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Sustainability Model to Select Optimal Site Location for Temporary Housing Units: Combining GIS and the MIVES–Knapsack Model

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Abstract: Selecting the best site location for temporary housing (TH) is one of the most critical decision-making processes in the aftermath of disasters. Many spatial variables and multi-criteria indicator problems are involved in the decision-making analysis. Incorrect treatment of these components often led to failure in previous post-disaster recovery programmes. Wrong decisions caused short- and long-term negative impacts on the environment and people as well as wasting capital spending. In this regard, this research paper aims to present a novel multi-criteria decision-making approach that helps decision makers select optimal site locations to consider spatial and sustainability-related aims by assessing numerous alternatives. This new model is based on combining a knapsack algorithm and the integrated value model for sustainability assessment (MIVES) to derive optimal alternatives. This model makes it possible to objectively quantify sustainability indicators (economic, environmental, and social aspects) and derive satisfaction indices for each site (or set of sites) in terms of TH location. The model is designed to receive and filter data from a geographic information system (GIS). Using this model in future post-disaster recovery programs is believed to increase stakeholders' satisfaction and maximise the sustainability associated with the selection.

Keywords: multiple criteria analysis; site location for post-disaster temporary housing; MIVES; knapsack problem; GIS

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1. Introduction

Spatial problems might be complex due to the possible number of criteria and objectives involved [1]. This complexity increases as the decision-making process is implemented in disaster-related emergencies. According to [1–6], one of the main reasons for TH delay is due to the time often invested in finding the safest areas for it. On the other hand, fast decision making for site selection might fail due to a wide range of related factors. In this regard, an unsuitable site selection process has already proven to be the cause of failure in previous post-disaster housing programmes, such as the cases of Bam (Iran) and Pescomaggiore (Italy) [7,8]. In general, inappropriate site location for post-event temporary housing units (THUs) may lead to short- and long-term problems such as: (1) secondary hazards, (2) expenses, (3) loss of previous communities, (4) effects on the host community, and (5) environmental pollution [3,5,9,10]. Likewise, THUs could be critical in terms of economic, social, and environmental sustainability pillars [10–12].

Mainly, the negative impacts of TH discussed by the researchers related to THUs, which need to be provided after the events [5], whereas other types, such as rental units, already exist in the affected area. Nevertheless, THUs, which have been used for many recovery programmes in recent decades, could not be refused due to THU benefits and local limitations, such as: (1) other alternatives cannot meet huge demands; (2) pressure from the displaced population (DP), media, and so on, to provide THUs; (3) special conditions and the urgency of the situation (e.g., adverse weather conditions, number of vulnerable DP), which require fast delivery time; and (4) DP reluctance [7,9,11,13].

THU site location could become a serious challenge due to increased urban populations [14], especially in areas prone to natural disasters [15], informal settlements [4], changing natural disasters [16], insufficient research on disaster operations management [17–20], other area-specific limitations, such as land scarcity, and increasing global concern for environmental sustainability. Thus, regarding the probability of DP growth aftermath following events, as well as adverse outcomes of inappropriate site location for post-event THUs, it is required to help emergency managers select optimal site locations to consider spatial and sustainability-related aims quickly and precisely.

In this regard, the main objective of this research is to present a novel model to select the most suitable site location for THUs using sustainability concepts to meet the 2030 Agenda for Sustainable Development, introduced by the United Nations. This model aims to facilitate the decision-making process while considering multiple and complex variables to be quantified, without compromising the accuracy and representativeness of the results. Consequently, a combination of GIS and MIVES–knapsack techniques were considered to compile a multi-criteria decision-making model meant to provide suitable site locations for THUs. This new approach is applied to four districts of Tehran's (Iran) metropolitan area to determine the best subset of site locations for THUs. According to the report issued by both the Japan International Cooperation Agency (JICA) and the Centre for Earthquake and Environmental Studies of Tehran (CEST), dangerous seismic events along the Mosha fault in Tehran are expected to occur. The proposed model is applied before the seismic event. Nevertheless, the model can also be applied after the disaster, with slight modifications.

The remainder of this paper is organised into four parts: (1) Section 2, literature review; (2) Section 3, the design of the MCDM approach; (3) Section 4, a case study considering the four districts of Tehran, identifying and quantifying the impacts of a possible seismic hazard; and (4) Sections 5–7, application of the model and analysis of results.

2. Literature Review

Chandio et al. [21] stated that to achieve sustainability goals, it is fundamental to include GIS techniques in decision making. Combining both GIS and decision-making techniques helps stakeholders analyse spatial decision problems [22]. Carver [1] confirmed that GIS-MCDM could have an essential role in the site identification and evaluation processes. In this regard, according to [1,21,22], combining MCDM and GIS techniques brings the following advantages: (1) including decision makers' preferences, (2) guaranteeing experts' collaboration and engagement, and (3) involving and quantifying huge numbers of indicators and alternatives.

GIS-based approaches incorporating MCDMs to overcome post-disaster-related spatial problems have been already performed. For instance, Hadavi et al. [23] used the TOPSIS method and GIS to select the site location of TH in district 6 of Tehran. Fan [24] combined both clustering and spatial data association algorithms to determine suitable site locations for emergency response centres. Kar and Hodgson [25] designed a model based on GIS and weighted linear combination to specify the most appropriate evacuation shelters for the aftermath of hurricanes. Yau et al. [26] conducted a research study to determine site location suitability for post-disaster transitional housing using GIS, 3D building models, and construction project management. Kocatepe et al. [27] suggested a GIS-based optimisation model to select appropriate shelter locations for the displaced population aged over 85 with special needs and/or with pets. Chen et al. [28] presented a GIS-based hierarchical location model for post-earthquake shelter locations. Li et al. [29] designed a model based on a combination of GIS and a hierarchical model to select post-disaster shelter in urban areas. Moroto et al. [30] used a GIS and logistic regression model to specify influential factors in selecting locations for NGOs' projects during the disaster management process.

Shi et al. [31], believing that the provision of urban emergency shelters is an essential part of disaster management, designed a model based on GIS and a weighted Voronoi diagram to obtain optimal solutions. Kılcı et al. [32] combined GIS and integer linear programming to allocate temporary shelter locations. Xu et al. [33] presented a multi-criteria method GIS for evacuation shelter locations. Cetinkaya et al. [34] prompted a GIS-based fuzzy analytic hierarchy method and TOPSIS to determine refugee camps.

The aforementioned GIS-MCDM hybrid models are intended to specify suitable zones so that decision makers can select the sites (inside the zones). Nonetheless, few of these models embrace stakeholder satisfaction objectively and, if so, quantification is rather subjective. Moreover, there are few, if any, studies that consider all pillars of sustainability, such as environmental and social, as a whole. Furthermore, Ma et al. [35] and Abid et al. [36] mentioned the need to combine intelligent optimization algorithms with GIS to deal with this decision-making problem due to the number of variables involved and the complexity associated with its quantification. However, few studies in THU site selection areas applied intelligent optimisation.

Several decision-making methods have been combined with GIS to solve spatial problems. However, MIVES, which has already been applied successfully in several different fields, such as post-disaster housing management (e.g., [9,10]; more publications that applied MIVES for other fields are listed in Section 3, Methodology), has yet to be used with GIS. Meanwhile, MIVES is a sustainability assessment method with remarkable features, such as being based on utility theory. These features of MIVES, which are explained in the next section, enable decision makers to achieve more accurate results regarding the sustainability concept (see [37] for more information about the advantages of MIVES over other methods).

3. Methodology

3.1. The Framework of the Model

As shown in Figure 1, by specifying the requirements and boundaries of the case study, a set of possible individual sites are initially identified by using GIS information. The MIVES, knapsack algorithm, and GIS are combined to generate sets of alternative sites and to assess the sustainability of each one. Alternatives are considered valid if the total area of each alternative (individual or set) provides areas within the required ranges. Then, the sustainability index (*SI*) of alternatives, both individual sites and sets of sites, are evaluated and ranked. Finally, decisions can be made based on ranking and sensitivity analyses.

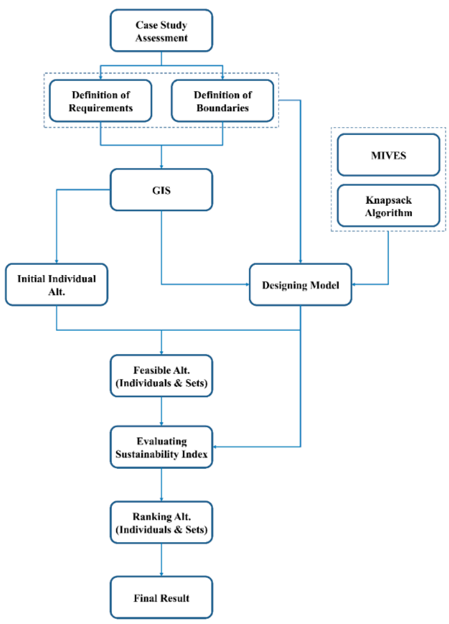

Figure 1. Methodology for selecting the most suitable site location.

