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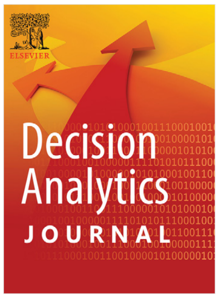

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A Location-Allocation Optimization Model for Post-Earthquake Emergency Shelters Using Network-Based Multi-Criteria Decision-Making

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Abstract

It is imperative for residents to have access to safe facilities after an earthquake. This ensures the safety and well-being of individuals while minimizing the risks posed by aftershocks. This research has used multi-criteria decision-making (MCDM) and network-based analysis to select and allocate emergency shelters (ESs). Several ESs are initially chosen as potential candidates. A weighting process is then used to evaluate various criteria, including proximity to the fault, fire stations, hospitals, main roads, the area of the ESs, and the population's vulnerability. The centers are evaluated and ranked using the CRiteria Importance Through Intercriteria Correlation (CRITIC) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methods. The Maximized Weighted Capacitated Coverage with a Radius (MWCCR) problem is used to address location and allocation issues for varying ESs using option rankings. The findings showed that increasing the number of centers does not always lead to a higher level of service delivery, assuming a consistent service delivery radius. The distribution of the centers is more crucial. Additionally, line density analysis is used to evaluate traffic conditions in the study area, assisting in finding areas with heavy traffic flow. When the radius of access for ESs is assumed to be small, the main roads bear less additional traffic, and with the increase of the radius, the amount of traffic on the main roads gradually increases. This is valuable information for emergency services following an earthquake.

Keywords: Multi-criteria decision-making, network-based model, emergency shelters, maximize weighted capacitated coverage with a Radius, TOPSIS; CRITIC

1-Introduction

Earthquakes, as natural disasters, can cause extensive damage. Due to their potential to cause widespread damage to critical urban infrastructure, they are a significant challenge for large cities. Therefore, organizing crisis planning, including implementing policies that govern urban decisions, is very important to respond effectively to earthquakes [1, 2]. After an earthquake, one of the priorities is to quickly and safely evacuate citizens to protect them from potential hazards such as earthquakes, fires, and the spread of infectious diseases [3]. Emergency shelters (ESs) are safe places with necessary services for evacuating citizens during earthquakes [4]. Therefore, it is crucial to construct secure and appropriately located emergency evacuation facilities to mitigate risks following an earthquake. These facilities should have sufficient resources to support affected citizens [5]. Researchers face challenges in selecting the appropriate location for emergency evacuation due to multiple criteria. The city officials should allocate a budget to adapt the facilities and create a wide range of services in these centers. Therefore, it is crucial to determine the optimal location and quantity of ESs to minimize costs. Selecting these centers' locations involves a location-allocation problem with two components. A positioning component determines the placement of ESs and outlines how these centers serve the population in the allocation section [6, 7]. Therefore, to determine appropriate locations for ESs, a solution must be selected to address the location allocation problem.

Various approaches have been used in studies on location allocation for ES planning. Some approaches have focused on allocating ESs to citizens in a single-objective manner, considering only one criterion, such as time or distance. Many studies commonly use single-objective techniques such as p-median, p-center, and maximum coverage. Multi-objective and hierarchical models have been used in some studies. Additionally, geographic information systems (GIS) methods, such as the Voronoi diagram, can be used [8, 9].

The study starts with a background review using a single-objective approach, followed by explanations related to the research. The study [10] addresses the issue of assigning ESs to demand points as a set covering problems. Also, a time limit or interval has been considered for each demand center, and linear programming (LP) has been used to model the problem. The study [11] used LP to maximize citizen coverage in evacuation planning. A GIS was utilized for this purpose. The study [12] proposes a modified particle swarm optimization (MPSO) algorithm for allocating ESs. The simulated annealing (SA) algorithm is used to overcome local optima and enhance search capability. The study [13] has developed a model to determine the optimal location for ESs and to assign evacuees to them using the shortest routes. The goal is to minimize the total evacuation time. The model that was created is a nonlinear mixed-integer programming model. The second-order cone programming technique has been utilized to solve the model. The proposed model considers the significance of both the quantity and location of ESs and the creation of indicators for efficiency and fairness. In a study by [14], a method based on mixed integer linear programming is proposed for selecting the location of ESs. The mathematical model presented aims to maximize the minimum weight of ESs. In a study by researchers [15], the location and allocation of ESs in the first district of Tehran were examined using GIS. They utilized the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), a straightforward clustering method, along with two meta-heuristic algorithms: particle swarm optimization (PSO) and ant colony optimization (ACO). The TOPSIS method and simple clustering have been used to select candidate centers based on multiple criteria. These criteria include slope, area, population density surrounding the centers, distance from faults, distance between centers, center utilization, distance from roads, and parcel distance. The point allocation approach has been utilized to assign weights to the criteria. The allocation problem was then solved using the two aforementioned meta-heuristic algorithms. The study [8] proposed multi-level location models to determine the optimal emergency location in Jianchuan, China, based on the severity of the emergency. The objective is to minimize transfer and construction expenses while maximizing the coverage rate. The study utilized GIS and weighted Voronoi diagram (WVD) models to analyze the capacity of ESs.

