0.2971	0.4375	0.1090	0.1190	0.1508	0.6242	0.3009	0.7585	0.5059	0.1250
Kohgeluyeh and Boyer-Ahmad (A_{23})	0.2949	0.8136	0.7064	0.1647	0.0966	0.0782	0.6370	0.1003	0.7596	0.3216	0.1176
Golestan (A_{24})	0.2609	0.3104	0.4889	0.0445	0.1734	0.1367	0.5314	0.0663	0.7641	1.0000	0.0769
Gilan (A_{25})	0.3313	0.2292	0.3298	0.1124	0.2627	0.1557	0.5776	0.1163	1.0000	1.0000	0.0385
Lorestan (A_{26})	0.2236	0.3295	0.3675	0.1523	0.2072	0.0941	0.5376	0.1964	0.7216	0.3216	0.0667
Mazandaran (A_{27})	0.3695	0.1767	0.4219	0.3660	0.2111	0.1532	0.5345	0.0507	0.9665	0.5059	0.0769
Markazi (A_{28})	1.0000	0.4059	0.4952	0.0955	0.1805	0.5588	0.6788	0.2880	0.7657	0.5059	0.1000
Hormozgan (A_{29})	0.2841	0.3266	0.3784	0.6375	0.2400	0.0204	0.3419	0.4490	0.7142	1.0000	0.0952
Hamadan (A_{30})	0.4484	0.3338	0.5049	0.0548	0.1797	0.5135	0.7750	0.0826	0.7640	0.3216	0.0741
Yazd (A_{31})	0.3886	0.5096	0.7624	0.4078	0.1179	0.0927	0.4745	0.4511	0.7132	0.5059	0.0769

Table A.1. (*Continued*)

Alternatives	Criteria								
	Land acquisition and construction	Network communications connection costs	Electric grid connection cost	Areas where waste heat data center can be reused	Change in the general policies and laws of the country	The existence of restrictive laws	Synchronization costs	Availability of public transportation and accessibilities	Government failure to comply with obligation
East Azarbaijan (A_1)	0.1590	0.7137	0.1563	0.2947	0.1218	0.1218	0.1218	0.6076	0.1218
West Azarbaijan (A_2)	0.2459	0.6011	0.1563	0.2461	0.0662	0.0662	0.0662	0.5049	0.0662
Ardabil (A_3)	0.2358	0.6364	0.1563	0.0958	0.0825	0.0825	0.0825	0.3325	0.0825
Isfahan (A_4)	0.1149	0.7951	0.1049	0.3860	0.1776	0.1776	0.1776	0.6248	0.1776
Alborz (A_5)	0.1590	0.7395	0.5313	0.2044	0.1218	0.1218	0.1218	0.0815	0.1218
Ilam (A_6)	0.2400	0.6906	0.0759	0.0437	0.0868	0.0868	0.0868	0.1821	0.0868
Bushehr (A_7)	0.3173	0.7612	0.1272	0.0877	1.0000	1.0000	1.0000	0.2513	1.0000
Tehran (A_8)	0.0189	1.0000	1.0000	1.0000	0.1536	0.1536	0.1536	0.1626	0.1536
Chaharmahal and Bakhtiari (A_9)	0.1781	0.6065	0.1496	0.0714	0.0707	0.0707	0.0707	0.1855	0.0707
South Khorasan (A_{10})	0.2977	0.6214	0.0246	0.0580	0.0832	0.0832	0.0832	0.6981	0.0832
Razavi Khorasan (A_{11})	0.2682	0.6445	0.1138	0.4850	0.0858	0.0858	0.0858	0.8455	0.0858
North Khorasan (A_{12})	0.2863	0.5360	0.0804	0.0651	0.0982	0.0982	0.0982	0.2305	0.0982
Khuzestan (A_{13})	0.2350	0.6662	0.1272	0.3550	0.2888	0.2888	0.2888	0.8631	0.2888
Zanjan (A_{14})	0.1966	0.6296	0.1362	0.0797	0.0919	0.0919	0.0919	0.3293	0.0919
Semnan (A_{15})	0.1707	0.8955	0.0246	0.0529	0.1155	0.1155	0.1155	0.1917	0.1155
Sistan and Baluchestan (A_{16})	0.2249	0.3731	0.0402	0.2092	0.0797	0.0797	0.0797	0.9658	0.0797

Table A.1. (*Continued*)