To evaluate the *SIs* of site alternatives, the integrated value model for sustainable assessment (MIVES) is applied. The knapsack algorithm is used to select the most suitable alternative by imposing that: (1) alternative areas should fall within the required range, and (2) alternatives should provide the highest *SIs*. Additionally, it must be highlighted that GIS permits access to accurate information on alternatives considering the indicators established in the MIVES decision-making model.

ArcGIS version 10.7 is generally used for spatial analysis. The model is implemented with C++ code by using dynamic programming to reduce operation time. Each subset or individual site could be selected by the designed model provided the condition expressed by Equation (1) is met. Indeed, in this site selection problem based on the knapsack problem concept [38,39], the value that is being maximised is the sustainability index (*SI*). The weight is the area or total areas of site(s) $\left(\sum_1^i A_n\right)$ and the weight capacity is constrained between the minimum and maximum required area (W_1 and W_2):

$$W_1 \leq \sum_1^i A_n \leq W_2 \tag{1}$$

$$\text{Maximise } \frac{\sum_1^i SI_n * A_n}{\sum_1^i A_n}$$

where A_i is area of the site i, W_1, W_2 is the minimum and maximum demanded area, i is the number of members in a subset, and SI_n is the sustainability index of site n.

3.2. MIVES Model

The MIVES method, a multi-criteria decision-making method based on the utility theory concept, is selected as the approach for assessing the sustainability index (*SI*) of site alternatives. Using value function shapes in the MIVES method enables decision makers to achieve more accurate results compared with other MCDMs. Furthermore, in this method, an already-structured decision-making tree (DMT), based on the three main pillars of sustainability, helps experts to assign the weights to the indexes more precisely. The MIVES method has successfully been applied in different fields: (1) post-disaster housing management [9,10,40,41]; (2) active learning at architecture school [42]; (3) school edifices [43]; (4) infrastructures [44–46]; (5) urban development [47]; (6) structural elements [48]; (7) technology development [49]; (8) architectural issues [50–52]; and others.

To obtain the *SI* for each alternative using MIVES, the following steps should be taken: (1) establish a DMT with the relevant and representative indicators that governs sustainability in post-disaster temporary housing site locations (see Figure 2); (2) specify minimum (X_{min}) and maximum (X_{max}) satisfaction values for each indicator; (3) quantify the value of the indicators of each alternative ($X_{Alt.i}$); (4) determine the tendency and shape of the value function of each indicator, as shown in Figure 3; (5) assign weights to the DMT components; and (6) derive the *SI* of each alternative.

The *SI* is obtained from Equation (2), V_i and λ_i being the value (satisfaction) and weight (relative importance), respectively, of each component of the DMT:

$$V = \sum \lambda_i \cdot V_i(x_i) \tag{2}$$

where $V_i\ (x_i)$ is the value function of each indicator, criterion, or requirement; λ_i is the weight of the indicator, criterion, or requirement.

Additionally, Equations (3) and (4) are applied to obtain each indicator value. Equation (4), which considers sets of indicator values ($V_i\ (x_i)$) to be between the range of zero and one, is applied to specify factor B for Equation (3):

$$V_i = A + B \cdot \left[1 - e^{-k_i \cdot \left(\frac{|X_{Alt_i} - X_{min}|}{C_i}\right)^{P_i}}\right] \tag{3}$$

where A is the response value X_{min} (indicator abscissa), generally $A = 0$; X_{Alt_i} is the indicator abscissa that generates the value V_i; P_i is A shape factor that determines whether the curve is concave or convex, linear or S-shaped; C_i is the factor that establishes the value of the abscissa for the inflexion point in curves with $P_i > 1$; K_i is the factor that defines the response value to C_i; and B is the factor preventing the function from leaving the range (0.00, 1.00), obtained with Equation (4).

$$B = \left[1 - e^{k_i \cdot \left(\frac{|X_{max} - X_{min}|}{C_i}\right)^{P_i}}\right]^{-1} \quad (4)$$

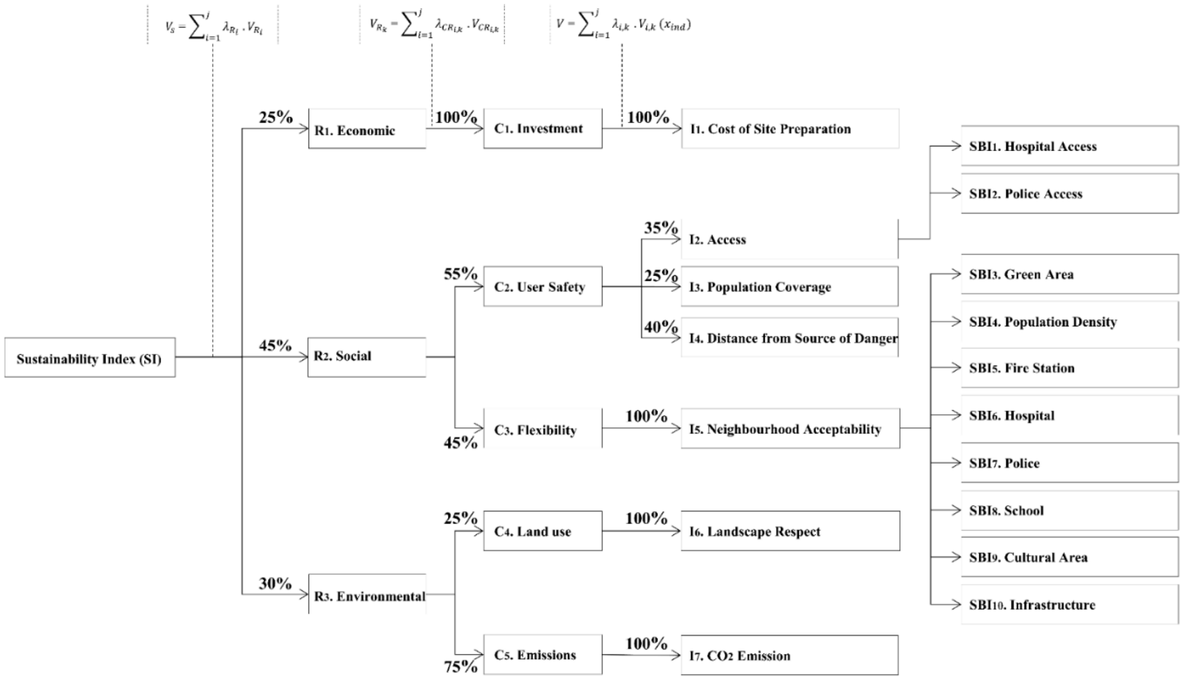

Figure 2. Decision-making tree, including requirements, criteria, indicators, and sub-indicators, and their weights.

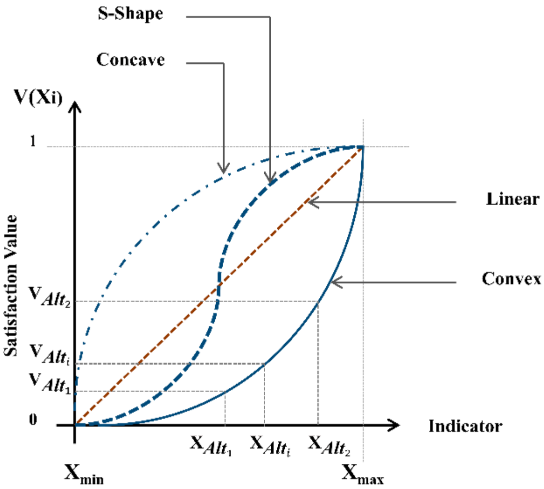

Figure 3. Value function shapes of MIVES indicators.

A DMT includes the three pillars of sustainability (economic, social, and environmental), and those criteria and indicators are applicable to the case under analysis. The DMT (Figure 2) was designed based on local stakeholders' preferences and was also identified through seminars and an extensive literature review. The *economic requirement* (R_1) represents the investment required for site location of THU over its entire life cycle, where the *investment* (C_1) is the determining criterion. The *social requirement* (R_2) assesses the social response to each alternative from the DP and third parties by embracing two criteria: (C_2) *user safety* and (C_3) *flexibility.* The *environmental requirement* (R_3) considers environmental impacts through the life cycle of the site location alternative considering (C_4) *land use* and (C_5) *emissions* criteria.

Cost of site preparation criterion (C_1) encompasses one indicator: the (I_1) *cost of site preparation* (cost/m^2) accounts for the costs from all activities related to the site preparation. Besides the costs of activities such as levelling, utilities, and mobilisation, this indicator (I_1) considers the quality of existing facilities on alternative sites. The *land price* was disregarded since, according to the results obtained through seminars with experts, the local government owns all possible alternative sites and, thus, *land price* is an insensitive parameter in the decision-making process.