Multi-objective models have also been widely used in the problem of location-allocation of ESs, some of them are explained below. In a study by [16], a model for aid distribution was developed using the multi-objective optimal planning method. This model is designed to assist in planning aid systems for natural disaster scenarios. This model had three objectives: minimizing total cost and travel time while maximizing the minimum satisfaction. In their study, the authors [17] discuss the simultaneous consideration of selecting the location of the ES and regional planning of the service areas. A bi-objective model is proposed to minimize the total traveled distance and cost while considering capacity and proximity constraints. A non-dominated sorting genetic algorithm (NSGA) has been developed for solving bi-objective problems. The Pareto-optimal strategy and feasibility-based rule have been used to balance objectives. The study [18] implemented a multi-objective model to allocate residents to shelters during earthquakes in Beijing, China, using it as a case study. The objectives of this model were to reduce the evacuation time from residential areas to a specific ES and to minimize the total area. Two limitations were considered regarding the capacity and service radius of ES. The PSO algorithm was initially modified by implementing the von Neumann structure and subsequently used to solve the problem. In a study [20], a mathematical model was implemented with two objectives: minimizing the total evacuation time and reducing the total area of ESs. A PSO algorithm was employed to solve the problem.

Some studies have focused solely on location and aimed to identify distribution centers for emergency evacuation, relief, and rescue during crises. Multi-criteria decision-making tools have been utilized for this purpose. In a study by [21], the analytical hierarchy process (AHP) method based on TOPSIS and the goal programming (GP) model were used to identify the best location for distribution centers. The TOPSIS method was utilized to rank places based on risk score, total area, population, and distance from the center. The GP model proposes two goals: maximizing points from TOPSIS and minimizing the number of distribution centers required to fulfill all demands. In a study by [22], criteria were classified based on the crisis management standard using GIS. The aid centers in the study area were assessed using standard criteria. The matrix was used to measure the research criteria using the entropy method (EM). The Preference Ranking Organization METhod for Enrichment Evaluations (PROMETHEE) was used to determine the optimal options.

A more complete literature review for the years 2018 to 2023 is shown in Table 1. Studies are classified based on problem definition, model, objective, ES evaluations, application, and scale. As mentioned, the problem can simultaneously be considered as location or location-allocation. Also, the single-objective or multi-objective model of the problem is meant and various objectives, which can be monetary or non-monetary, can be considered in these issues. In some studies, the candidate ESs are evaluated and weighted regarding structural and spatial characteristics, shown in the corresponding column. Also, the issue of locating and allocating ESs can be important in various crises such as floods, earthquakes, infectious diseases, etc. The meaning of scale in the last column is the extent of the study, and studies that have been carried out on urban scales are shown with micro, and other studies considered in higher extent are shown with macro in Table 1.

Table 1- Literature review based on problem, medel, objectives, and applications.