Alternatives	Criteria								
	Land acquisition and construction	Network communications connection costs	Electric grid connection cost	Areas where waste heat data center can be reused	Change in the general policies and laws of the country	The existence of restrictive laws	Synchronization costs	Availability of public transportation and accessibilities	Government failure to comply with obligation
Fars (A_{17})	0.1625	0.7463	0.1049	0.3656	0.1297	0.1297	0.1297	1.0000	0.1297
Qazvin (A_{18})	0.1451	0.6784	0.1674	0.0960	0.1226	0.1226	0.1226	0.2872	0.1226
Qom (A_{19})	0.1347	0.7992	0.1451	0.0974	0.0866	0.0866	0.0866	0.0872	0.0866
Kordestan (A_{20})	0.2405	0.5984	0.1183	0.1208	0.0846	0.0846	0.0846	0.3780	0.0846
Kerman (A_{21})	0.2838	0.5807	0.0580	0.2385	0.1787	0.1787	0.1787	0.7655	0.1787
Kermanshah (A_{22})	0.3001	0.5997	0.1585	0.1472	0.1169	0.1169	0.1169	0.4510	0.1169
Kohgeluyeh and Boyer-Ahmad (A_{23})	1.0000	0.6092	0.1161	0.0537	0.1056	0.1056	0.1056	0.2742	0.1056
Golestan (A_{24})	0.3488	0.6038	0.1563	0.1409	0.0712	0.0712	0.0712	0.2716	0.0712
Gilan (A_{25})	0.2620	0.6947	0.4174	0.1907	0.0659	0.0659	0.0659	0.5218	0.0659
Lorestan (A_{26})	0.3949	0.5712	0.1161	0.1327	0.0652	0.0652	0.0652	0.4402	0.0652
Mazandaran (A_{27})	0.2606	0.8670	0.3348	0.2475	0.1087	0.1087	0.1087	0.4457	0.1087
Markazi (A_{28})	0.1440	0.7313	0.1473	0.1077	0.1794	0.1794	0.1794	0.3424	0.1794
Hormozgan (A_{29})	0.2748	0.6811	0.0759	0.1339	0.6887	0.6887	0.6887	0.5166	0.6887
Hamadan (A_{30})	0.2503	0.6201	0.2031	0.1310	0.0762	0.0762	0.0762	0.3156	0.0762
Yazd (A_{31})	0.2956	0.8657	0.0513	0.0858	0.1483	0.1483	0.1483	0.3080	0.1483

Table A.2. Distance among provinces of Iran (parameter of $D[i,j]$).

Provinces	East Azarbaijan	West Azarbaijan	Ardabil	Isfahan	Alborz	Ilam	Bushehr	Tehran	Chaharmahal and Bakhtiari	South Khorasan	Khorasan-e-Razavi	Khorasan-e-Shomali	Khuzestan	Zanjan	Semnan	Sistan and Baluchestan
East Azarbaijan	0	308	219	1,038	589	772	1,560	599	1,142	1,912	1,493	1,321	1,075	280	835	2,166
West Azarbaijan	308	0	527	1,074	721	766	1,549	907	1,178	2,220	1,802	1,620	1,064	588	1,143	2,264
Ardabil	219	527	0	1,030	545	975	1610	591	1,134	1,814	1,333	1,080	1,305	377	828	2,154
Isfahan	1038	1,074	1,030	0	452	678	580	439	104	1,173	1,222	1,152	745	757	675	1,190
Alborz	589	721	545	452	0	691	1,082	48	583	1174	954	790	842	293	271	1,516
Ilam	772	766	975	678	691	0	932	710	719	1,788	1,604	1,423	447	598	946	1,868
Bushehr	1,560	1,549	1610	580	1,082	932	0	1,228	684	1,599	1,648	1,941	485	1,338	1,464	1,404
Tehran	599	907	591	439	48	710	1,228	0	543	1,313	894	713	874	319	236	1,567
Chaharmahal and Bakhtiari	1,142	1,178	1,134	104	583	719	684	543	0	1,277	1,326	1,256	849	862	779	1,294
South Khorasan	1,912	2,220	1,814	1,173	1,174	1,788	1,599	1,313	1,277	0	481	734	1,918	1623	1,139	470
Khorasan-e-Razavi	1,493	1,802	1,333	1,222	954	1,604	1,648	894	1,326	481	0	253	1,768	1,213	658	951
Khorasan-e-Shomali	1,321	1,620	1,080	1,152	790	1,423	1,941	713	1,256	734	253	0	1,587	1,032	543	1,204
Khuzestan	1,075	1,064	1,305	745	842	447	485	874	849	1918	1,768	1,587	0	967	1,110	1,759
Zanjan	280	588	377	757	293	598	1,338	319	862	1,623	1,213	1,032	967	0	555	1,886
Semnan	835	1,143	828	675	271	946	1,464	236	779	1,139	658	543	1,110	555	0	1,609
Sistan and Baluchestan	2,166	2,264	2,154	1,190	1,516	1,868	1,404	1,567	1,294	470	951	1,204	1,759	1,886	1,609	0
Fars	1,523	1,559	1,515	485	939	1,100	304	924	589	1,325	1,374	1,637	659	1,243	1,160	1,100
Qazvin	455	763	451	480	110	617	1060	150	584	1463	1,044	863	882	175	386	1,717
Qom	731	1,039	723	279	189	684	876	132	367	1,445	1,026	845	715	451	368	1,375
Kordestan	52	446	655	627	505	320	1,108	501	732	1,814	1,395	1,214	623	278	737	1,818
Kerman	1,637	1,735	1,629	661	1,026	1,339	875	1,038	765	999	889	1,142	1,230	1,357	1,274	529
Kermanshah	588	582	791	653	519	184	972	526	731	1,800	1,420	1,239	487	414	762	1,817
Kohgeluyeh and Boyer-Ahmad	1,337	1,373	1,329	299	797	977	281	738	229	1,405	1,454	1,451	433	1,057	974	1,274
Golestan	996	1,304	764	836	454	1,107	1,625	397	940	1,050	569	316	1,271	716	377	1,520
Gilan	485	793	266	764	284	774	1,524	325	868	1,548	1,067	814	1,039	348	561	1,892
Lorestan	879	783	930	370	505	308	860	499	474	1,543	1,393	1,212	375	592	735	1,560
Mazandaran	866	1,174	634	706	320	977	1,495	267	810	1,180	699	446	1,141	586	205	1,650
Markazi	785	786	843	288	298	514	868	293	392	1,606	1,187	1,006	581	505	529	1,478
Hormozgan	1,933	2026	1,925	975	1,317	1,729	927	1,334	1,061	1,213	1,374	1,627	1,278	1,653	1,570	743
Hamadan	609	610	667	464	337	373	1044	337	568	1,637	1,231	1,050	638	329	573	1,654
Yazd	1,276	1,374	1268	300	664	978	726	677	404	873	922	1,390	1,081	996	913	890