The *user safety* (C_2) comprises three indicators (I_2–I_4). The indicator (I_2), *access,* takes into account the accessibility of alternative sites, considering emergency services and the DP. However, as immediate access from emergency services is significantly more important than DP access, all alternatives were located to guarantee sufficient access to services for the DP. In this sense, only emergency services are assessed: *access to hospital* (SBI_1) and *access to police* (SBI_2).

The indicator (I_3), *population coverage,* prevents decentralisation of the site alternative by rewarding greater coverage based on DP distributions. This indicator can be assessed by means of Equation (5). The indicator (I_4), *distance from sources of danger,* considers potential dangers, such as faults, rivers, and plants/warehouses processing/storing hazardous materials, in order to prevent secondary hazards regarding two factors: (1) distance from sources of danger and (2) quality or intensity of the dangers:

$$PC_i = \sum_1^m \left(\frac{D_{a_i \to R_m}}{P_{R_m}} \right) \tag{5}$$

where PC_i is the population coverage parameter for site alternative I, $D_{a_i \to R_m}$ is the distance between the centre of gravity of site alternative i and the centre of gravity of region m, m is number of assessed regions, and P_{R_m} is the predicted DP in region m.

Flexibility (C_3) includes one indicator: (I_5) *neighbourhood accessibility*, which comprises ten sub-indicators, as shown in Figure 2, that are taken into account to assess the potential of a host area to accommodate the DP and the impacts that this accommodation would have on it.

Land use (C_4), comprises *landscape respect* (I_6) for considering the impacts of site location on the ecosystem. The criterion *emissions* (C_5) compiles the *CO_2 emissions* indicators (I_7), expressed in terms of the equivalent CO_2 emissions [53] associated with all activities required to prepare the site, including transport.

It should be noted that there are many interactions between indicators and sub-indicators. Based on the indicators' impact identification, presented in Table 1, experts and decision makers can establish sets of weights that represent the stakeholders' preferences.

Table 1. Main factors and impacts of the indicators.

Indicator	Factor	Impact	References
I_1. Cost of site preparation	• Site characteristics (slope, topography, level of groundwater, etc.) • Utilities (energy and water) • Infrastructure	• Investors • Energy Consumption • CO_2 emission • Delivery time	[11,54–56]
I_2. Access	• Emergency service access • DP access • Access time • Quality of service	• Operation cost • DP safety and comfort • Energy consumption • CO_2 emission	[25,32,57,58]
I_3. Population coverage	• DP density • Allocated site • Travel distance	• DP satisfactions • Energy consumption • CO_2 emission	[10,59–61]
I_4. Distance from source of danger	• Risk • Distance • Probability • Intensity	• Occupants' safety • Operation cost • Environmental	[62–64]
I_5. Neighbourhood acceptability	• Population • Facilities (hospital, school, green area, etc.) • Culture	• DP comfort * • Disturbance to resident * • Environmental	[25,65–69]
I_6. Landscape respect	• Isolated district • Soil pollution • Water pollution • Land-use change	• Investors • DP safety • Resident' safety • Environmental	[11,70–72]
I_7. CO_2 emission	• Preparation activity • Transportation	• Investors • DP safety • Resident' safety • Environmental	[9,40,73]

* DP is displaced population, newly residing on sites, and resident is the host community, which lived in the area of the allocated sites for DP before the event.

4. Case Study (Earthquake in Tehran)

The four districts (2, 3, 6, and 7) of Tehran (Figure 4) among 22 districts, capital of Iran, in the aftermath of a seismic event at the Mosha fault are considered as a case study. The Tehran megacity (35° N, 51° E at the high altitude of 900 to 1800 m) is the highest populated city (8.8 million citizens and up to 15 million inhabitants in the whole metropolitan) in Iran. There are several faults in Tehran. The main active fault is the Mosha fault, which is close to the case study districts. These four districts, which have diverse characteristics, such as population density, facilities, households, etc. (Table 2), represent all districts of Tehran. The data were collected from a report by the Japan International Cooperation Agency (JICA) [74] and the Centre for Earthquake and Environmental Studies of Tehran (CEST), as shown in Table 2.

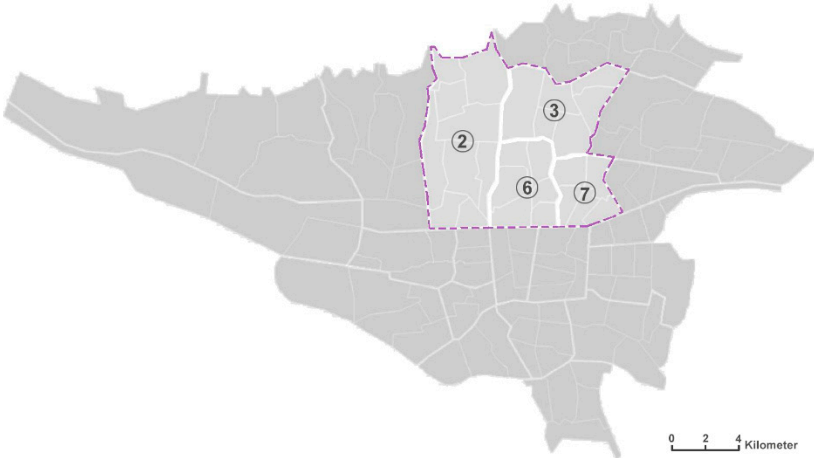

Figure 4. Tehran map (including the case study districts).

According to the JICA and CEST study (2000), in the case of an earthquake with the expected intensity occurring during the day, the number of DP from the four districts would exceed 160,000 people. In this research study, it is assumed that the total area of all the required sites should be sufficient to settle one-third of the DP, whilst the remaining two-thirds of DP could be accommodated in other types of TH.

Additionally, in order to increase the number of alternatives and potential subsets as well as the complexity of the problem, it was assumed that some sites would be located outside the city centre, close to entry roads, and that half of the DP would be settled there, whilst the other half would be settled on alternative sites in the city centre. This required a total area of nearly 100 hectares. In this study, a required area of almost 20 m^2 per person was obtained, based on the possibility of using multi-storey THUs due to land scarcity in Tehran. Nonetheless, 30 and even 45 m^2 per person was considered to be the required area by [54,75].

Table 2. Relevant information of the four studied districts.

	Case Study Districts				**Reference**
	District 2	**District 3**	**District 6**	**District 7**	
Area (ha)	4701	2922	2137	1534	[74,76–78]
Population (No.)	707,119	333,621	255,270	312,500	[45,77]
Population density (pers./ha)	150.42	114.18	119.45	203.72	[77]
Green area (m^2/pers.)	20.64	15.72	12.37	4.4	[77–80]
Medical services (m^2/pers.)	0.56	1.46	1.69	2.03	[74,77,81]
Police stations (pers./NO.)	20,203.40	8554.38	3272.69	6009.62	[74,77,80]
Fire stations (m^2/pers.)	0.0143	0.0190	0.0258	0.0117	[77,80,82]
Schools (m^2/pers.)	735	586	795	431	[77,80]
Cultural	0.04	1.06	0.6	2.96	[77]
Infrastructure	0.21	0.26	0.55	0.13	[77]
Level of urban development (%)	77.94	89.96	9.91	72.48	[79,80]
Damaged buildings proportion (%)	11.1	16.4	12.7	12.8	[74]
Causalities (%)	0.10	0.20	0.20	0.20	[74]

5. The New Model Application

After defining the requirements and boundaries (Figure 1), the initial GIS model is applied to the four districts of Tehran to determine possible alternatives. In this section of the study, the initial indicators, including site areas, functions (land use), properties, and location of the lands, were defined based on the problem requirements and boundaries to determine feasible sites among all alternatives in the four districts of Tehran. The total area of alternatives is 1979 ha, whilst the total area of the four districts is 11,294 ha. The areas of the chosen sites ranged from 5.1 to 179.8 ha, as the model searched for alternative sites covering an area of more than 5.0 ha. Available sites could be chosen, provided the sites do not belong to private parties; moreover, sites are not located in conservation areas. Furthermore, chosen sites should meet the other criteria, including connectivity and accessibility. Then, ArcGIS version 10.7 was applied to select possible sites based on the aforementioned selection criteria, using the layers in the geodatabase of the Tehran municipality. A total of 92 alternative sites were introduced, as shown in Figure 5. All land uses on alternative sites are shown in Figure 5, such as parks and green areas, educational, military, mixed-use, hospital, recreational, and other purposes. Some of these sites would need to be prepared before use; nonetheless, some of them were already being used for other functions.