Paper	Year	Problem definition	Model	Objectives		ES evaluations	Application	Scale
				Monetary	Non-monetary			
[22]	2018	Location allocation	Single	-	Min total time	-	Flood	Micro
[23]	2018	Location allocation	Single	-	Min total distance	TOPSIS	Earthquake	Micro
[24]	2018	Location allocation	Multi	-	Min total distance Min total time Min number of shelters Min total shelter area	Weighted method	Earthquake	Micro
[25]	2019	Location allocation	Multi	-	Min total shelter area Min total distance	-	Earthquake	Micro
[26]	2021	Location allocation	Single	-	Min total weighted distance Max cover demand Min distance or time Max attendance	-	Flood	Macro
[27]	2021	Location allocation	Multi	Min total cost	Min total time Min number of shelters	-	Flood	Macro
[28]	2021	Location	-	-	-	Multiple Criteria Evaluation	Flood Traffic	Micro
[29]	2021	Location allocation	Multi	Min total cost	Min total time	-	Flood	Macro
[30]	2021	Evacuation simulation	-	-	-	GIS Spatial Analysis and Statistics	-	Micro
[31]	2021	Location allocation	Multi	-	Min total time Max the suitability Min number of sites	fuzzy-VIKOR	Earthquake	Micro
[32]	2022	Location	Multi	-	-	AHP	Earthquake	Simulated
[33]	2022	Location allocation	Multi	-	Min total time Max demand satisfaction	-	COVID-19	Micro
[34]	2022	Location allocation	Multi	-	Min investment Min total time	-	-	Micro
[35]	2022	Location	Multi	Min total cost	Min total time	-	Earthquake	Micro
[36]	2022	Location allocation	Multi	-	Min total shelter area Min total distance	Suitability evaluation method	Earthquake	Micro
[37]	2022	Location allocation	Single	-	Max min weight	-	Earthquake	Micro
[38]	2022	Location allocation routing	Multi	Min total cost	Min total time	fuzzy method	Earthquake	Micro
[39]	2023	Location allocation	Single	-	Max cover demand	-	-	Micro
[40]	2023	Location allocation	Single	-	Min total distance Max cover demand		Flood Landslide	Macro
[41]	2023	Location	Multi	Min total cost	Min number of new shelters Min the square	-	Earthquake	Micro
[42]	2023	Location	-	-	-	k-means clustering	-	Macro
[43]	2023	Location	-	-	-	Large Group Decision-Making (LGDM)	Earthquake	Micro

The structure of this study is similar to the study [36], which has used a two-stage approach with the difference that in this study, the approach of CRiteria Importance Through Intercriteria Correlation (CRITIC) and TOPSIS is used for weighting and ranking ESs. Also, as is shown in Table 1, Previous studies used more straightforward weighting methods. The criteria used in this study included the distance from the fault, fire stations, hospitals, main roads, the area of ESs, and population vulnerability. The population vulnerability layer is a new criterion not explored in previous research. After considering the criteria, the ESs have been ranked using the TOPSIS method. The problem of maximizing weighted capacitated coverage with a radius (MWCCR) is used to optimize the locations and allocations of ESs. This problem has been solved to determine the number of required centers, the percentage of population covered, the occupancy percentage of ESs, and the distance traveled. Moreover, the number of individuals covered is categorized by age and gender. The traffic conditions were analyzed using line density analysis to evaluate various allocation methods. This type of analysis, essential for crisis management, has not been used in previous studies.

This article is organized as follows. Preliminaries are described in Section 2. Materials and methods including calculation of population vulnerability, CRITIC and TOPSIS methods are described in Section 3. Results and discussion that include case study description, ranking of candidate hubs description, location-assignment results, and traffic growth forecast are presented in Section 4. This article ends with the conclusion of the model implementation in section 5.

2- Preliminaries

In this section, all related symbols used in this article are presented. In addition, the problem is defined, and its mathematical modeling is explained.

2-1- Definitions

Numerous studies and research have been conducted on the issue of locating and allocating ESs. This issue aims to select multiple temporary ES locations. Each center will be selected based on its capacity to serve a population that can easily reach it. Therefore, we assume the set $S=\{1,2,...,N\}$ as the ESs and the set $D=\{1,2,...,M\}$ as the demand centers or population centers. In this case, we are searching for the set A = $\{(s,d)|s\epsilon S^*, d\epsilon D^*\}$. Set A is proposed as a solution to the location-allocation problem, where each element represents an allocation from ES s to demand center d. Moreover, S* is a set of selected centers based on specific criteria before allocation This set has N* members, which N*≤N. Moreover, D* represents the set of demand centers covered by ESs. The number of demands is M*, which M*≤M. The choice of set A as a solution can vary depending on the problem's goals and the criteria for selecting ESs. In this study, we examine the set $W=\{w_1,w_2,w_3,...,w_N\}$, which determines the weight of each corresponding ES. The weights can be determined based on different criteria. Specific centers will likely be selected when solving the location allocation problem. For instance, in Figure 1, when selecting one of the three ESs based on the highest service coverage within a specific radius, the weighted mode chooses the ES with the highest weight. In contrast, in the unweighted state, a center is randomly selected.