Table A.2. (*Continued*)

Provinces	Fars	Qazvin	Qom	Kordestan	Kerman	Kermanshah	Kohgeluyeh and Boyer-Ahmad	Golestan	Gilan	Lorestan	Mazandaran	Markazi	Hormozgan	Hamadan	Yazd
East Azarbaijan	1,523	455	731	52	1,637	588	1,337	996	485	879	866	785	1,933	609	1,276
West Azarbaijan	1,559	763	1,039	446	1,735	582	1,373	1,304	793	783	1,174	786	2,026	610	1,374
Ardabil	1,515	451	723	655	1,629	791	1,329	764	266	930	634	843	1,925	667	1,268
Isfahan	485	480	279	627	661	653	299	836	764	370	706	288	975	464	300
Alborz	939	110	189	505	1,026	519	797	454	284	505	320	298	1,317	337	664
Ilam	1,100	617	684	320	1,339	184	977	1,107	774	308	977	514	1,729	373	978
Bushehr	304	1,060	876	1,108	875	972	281	1,625	1,524	860	1,495	868	927	1,044	726
Tehran	924	150	132	501	1,038	526	738	397	325	499	267	293	1,334	337	677
Chaharmahal and Bakhtiari	589	584	367	732	765	731	229	940	868	474	810	392	1,061	568	404
South Khorasan	1,325	1,463	1,445	1814	999	1,800	1,405	1,050	1,548	1,543	1,180	1606	1,213	1,637	873
Khorasan-e-Razavi	1,374	1,044	1,026	1,395	889	1,420	1,454	569	1,067	1,393	699	1,187	1,374	1,231	922
Khorasan-e-Shomali	1,637	863	845	1,214	1,142	1,239	1,451	316	814	1,212	446	1,006	1,627	1,050	1,390
Khuzestan	659	882	715	623	1,230	487	433	1,271	1,039	375	1,141	581	1,278	638	1,081
Zanjan	1,243	175	451	278	1,357	414	1,057	716	348	592	586	505	1,653	329	996
Semnan	1,160	386	368	737	1,274	762	974	377	561	735	205	529	1,570	573	913
Sistan and Baluchestan	1,100	1,717	1,375	1,818	529	1,817	1,274	1,520	1,892	1,560	1,650	1,478	743	1,654	890
Fars	0	965	764	1,113	571	1,112	1,74	1,321	1,249	855	1,191	773	619	949	425
Qazvin	965	0	282	453	1,172	433	779	547	185	507	417	303	1,455	244	780
Qom	764	282	0	474	846	499	595	529	457	340	399	134	1,142	289	485
Kordestan	1113	453	474	0	1,289	136	927	898	565	427	768	340	1,585	164	928
Kerman	571	1,172	846	1,289	0	1,288	745	1,435	1,363	1,031	1,305	949	485	1,125	361
Kermanshah	1,112	433	499	136	1,288	0	952	923	590	320	793	365	1,769	189	953
Kohgeluyeh and Boyer-Ahmad	174	779	595	927	745	952	0	1,135	739	699	1,005	587	756	763	532
Golestan	1,321	547	529	898	1,435	923	1,135	0	498	896	130	690	1,731	734	1,074
Gilan	1,249	185	457	565	1,363	590	739	498	0	664	368	577	1,659	401	1,002
Lorestan	855	507	340	427	1,031	320	699	896	664	0	766	206	1,327	263	670
Mazandaran	1,191	417	399	768	1,305	793	1,005	130	368	766	0	560	1,601	604	944
Markazi	773	303	134	340	949	365	587	690	577	206	560	0	1,245	176	588
Hormozgan	619	1,455	1,142	1,585	485	1,769	756	1,731	1,659	1,327	1,601	1,245	0	1,421	657
Hamadan	949	244	289	164	1,125	189	763	734	401	263	604	176	1,421	0	734
Yazd	425	780	485	928	361	953	532	1,074	1,002	670	944	588	657	734	0

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