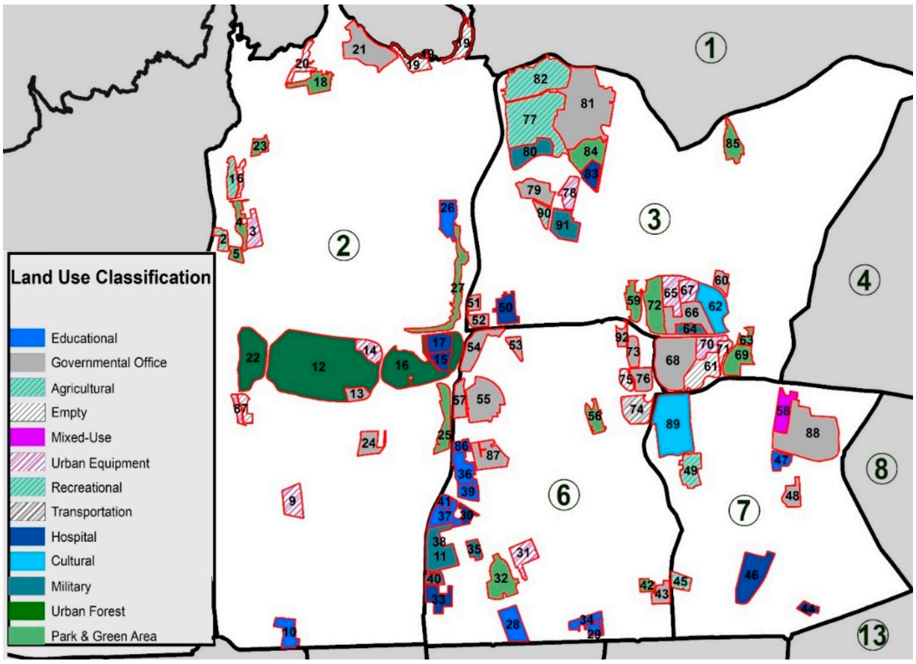

Figure 5. The case study districts (including 92 selected alternative sites).

The second part of the model, consisting of combining MIVES–knapsack and GIS, is designed to determine the most suitable alternatives from a sustainability perspective. As previously mentioned in Section 4, the total area of alternative sites (individuals or sets) should be almost 100 ha. To increase the number of potential alternatives, a slight variation of $\pm$5% (100 $\pm$ 5 ha) was also considered as valid.

To assess the *SI* of the subsets, value functions were fixed to quantify the satisfaction of each indicator gathered in the DMT (Figure 2). Coefficients and boundaries (X_{min} and X_{max}) were established for the indicators (Tables 3 and 4) based on data from the literature, international guidelines, Iranian standards, and seminars delivered by experts. The resulting value functions took the following shapes: seven decreasing, including three convex functions (DCx), one concave (DCv), and three S-shaped (DS), and eight increasing, including eight S-shaped functions (IS).

Table 3. Coefficients and parameters of each indicator.

Indicator	Unit	X_{max}	X_{min}	C	K	P	Shape	References
I_1	IRR/m^2	0.40×10^5	0.00	3.50×10^4	0.10	3.00	DCx	[81,83]
I_2	See sub-indicators (Table 4)							[79,82,84]
I_3	m/pop	1.00	0.10	1.00	4.00	1.10	DCv	[74,80,85]
I_4	m	0.40×10^4	0.00	1.50×10^3	2.00	2.50	IS	[63,86]
I_5	See sub-indicators (Table 4)							[74,80]
I_6	pts.	1.00	0.00	0.50	0.50	3.00	IS	[74,78]
I_7	km	28.00	8.00	20.00	0.50	2.20	DCx	[74]

Table 4. Coefficients and parameters of each sub-indicator.

I_x	Sub-Indicator	Unit	X_{max}	X_{min}	C	K	P	Shape	References
I_2	SBI_1	m	0.30×10^4	0.00	0.65×10^3	0.30	2.00	DS	[79,82,84,87]
	SBI_2	m	1.40×10^3	0.00	0.45×10^3	0.20	3.00	DS	[79,80,88]
I_5	SBI_3	m^2/pers.	25.00	4.00	8.00	0.50	2.60	IS	[78–80,89]
	SBI_4	pers./ha	0.41×10^3	30.00	0.36×10^3	0.05	2.50	DCx	[74,79,80,89]
	SBI_5	m^2/pers.	0.50	0.30×10^{-2}	0.30	0.18×10^3	2.00	IS	[79,82,84,89]
	SBI_6	m^2/pers.	2.30	0.50	0.80	0.20	5.00	IS	[79,80,89]
	SBI_7	pers./NO.	0.23×10^5	0.13×10^4	0.14×10^5	1.00	3.00	DS	[79,80,89]
	SBI_8	m^2/pers.	6.00	1.20	0.75	0.75×10^{-1}	2.60	IS	[79,80,89]
	SBI_9	m^2/pers.	1.50	0.00	0.35	0.10	3.50	IS	[80,89]
	SBI_{10}	m^2/pers.	1.00	0.20	0.30	0.20	3.00	IS	[89]

A point-assignment system was applied for I_6. Furthermore, it should be emphasised that the sub-indicator weights were considered to be the same for the *access* indicator (I_2) and *neighbourhood acceptability* indicator (I_5) regarding weights assigned by experts in the seminars.

The weights were allocated to the indicators using two approaches: (1) assigned by experts using the analytical hierarchy process (AHP), with the resulting weights (average values) presented in Figure 2, and (2) Shannon entropy (SE). The weights (λ_i) were determined by holding meetings and seminars with professors from the Universitat Politècnica de Catalunya (UPC) and Universitat Internacional de Catalunya (UIC) and experts from the Tehran Disaster Mitigation and Management Organization (TDMMO). The coefficients of variation for each λ_i did not exceed 10%; excluding outliers, which were eliminated.

Furthermore, to verify the adequacy of the model and minimise sources of error when assigning weights, these were previously estimated by SE using two approaches: (1) considering the indicator weights assigned by the experts (SE/AHP) and (2) disregarding the weights proposed by the experts (SE/NW).

The computational framework consisted of running the model three times with the same input data, each run with the sets of weights resulting from applying each of the aforementioned techniques. Indeed, the model is applied to select the most suitable alternatives among all 92 alternative sites and wide range of possible sets. All possible sets, formed by a combination of different sites, are assessed provided that all these sets meet the first condition mentioned in Section 3. To calculate the value of indicators I_1–I_7 for each alternative ($X_{Alt.i}$), the information derived from GIS is automatically used whilst the remaining coefficients and parameters are specified as input data for the model (Tables 2 and 3). The algorithm seeks suitable sets by optimising *SI* (three pillars of sustainability) for individual sites, considering weights assigned to indices.

6. Result and Discussion

The results obtained from applying the model, considering different weighting approaches, are shown in Table 5. The top-five ranked subsets presented in Table 5 were obtained with the three different weighting techniques (AHP, SE/AHP, and SE/NW). The suitable alternatives resulting from the model make it possible to confirm that a wide range of feasible sites was obtained. Consequently, the results should be rigorously analysed to select the most suitable subset.

Table 5. Sustainable subsets obtained by the algorithm based on the three weighting methods.

Method	Subset	*SI*	Selected Sites	Total Area (ha)
AHP	$\mathbf{A_1}$	**0.8489**	$\mathbf{S_{11}, S_{28}, S_{33}, S_{40}, S_{44}, S_{47}, S_{60}}$	**97.18**
	A_2	0.8488	$S_{11}, S_{28}, S_{29}, S_{33}, S_{40}, S_{44}, S_{47}, S_{60}$	102.78
	A_3	0.8485	$S_{11}, S_{28}, S_{33}, S_{34}, S_{44}, S_{47}, S_{60}$	100.94
	A_4	0.8483	$S_{11}, S_{28}, S_{33}, S_{40}, S_{44}, S_{47}, S_{60}, S_{92}$	103.06
	A_5	0.8475	$S_{28}, S_{31}, S_{33}, S_{34}, S_{35}, S_{40}, S_{44}, S_{47}, S_{60}$	98.39
SE/AHP	$\mathbf{B_1}$	**0.9824**	$\mathbf{S_{28}, S_{33}, S_{34}, S_{39}, S_{40}, S_{44}, S_{47}, S_{74}}$	**97.73**
	B_2	0.9823	$S_{28}, S_{30}, S_{33}, S_{40}, S_{44}, S_{47}, S_{74}, S_{76}$	98.06
	B_3	0.9823	$S_{28}, S_{30}, S_{33}, S_{34}, S_{35}, S_{39}, S_{40}, S_{44}, S_{47}, S_{48}$	100.10
	B_4	0.9823	$S_{28}, S_{29}, S_{30}, S_{33}, S_{34}, S_{40}, S_{44}, S_{47}, S_{74}$	100.35
	B_5	0.9822	$S_{28}, S_{30}, S_{33}, S_{34}, S_{40}, S_{44}, S_{47}, S_{74}, S_{92}$	100.64
SE/NW	$\mathbf{C_1}$	**0.9323**	$\mathbf{S_{28}, S_{30}, S_{33}, S_{34}, S_{39}, S_{40}, S_{43}, S_{44}, S_{47}, S_{48}}$	**103.02**
	C_2	0.9320	$S_{30}, S_{33}, S_{34}, S_{39}, S_{40}, S_{44}, S_{47}$	96.60
	C_3	0.9319	$S_{28}, S_{29}, S_{30}, S_{33}, S_{34}, S_{39}, S_{40}, S_{44}, S_{47}, S_{48}$	98.56
	C_4	0.9314	$S_{11}, S_{30}, S_{33}, S_{34}, S_{40}, S_{44}, S_{47}, S_{48}, S_{53}$	103.06
	C_5	0.9312	$S_{28}, S_{30}, S_{33}, S_{34}, S_{40}, S_{43}, S_{44}, S_{47}, S_{48}, S_{53}$	100.69