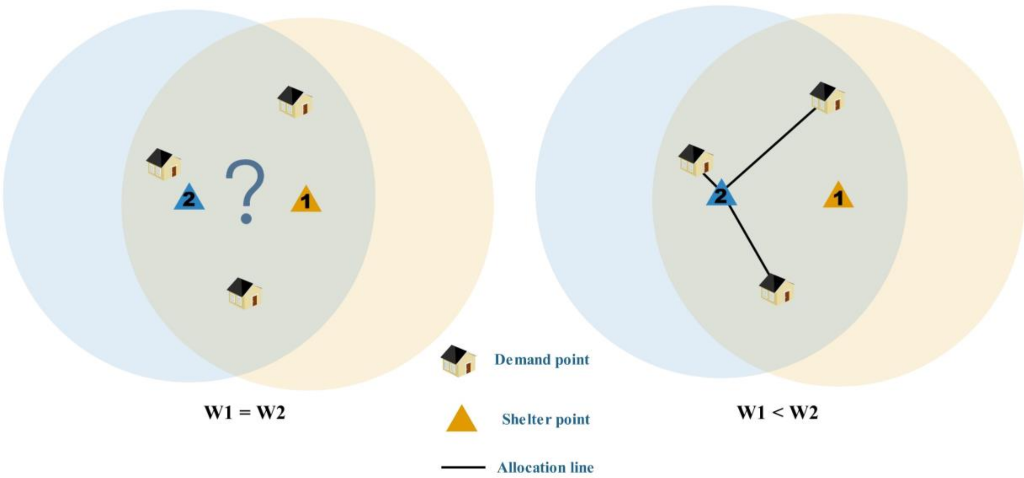


Figure 1 – Schematic illustration of the effect of weight on Ess allocation

2-2- Maximize Weighted Capacitated Coverage with a Radius (MWCCR)

The section explains MWCCR modeling. This model, like any other, is based on the following assumptions.

• Demand centers are population blocks where the population is concentrated at a central point.

• An earthquake occurred at night, and the entire population is in residential areas.

• Each demand center can be assigned to only one emergency ES, and the entire population is allocated to one ES in each assignment.

• Emergency ESs include mosques, schools, and public parking lots, which are assumed to have adequate earthquake resistance.

This model aims to maximize the number of people served while considering each service center's capacity and coverage radius constraints. In the modeling process, we encounter three sets of ESs (I), demand centers (J), and weight of centers (W). We are also seeking allocations (A) that cover the highest demand. The study includes nomenclature, indices, parameters, decision variables, and proposed modeling as follows:

Nomenclature set

I	Set of all ES locations
J	Set of all demand locations
W	Set of all weight of centers

Indices

$i \in I$	-
$j \in J$	-

Parameters

w_i	Weight of ES point $i \in I$
p_j	The population of demand point $j \in J$
C_j	The capacity of the ES point $i \in I$
d_{ij}	Transfer distance between the ES point and the demand point $j \in J$
R	Cover radius for each ES point

Decision variable

x_{ij}	1, if demand point *j* is allocated to ES point *i* and zero, otherwise
y_i	1, if ES point *i* is selected in the location-allocation process and zero, otherwise

$$\max \sum_{i \in I} \sum_{j \in J} w_i \, p_j x_{ij} \tag{1}$$

$$\sum_{i \in I} x_{ij} \le 1 \quad \forall j \in J \tag{2}$$

$$\sum_{j \in J} p_j x_{ij} \le C_i y_i \quad \forall i \in I \tag{3}$$

$$d_{ij} x_{ij} \le R \ \forall i \in I, j \in J \tag{4}$$

$$x_{ij}, y_i \in \{0,1\} \quad \forall i \in I, j \in J \tag{5}$$

The goal of the problem is to maximize the number of people served, as stated in Equation (1). Equation (2) restricts the problem of assigning each demand to only one ES. Equation (3) is associated with the capacity and limits the allocation of each ES to no more than its capacity. Equation (4) ensures that each center is assigned only the requests placed within a specific neighborhood radius. The Equation (5) is related to the binary decision variables. In this study, which aims to allocate emergency evacuation centers to residents after an earthquake, the capacity of each center has been determined using Equation (6):

$$Cap_i = \frac{A_i}{S} \tag{6}$$

Where (the capacity of the *i*th service center) is based on the number of people, A_i the total area of the infrastructure of the service center, and *S* is the area required for each person.