The *SIs* of the highest-ranked subsets (A_1, B_1, and C_1), which were selected based on the three different weighting techniques, are 0.85, 0.98, and 0.93, respectively. As shown in Table 5, the alternative sites (S_{28}, S_{33}, S_{40}, S_{44}, and S_{47}) were chosen to be the most sustainable by the algorithm for all subsets (A_1, B_1, and C_1), independently of the weighting technique (AHP, SE/AHP, and SE/NW). In this case, most sites from subset A_1 are from the common sites (S_{28}, S_{33}, S_{40}, S_{44}, and S_{47}) compared with B_1 and C_1. This is also reflected in Figure 6, which makes it possible to confirm that the frequency of sites (S_{28}, S_{30}, S_{33}, S_{34}, S_{40}, S_{44}, and S_{47}) is higher than other sites considering the top-five ranked subsets. From the aforementioned high frequency selected site, three sites (S_{33}, S_{44}, and S_{47}) were selected for each of the top-five ranked subsets of the three weighting techniques.

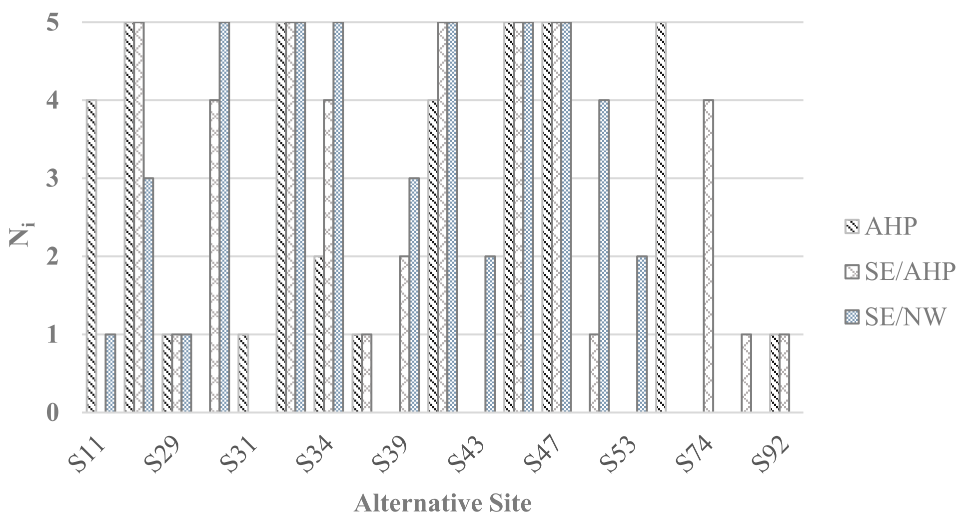

Figure 6. Frequency of each site (N_i) depending on the weighting technique.

The alternative sites (S_{28}, S_{33}, S_{40}, S_{44}, and S_{47}), which were chosen to be the most sustainable by the three weighting techniques, have already been used for other functions. The current use of these lands is educational (S_{28} and S_{47}), medical (S_{33} and S_{44}), and one site is military (S_{40}). These results demonstrated that the model works properly, as the sites, which have been used before the events, mostly could achieve high satisfaction values of the three pillars of sustainability (economic, social, and environmental). Additionally, it should be noted that these five sites are located within district 6, coinciding with the central area of the four districts (Figure 5). As already shown in Table 2, district 6 has a privileged situation in terms of fire stations, police stations, schools, and infrastructure. Meanwhile, this district presents a lower urban development degree in comparison with the other three districts.

The sites of subset A_1, which were selected based on the AHP weighting technique, were located within the three districts (3, 6, and 7); the other techniques led to selecting the sites located within the two districts (6 and 7). Among the sites of the first-ranked subsets (A_1, B_1, and C_1), there was no site selected from district 2, as shown in Figure 7. This could be due to some weaknesses of this district, such as high population density and low number of emergency services per capita. It should be mentioned that this district could be affected slightly compared with the other case study districts, and consequently, this district has a lower number of DP. In this case, there is a paradox in selecting suitable sites for this district. On the one hand, lower damage leads to less need for site locations for DP; however, DP from other districts could be settled in this district. On the other hand, according to several previous research studies, DP would prefer to stay close to their damaged properties. In this regard, *population coverage* (I_3) was determined to make greater coverage based on DP distributions to overcome this problem. Thus, most of the selected sites are located on the border of the four districts, as shown in Figure 7. Nevertheless, it is required to consider this paradox mentioned above specifically in future studies.

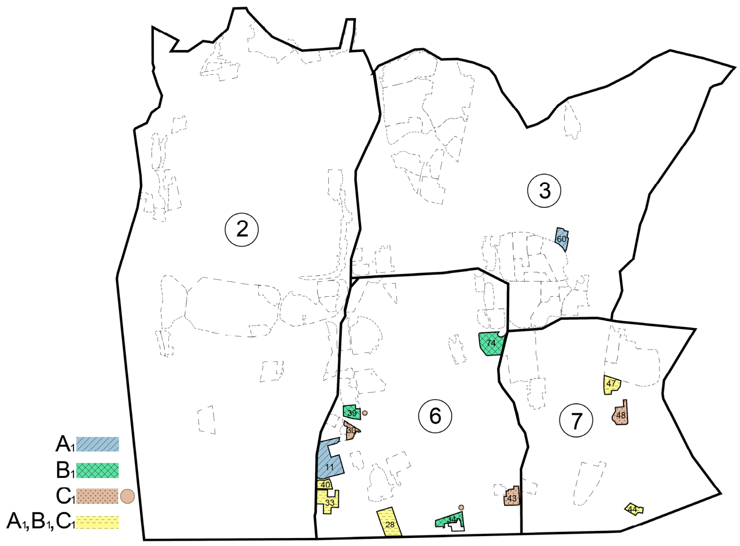

Figure 7. Distribution of the highest-ranked subsets (A_1, B_1, and C_1) obtained by the algorithm based on the three weighting methods.

The areas of high selected frequency sites (seven sites) range between 5.36 and 20.53 ha. All satisfaction values of I_1, I_4, and I_6 (from the economic, social, and environmental requirements, respectively) for the seven sites are maximum (1.0), as shown in Table 6. Among these seven alternatives, S_{30} has the highest satisfaction values for SBI_1 and I_3. Additionally, five sites (S_{28}, S_{30}, S_{33}, S_{34}, and S_{40}), located in district 6, obtained the highest satisfaction values for SBI_3, SBI_4, SBI_5, $SBI7_1$, and SBI_8. S_{40} and S_{47} achieved the best satisfaction values for SBI_2 and I_7, respectively. Additionally, it should be mentioned that the current use of these lands is educational (S_{28} and S_{34}), one site is military (S_{40}), and the others are medical (S_{30} and S_{33}).

Table 6. Satisfaction value for the indicators and sub-indicators of the seven sites without considering the assigned weights to the indices.

Satisfaction Value (V_i)															
Alt.	**I_1**	**I_2**		**I_3**	**I_4**	**I_5**								**I_6**	**I_7**
		SBI_1	**SBI_2**			**SBI_3**	**SBI_4**	**SBI_5**	**SBI_6**	**SBI_7**	**SBI_8**	**SBI_9**	**SBI_{10}**		
S_{28}	1.00	1.00	0.98	0.85	1.00	0.43	0.52	0.65	0.77	0.96	1.00	0.48	0.28	1.00	0.70
S_{30}	1.00	1.00	1.00	0.91	1.00	0.43	0.52	0.65	0.77	0.96	1.00	0.48	0.28	1.00	0.58
S_{33}	1.00	1.00	1.00	0.83	1.00	0.43	0.52	0.65	0.77	0.96	1.00	0.48	0.28	1.00	0.70
S_{34}	1.00	1.00	0.99	0.87	1.00	0.43	0.52	0.65	0.77	0.96	1.00	0.48	0.28	1.00	0.66
S_{40}	1.00	1.00	1.00	0.85	1.00	0.43	0.52	0.65	0.77	0.96	1.00	0.48	0.28	1.00	0.68
S_{44}	1.00	1.00	0.98	0.79	1.00	0.00	0.22	0.14	0.99	0.85	0.00	1.00	0.00	1.00	0.66
S_{47}	1.00	0.93	0.88	0.90	1.00	0.00	0.22	0.14	0.99	0.85	0.00	1.00	0.00	1.00	0.73

As shown in Tables A1, A3 and A5, both satisfaction values and *SIs* of the highest-ranked alternative sets using the three weighting methods are presented to implement sensitivity analysis on the indicator weights. According to Triantaphyllou and Sánchez [90], sensitivity coefficients of indicators and sub-indicators are determined, as shown in Tables A2, A4 and A6. More detailed descriptions of the sensitivity coefficient have been reported elsewhere, such as [90]. The results in Table A2 confirm that the most sensitive indicator based on the AHP weighting technique is I_7, and the least sensitive is SBI_1. Table A4 demonstrates that the most sensitive indicator based on the SE/AHP weighting technique is SBI_9, and the least is SBI_4. The results in Table A6 show that the most sensitive indicator based on the SE/NW weighting technique is SBI_9, and the least is I_7. In general, the results of these three weighting techniques are different.

In this regard, the weights assigned to the indices by the three techniques are assessed. As shown in Table 7, the weights assigned to the indicators by the SE/AHP method cannot be reliable due to the weight allocated to I_1. Although almost all the experts ranked this indicator at the first level, the weight of this indicator could not be 79%, and the rest of the indicators could be only 21%.

Table 7. Allocated final weights obtained by the three weighting methods.

	I_1	**I_2**		**I_3**	**I_4**	**I_5**								**I_6**	**I_7**
		SBI_1	**SBI_2**			**SBI_3**	**SBI_4**	**SBI_5**	**SBI_6**	**SBI_7**	**SBI_8**	**SBI_9**	**SBI_{10}**		
AHP	25.00%	5.20%	3.47%	6.19%	9.90%	2.53%	2.53%	2.53%	2.53%	2.53%	2.53%	2.53%	2.53%	7.50%	22.50%
SE/AHP	79.01%	5.73%	2.02%	0.58%	2.10%	0.40%	0.18%	0.25%	0.61%	1.57%	1.71%	3.26%	0.79%	1.16%	0.64%
SE/NW	35.93%	12.52%	6.64%	1.07%	2.41%	1.81%	0.79%	1.13%	2.72%	7.04%	7.70%	14.63%	3.53%	1.75%	0.33%

To this end, the results of SE/AHP have been eliminated from the final analysis. As shown in Figure 8, the weights assigned to the indicators by the two techniques (AHP and SE/NW) are considerably different for some indicators, for instance, I_7. In this regard, the weights of the AHP, SE/NW techniques, and the average weights (AW) of these two are considered, as shown in Figure 8.

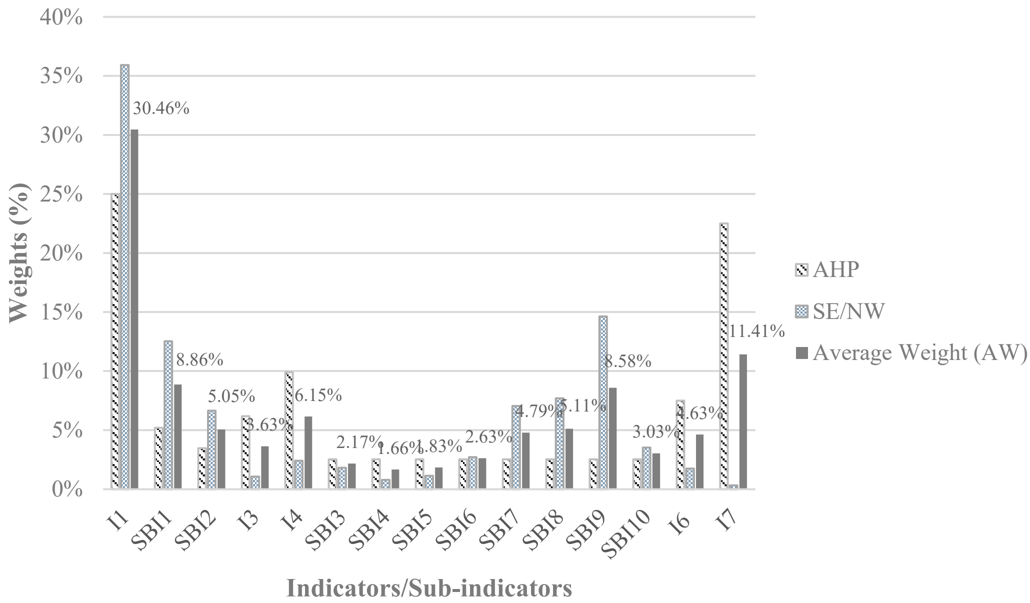

Figure 8. Final weights allocated to the indices (indicators and sub-indicators) by the two weighting methods (AHP and SE/NW) and average weights.

Then, the model with the same input data, except the weights assigned to indices by the aforementioned average weights (AW) is applied to the 92 alternative sites to select a suitable subset. As shown in Table 8, a subset (D_1) with the *SI* of 0.8899 has been selected as the best solution. The subset D_1 includes all high-frequency selected sites (S_{28}, S_{30}, S_{33}, S_{34}, S_{40}, S_{44}, and S_{47}). The *SI* of D_1 is ranked between the *SIs* of A_1 and C_1; however, the total area of sites in this subset (D_1) is closer to the exact chosen area.

Table 8. Comparison of sustainable subsets obtained by the algorithm based on the AHP and SE/NW weighting methods and average weights.

Method	Subset	*SI*	Selected Sites	Total Area (ha)
AHP	A_1	0.8489	S_{11}, S_{28}, S_{33}, S_{40}, S_{44}, S_{47}, S_{60}	97.18
SE/NW	C_1	0.9323	S_{28}, S_{30}, S_{33}, S_{34}, S_{39}, S_{40}, S_{43}, S_{44}, S_{47}, S_{48}	103.02
AW	D_1	0.8899	S_{11}, S_{28}, S_{33}, S_{34}, S_{40}, S_{44}, S_{47}	99.43

Figure 9 shows the indicator and sub-indicator values (V_i) of the highest-ranked subsets by the AHP, SE/NW, and AW methods. In this case, it should be noted that no weights were applied. V_i can be understood as the satisfaction index associated with each indicator.

As shown in Figure 9, the highest numbers (seven) of indices (an indicator and sub-indicators) with the minimum satisfaction values are concerned with subset C_1, which was selected by the SE/NW weighting technique. These seven indices are SBI_1, SBI_3, SBI_4, SBI_5, SBI_8, SBI_{10}, and I_7 from subset C_1. In contrast, the highest numbers (five) of indices with the maximum satisfaction values belongs to subset D_1, which was selected based on the average weights (AW). These five indices are SBI_1, SBI_5, SBI_7, SBI_8, and SBI_{10} from subset D_1; all the indices are related to the social requirement. Subset A1, which is the highest ranked regarding the AHP weighting technique, has three indices with the highest satisfaction values (SBI_3, SBI_4, and I_7).

In general, according to the aforementioned findings, results from a model tend to be more reliable when experts are somehow involved in assigning the weights to the indices. Additionally, although satisfaction values for some indices correspond to the weights allocated to these indices, it is not possible to generalise this issue to all indices.

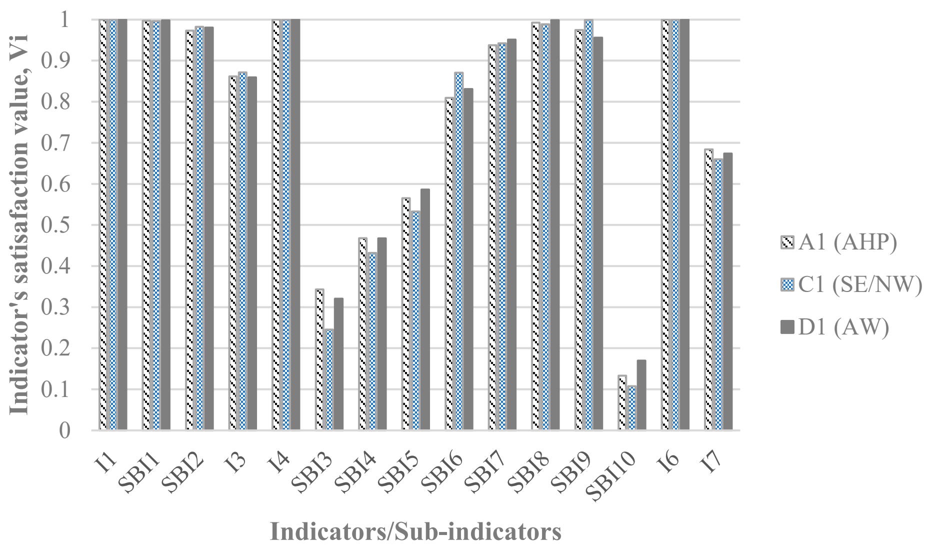

Figure 9. Satisfaction value of the indicators and sub-indicators without considering the weights assigned by applying each of the three methods (AHP, SE/NW, and AW).