3- Material and methods

In this section, we will introduce the proposed research methodology. According to Figure 2, raw data has been collected, including information on faults, fire stations, hospitals, main roads, population blocks, and candidate ESs. Various layers of information were generated using analysis and GIS tools that relied on distance and neighborhood factors. One layer of information in this study was population vulnerability, which was determined using criteria such as gender, age, and marital status. The layers created in the previous stage were utilized to assign weights to the ESs. The criteria weighting and ranking of ESs were done using CRITIC and TOPSIS methods, respectively. The MWCCR model was implemented after considering the criteria. Allocation plans were determined as a result. An analysis was conducted on the population served and the additional traffic generated during the crisis, using the results obtained in this stage. The following section outlines various components of the proposed method, including the calculation of population vulnerability, CRITIC, and TOPSIS.

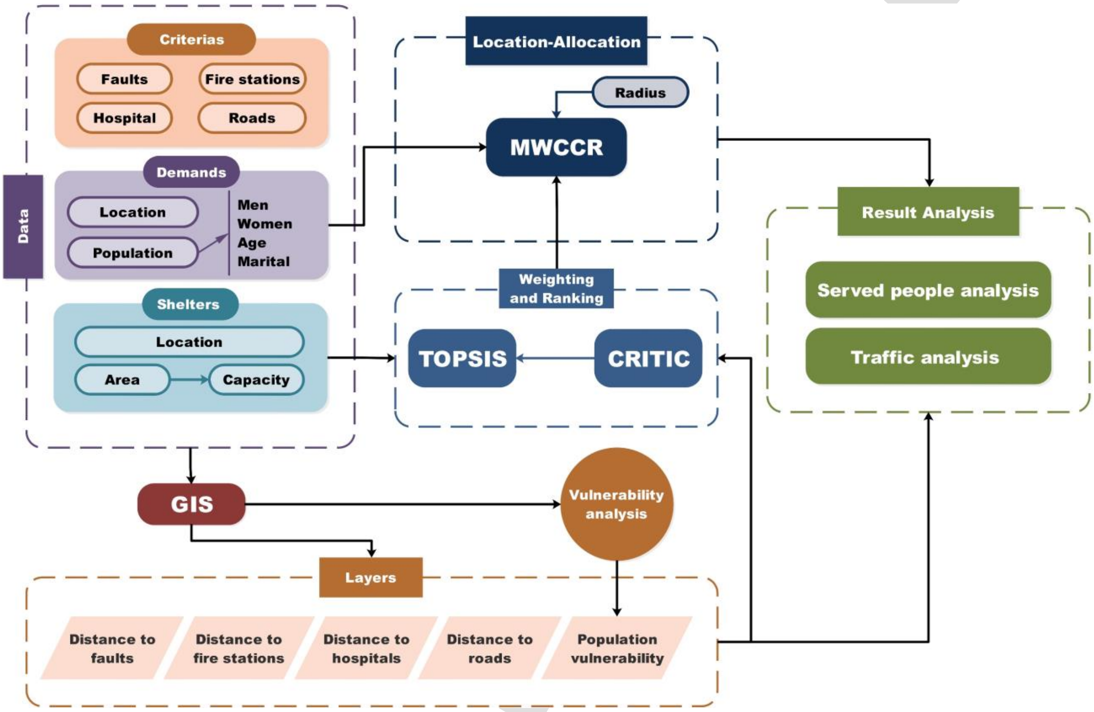


Figure 2 – Flowchart of the proposed method

3-1- Population vulnerability calculation

The vulnerability of city residents to accidents varies depending on factors such as age, gender, and marital status [44]. One of the criteria considered in this study for ranking ESs was the vulnerability of individuals. Vulnerable areas with more vulnerable populations are more likely to be selected and ranked higher during the location process. The population's vulnerability at the city block level was determined using Equation 7.

$$V_i = \frac{\sum_{t \in \{1,2,3\}} (p_t^w v_t^w + p_t^m v_t^m)}{P_i} \quad (7)$$

The population is divided into three groups: people under six years old (t=1), between 6 and 65 years old (t=2), and over 65 years old (t=3). Is the population vulnerability of the ith block, P_i is the total population of the ith block, p_t^w is the population of women in the tth group, and v_t^w is the vulnerability weight of women in the tth group. Moreover, p_t^m, v_t^m are the population of men and their vulnerability in the *t*th group, respectively. Moreover, the group of people between 6 and 65 years old are divided into four groups: single (*s*=1), married (*s*=2), widowed (*s*=3), and divorced (*s*=4), and the vulnerability weight for This category of people obtained from Equations 8 and 9:

$$v_2^m = \frac{\sum_{s\in\{1,2,3,4\}} p_{2s}^m v_{2s}^m}{p_2^m} \tag{8}$$

$$v_2^w = \frac{\sum_{s\in\{1,2,3,4\}} p_{2s}^w v_{2s}^w}{p_2^w} \tag{9}$$

Where p_{2s}^m and v_{2s}^m are the population of men between 6 and 65 years and their vulnerability are in the *s*th set, respectively. The p_{2s}^w and v_{2s}^w are the population of women between 6 and 65 years and their vulnerability in the *s*th set, respectively.