Based on the analysis of results, it can be concluded that the proposed model, which is made by the combination of GIS and the MIVES–knapsack approach, could be a robust decision-making model for the configuration of post-disaster housing sites. Furthermore, applying the average weights (AW) derived from AHP and SE/NW weighting techniques could lead to more suitable results.

7. Conclusions

This paper proposes a new sustainability-oriented GIS-based technique to solve spatial problems after disasters. On the whole, the approach is designed to make it possible to select TH site location based on local requirements. The technique was built on a synergistic combination of GIS and MIVES–knapsack methods to identify and seek sets that meet the area requirements and maximise the sustainability indices (weighted satisfaction of the economic, environmental, and social requirements). GIS permits accurate information on alternatives considering the indicators established in the MIVES decision-making model and determining feasible sites among all options in the initial phase of the decision-making process. The MIVES method, which is a multi-criteria decision-making method based on the utility theory concept, is used to evaluate sustainability indexes of alternatives (sites and subsets). The knapsack algorithm is applied to accurately and quickly select the most suitable subsets, including the most appropriate alternatives, among numerous possible solutions, considering the requirements of this research study. The weights were derived from a hybrid approach consisting of using seminars with experts and AHP, together with the Shannon entropy method.

The proposed model was applied to an earthquake scenario in Tehran. Regarding the results from the analysis, including sensitivity analysis, the sites of the first-ranked subset (A_1) selected based on the AHP technique could be more reliable and accurate. Although the *SI* of this subset (A_1) is lower than the other subsets (B_1 and C_1) obtained based on the other weighting techniques (SE/AHP and SE/NW). In this regard, the following conclusions can be drawn:

- The high ranked subsets (A_1, B_1, and C_1), with the *SIs* of 0.85, 0.98, and 0.93, respectively, were introduced based on the three different weighting techniques (AHP, SE/AHP, and SE/NW).
- Sites already in use for specific purposes were found to be suitable (and with high satisfaction values) for temporary housing locations after earthquakes. Most sites of the subsets (A_i), which were chosen by the model using AHP, are categorized as those

sites mentioned above. In other words, the sites of the subsets (A_i) do not need to be prepared after disasters.

- The results of this model demonstrate that a weighting technique, based on experts' and stakeholders' preferences (e.g., AHP), could be more reliable. Nonetheless, the results derived from this weighting technique need to be assessed. Additionally, the subsets selected based on AHP have better distributions (within the three districts) to cover DP adequately compared with the other weighting technics.
- The results obtained from applying the model, considering the three different weighting approaches, demonstrate that no site was selected within district 2. This could be due to some characteristics of this district, such as the lower damage rate, high population density, etc. However, it is required to consider this issue in another research study, focusing on population coverage and DP preferences.

Future research should develop a model based on real-time data analysis. Additionally, a new phase could be designed and added to the model to consider sensitivity analysis of different weighting techniques. This new phase could help the model become more automated and user-friendly.

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Nomenclature

Smax	Maximum satisfaction
Smin	Minimum satisfaction
R_k	Requirement *k*
C_k	Criterion *k*
I_k	Indicator *k*
SBI_k	Sub-indicator *k*
V	Value
SI	Sustainability index
DCv	Decrease concavely
DCx	Decrease convexly
ICx	Increase convexly
IS	Increase S-shape
DS	Decrease S-shape
Xmax	Maximum value indicator
Xmin	Minimum value indicator
pts.	Points
Pop	Population
min.	Minute(s)
pers.	Person(s)
N Hosp.	Number of hospitals
N Sch.	Number of schools
N PS.	Number of police stations
N FS.	Number of fire stations
IRR	Iran rial rates (Iranian currency)
Ec.	Economic
S.	Social
En.	Environmental
SE/AHP	Shannon's entropy with considering the weights assigned to the indicators
SE/NW	Shannon's entropy without considering the weights assigned to the indicators

Appendix A

Table A1. Ranked sets, including sites, *SIs*, and satisfaction values of indices, based on sustainability index by MIVES–knapsack considering AHP weights.

Alt.	Sites of Selected Set	*SI*	Total Area	Indicator and Sub-Indicator Satisfaction Values														
				I_1	SBI_1	SBI_2	I_3	I_4	SBI_3	SBI_4	SBI_5	SBI_6	SBI_7	SBI_8	SBI_9	SBI_{10}	I_6	I_7
A_1	S_{11}, S_{28}, S_{33}, S_{40}, S_{44}, S_{47}, S_{60}	0.8489	97.18	1.00	0.9972	0.9728	0.8615	1.00	0.3433	0.4679	0.5651	0.8094	0.9376	0.9924	0.9744	0.1331	1.00	0.6839
A_2	S_{11}, S_{28}, S_{29}, S_{33}, S_{40}, S_{44}, S_{47}, S_{60}	0.8488	102.78	1.00	0.9971	0.9719	0.8616	1.00	0.3480	0.4705	0.5702	0.8072	0.9391	0.9937	0.9667	0.1396	1.00	0.6822
A_3	S_{11}, S_{28}, S_{33}, S_{34}, S_{44}, S_{47}, S_{60}	0.8485	100.94	1.00	0.9971	0.9711	0.8634	1.00	0.3465	0.4697	0.5686	0.8079	0.9386	0.9933	0.9693	0.1375	1.00	0.6808
A_4	S_{11}, S_{28}, S_{33}, S_{40}, S_{44}, S_{47}, S_{60}, S_{92}	0.8483	103.06	1.00	0.9971	0.9623	0.8670	1.00	0.3482	0.4707	0.5704	0.8071	0.9392	0.9938	0.9663	0.1399	1.00	0.6797
A_5	S_{28}, S_{31}, S_{33}, S_{34}, S_{35}, S_{40}, S_{44}, S_{47}, S_{60}	0.8475	98.39	1.00	0.9969	0.9660	0.8727	1.00	0.3444	0.4685	0.5662	0.8089	0.9379	0.9927	0.9728	0.1346	1.00	0.6753

Table A2. Percent change in indicators' weights and sensitivity coefficients: ranked sets by MIVES–knapsack considering AHP weights.

Pair of Alternatives	Indicators and Sub-Indicators														
	I_1	SBI_1	SBI_2	I_3	I_4	SBI_3	SBI_4	SBI_5	SBI_6	SBI_7	SBI_8	SBI_9	SBI_{10}	I_6	I_7
A_1–A_2	N/F	N/F	N/F	−1357.41	N/F	−96.31	−168.63	−88.64	N/F	−299.36	−328.56	58.3554	−69.44	N/F	29.44
A_1–A_3	N/F	N/F	N/F	−367.39	N/F	−544.01	−952.51	−500.07	N/F	−1686.66	−1806.42	N/F	−393.69	N/F	62.82
A_1–A_4	N/F	N/F	N/F	−192.92	N/F	−527.66	−923.87	−485.73	N/F	−1640.72	−1807.57	N/F	−380.21	N/F	69.94
A_1–A_5	N/F	N/F	N/F	−206.06	N/F	−5362.94	−9390.09	−4921.1	N/F	−16,566.7	−17,122.7	N/F	−3902.15	N/F	73.62
A_2–A_3	N/F	N/F	N/F	−292.73	N/F	N/F	N/F	N/F	−1845.38	N/F	N/F	−491.92	N/F	N/F	N/F
A_2–A_4	N/F	N/F	N/F	−163.39	N/F	−9383.29	−16,428.26	−8671.04	N/F	−29,410.7	−35,139.5	N/F	−6682.79	N/F	98.49
A_2–A_5	N/F	N/F	N/F	−191.98	N/F	N/F	N/F	N/F	−3052.97	N/F	N/F	−851.59	N/F	N/F	84.60
A_3–A_4	N/F	−12,724.34	70.63	−97.84	N/F	−497.08	−870.30	−458.79	N/F	−1554.1	−1809.92	N/F	−355.32	N/F	91.06
A_3–A_5	N/F	N/F	N/F	−172.47	N/F	N/F	N/F	N/F	−3889.40	N/F	N/F	−1120.93	N/F	N/F	79.7
A_4–A_5	N/F	N/F	−599.86	−218.61	N/F	N/F	N/F	N/F	−1693.20	N/F	N/F	−469.94	N/F	N/F	77.04
Sensitivity Coefficient	N/F	<<1.0	0.0142	0.0102	N/F	0.0104	0.0059	0.0112	0.0006	0.0033	0.003	0.0171	0.0144	N/F	0.034

N/F = Not feasible.

Table A3. Ranked sets, including sites, *SIs*, and satisfaction values for indices, based on sustainability index by MIVES–knapsack considering SE/AHP weights.

Alt.	Sites of Selected Set	*SI*	Total Area	Indicator and Sub-Indicator Satisfaction Values														
				I_1	SBI_1	SBI_2	I_3	I_4	SBI_3	SBI_4	SBI_5	SBI_6	SBI_7	SBI_8	SBI_9	SBI_{10}	I_6	I_7
B_1	S_{28}, S_{33}, S_{34}, S_{39}, S_{40}, S_{44}, S_{47}, S_{74}	0.9824	97.73	1.00	0.9978	0.9911	0.8864	1.00	0.3187	0.4664	0.5848	0.8319	0.9511	0.9980	0.9587	0.1680	1.00	0.6535
B_2	S_{28}, S_{30}, S_{33}, S_{40}, S_{44}, S_{47}, S_{74}, S_{76}	0.9823	98.06	1.00	0.9975	0.9865	0.8950	1.00	0.3191	0.4666	0.5851	0.8317	0.9511	0.9980	0.9581	0.1683	1.00	0.6540
B_3	S_{28}, S_{30}, S_{33}, S_{34}, S_{35}, S_{39}, S_{40}, S_{44}, S_{47}, S_{48}	0.9823	100.10	1.00	0.9963	0.9806	0.8715	1.00	0.2405	0.4294	0.5290	0.8733	0.9417	0.9872	0.9994	0.1039	1.00	0.6667
B_4	S_{28}, S_{29}, S_{30}, S_{33}, S_{34}, S_{40}, S_{44}, S_{47}, S_{74}	0.9823	100.35	1.00	0.9978	0.9914	0.8835	1.00	0.3215	0.4677	0.5867	0.8303	0.9514	0.9982	0.9541	0.1705	1.00	0.6584
B_5	S_{28}, S_{30}, S_{33}, S_{34}, S_{40}, S_{44}, S_{47}, S_{74}, S_{92}	0.9822	100.64	1.00	0.9978	0.9869	0.8882	1.00	0.3218	0.4679	0.5869	0.8302	0.9514	0.9982	0.9536	0.1708	1.00	0.6560

Table A4. Percent change in indicators' weights and sensitivity coefficients: ranked sets by MIVES–knapsack considering SE/AHP weights.

Pair of Alternatives	Indicators and Sub-Indicators														
	I_1	SBI_1	SBI_2	I_3	I_4	SBI_3	SBI_4	SBI_5	SBI_6	SBI_7	SBI_8	SBI_9	SBI_{10}	I_6	I_7
B_1–B_2	N/F	N/F	74.74	−139.45	N/F	−4702.26	−23,327.76	−11287.9	N/F	−11033.9	−21729.3	N/F	−2712.48	N/F	−2029.6
B_1–B_3	N/F	91.42	38.63	95.35	N/F	25.98	N/F	58.25	−32.71	55.77	44.35	−6.18	16.27	N/F	−96.20
B_1–B_4	N/F	N/F	N/F	−1702.30	N/F	−1460.19	−7246.99	−3512.70	N/F	−3435.80	−6967.52	N/F	−840.05	N/F	−1154.7
B_1–B_5	N/F	N/F	−1854.24	N/F	N/F	−804.15	−3990.85	−1934.05	N/F	−1891.58	−3823.70	62.18	−462.77	N/F	−291.74
B_2–B_3	N/F	16.37	10.12	8.81	N/F	3.78	18.41	8.49	−4.76	8.13	6.48	−0.89	2.37	N/F	−14.67
B_2–B_4	N/F	−827.96	−1309.63	N/F	N/F	−1028.40	−5104.28	−2474.67	N/F	−2420.70	−4928.56	78.78	−591.43	N/F	−914.57
B_2–B_5	N/F	−135.22	−22.31	32.91	N/F	−221.06	−1097.15	−531.82	N/F	−520.19	−1055.71	17.01	−127.17	N/F	−78.33
B_3–B_4	N/F	−118.07	−80.82	−106.28	N/F	−31.36	−152.63	−70.49	39.42	−67.54	−54.89	6.90	−19.58	N/F	N/F
B_3–B_5	N/F	−11.16	−4.60	−14.42	N/F	−3.06	−14.88	−6.87	3.84	−6.58	−5.34	0.68	−1.91	N/F	18.62
B_4–B_5	N/F	N/F	N/F	−337.85	N/F	−7585.09	−37,661.06	−18,286.7	N/F	−17,897.9	−37,419.7	N/F	−4351.86	N/F	N/F
Sensitivity Coefficient	N/F	0.0896	0.2172	0.1135	N/F	0.3270	0.0672	0.1455	0.2601	0.1519	0.1873	1.4750	0.5237	N/F	0.0682

N/F = Not feasible.

Table A5. Ranked sets, including sites, *SIs*, and satisfaction values of indices, based on sustainability index by MIVES–knapsack considering SE/NW weights.

Alt.	Sites of Selected Set	*SI*	Total Area	Indicator and Sub-Indicator Satisfaction Values														
				I_1	SBI_1	SBI_2	I_3	I_4	SBI_3	SBI_4	SBI_5	SBI_6	SBI_7	SBI_8	SBI_9	SBI_{10}	I_6	I_7
C_1	S_{28}, S_{30}, S_{33}, S_{34}, S_{39}, S_{40}, S_{43}, S_{44}, S_{47}, S_{48}	0.9323	103.02	1.00	0.9958	0.9822	0.8715	1.00	0.2454	0.4318	0.5328	0.8707	0.9424	0.9886	0.9991	0.1076	1.00	0.6598
C_2	S_{30}, S_{33}, S_{34}, S_{39}, S_{40}, S_{44}, S_{47}	0.9320	96.60	1.00	0.9976	0.9869	0.9031	1.00	0.3174	0.4658	0.5840	0.8326	0.9510	0.9980	0.9606	0.1669	1.00	0.6343
C_3	S_{28}, S_{29}, S_{30}, S_{33}, S_{34}, S_{39}, S_{40}, S_{44}, S_{47}, S_{48}	0.9319	98.56	1.00	0.9957	0.9835	0.8692	1.00	0.2378	0.4281	0.5269	0.8746	0.9414	0.9865	0.9995	0.1019	1.00	0.6693
C_4	S_{11}, S_{30}, S_{33}, S_{34}, S_{40}, S_{44}, S_{47}, S_{48}, S_{53}	0.9314	103.06	1.00	0.9961	0.9682	0.8732	1.00	0.2455	0.4318	0.5328	0.8707	0.9424	0.9886	0.9991	0.1076	1.00	0.6539
C_5	S_{28}, S_{30}, S_{33}, S_{34}, S_{40}, S_{43}, S_{44}, S_{47}, S_{48}, S_{53}	0.9312	100.69	1.00	0.9949	0.9714	0.8714	1.00	0.2415	0.4299	0.5298	0.8727	0.9418	0.9875	0.9994	0.1047	1.00	0.6571

Table A6. Percent change in indicators' weights and sensitivity coefficients: ranked sets by MIVES–knapsack considering SE/NW weights.

Pair of Alternatives	Indicators and Sub-Indicators														
	I_1	SBI_1	SBI_2	I_3	I_4	SBI_3	SBI_4	SBI_5	SBI_6	SBI_7	SBI_8	SBI_9	SBI_{10}	I_6	I_7
C_1–C_2	N/F	−142.46	−101.44	−94.08	N/F	−24.29	−118.28	−54.65	30.53	−52.39	−43.83	5.62	−15.15	N/F	N/F
C_1–C_3	N/F	N/F	−502.15	N/F	N/F	N/F	N/F	N/F	−402.42	N/F	N/F	−781.47	N/F	N/F	−1388.99
C_1–C_4	N/F	−2503.19	95.75	−4726.02	N/F	−73,087.87	−347,081.84	$-15 \cdot 10^5$	N/F	−144415	−67275	N/F	−49,609.74	N/F	N/F
C_1–C_5	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	−2023.74	N/F	N/F	−3512.92	N/F	N/F	N/F
C_2–C_3	N/F	47.00	48.36	30.44	N/F	7.62	37.01	17.02	−9.61	16.28	12.42	−1.93	4.80	N/F	−96.66
C_2–C_4	N/F	N/F	46.18	N/F	N/F	44.02	N/F	99.06	−55.32	94.95	79.51	−10.18	27.45	N/F	−900.24
C_2–C_5	N/F	N/F	75.97	N/F	N/F	57.13	N/F	N/F	−71.91	N/F	97.84	−13.86	35.79	N/F	−1058.94
C_3–C_4	N/F	−984.75	45.69	−1072.88	N/F	−333.17	−1576.48	−695.11	N/F	−651.40	−283.18	N/F	−228.38	N/F	N/F
C_3–C_5	N/F	N/F	83.75	−2828.14	N/F	−1005.22	−4747.38	−2088.35	N/F	−1954.52	−820.78	N/F	−692.63	N/F	N/F
C_4–C_5	N/F	N/F	−101.69	N/F	N/F	N/F	N/F	N/F	−382.37	N/F	N/F	−662.28	N/F	N/F	−2025.91
Sensitivity Coefficient	N/F	0.0213	0.0219	0.0328	N/F	0.1312	0.0270	0.0587	0.1041	0.0614	0.0805	0.5178	0.2085	N/F	0.010

N/F = Not feasible.

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