3-2- CRITIC

The CRITIC technique, as suggested by Diakulaki et al. in 1995 [45], is an objective method for determining the weight of indicators. This technique utilizes statistical measures of dispersion and correlation to assign weights to indicators. Indicators with a higher standard deviation and less dependent on various criteria are considered more important and given more weight. The technique consists of seven steps, which will be explained in the following paragraphs. The decision matrix should be normalized using the fuzzy method as the first step. Based on this method, the values range from 0 to 1, and Equation 10 is used.

$$r_{ij} = \frac{a_{ij} - \min(a_{ij})}{\max(a_{ij}) - \min(a_{ij})} \quad \forall \mathrm{j} \in \{1, 2, 3, ..., n\} \tag{10}$$

Where r_{ij} is the normalized value of the *i*th row and *j*th column of the decision matrix, a_{ij} is the value of the *j*th index of the *i*th option, and *n* is the number of indices. Moreover, the second step calculates the standard deviation value for each index. The standard deviation is calculated for the values of each column in the decision matrix at this stage. For this purpose, Equation 11 is used.

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{m} (r_{ij} - \mu_j)^2}{m}} \tag{11}$$

Where is the standard deviation value of the *j*th index, μ_j is the average of the *j*th index, and *m* is the number of options. In the third step, the non-dimensionalized decision matrix calculates the correlation coefficient between each pair of indicators. Spearman's method is commonly used to calculate correlation when the values are ranked. The result of this step is a correlation matrix with dimensions. Spearman's correlation coefficient is represented by Equation 12.

$$r_{jh} = 1 - \frac{6\sum_{j=1}^{n} d_{jh}^{2}}{m(m^{2}-1)} \tag{12}$$

Where is the rank difference between the *j*th and *h*th indexes. In the fourth step, the non-correlation matrix is calculated. To calculate the non-correlation matrix, subtract 1 from the values of the correlation matrix. In the fifth step, the sum of the columns of the non-correlation matrix is calculated. Furthermore, in the sixth step, the standard deviation value of each index is multiplied by the sum of the corresponding column, as shown in Equation 13.

$$C_j = \sigma_j \times \sum_{h=1}^{n} I_{jh} \tag{13}$$

Where is the value of the range of the *j*th row and the *h*th column of the non-correlation matrix. Moreover, the higher the value, the higher the importance and weight of the relevant index. Finally, in the seventh step, the values are divided by their sum to reach the weight values.

3-3- TOPSIS

The TOPSIS technique, introduced by Huang and Yun in 1981 [46], is an efficient method in multi-criteria decision-making(MCDM). The effectiveness of this technique relies on the distance between the ideal positive and negative responses. The closer an option is to the ideal positive solution, and the further it is from the ideal negative answer, the more suitable it becomes. The ideal solution is hypothetical and has the highest value among all options. The ideal negative solution is the one that has the worst values in all possible scenarios. The essential information for utilizing this technique includes the decision matrix and the criteria weights. The weights of the criteria were determined using the CRITIC method. The decision matrix should be normalized using the Euclidean method to implement this technique, as described in Equation 14.

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{j=1}^{J} a_{ij}^{2}}} \tag{14}$$

Where r_{ij} is the normalized value, a_{ij} is the value of the *i*th option in the *j*th criterion, and the number of criteria is *J*. In the next step, the weighted normalized value is calculated by multiplying the weight of each criterion by its corresponding normalized value, as described in Equation 15.

$$t_{ij} = r_{ij} \times w_j \tag{15}$$

Where w_j is the weight corresponding to the *j*th criterion. Afterward, it is essential to specify the ideal positive and negative solutions should be specified. The ideal positive solution is to maximize positive criteria and minimize negative criteria. The negative ideal solution is defined as the highest value for negative criteria and the lowest value for positive criteria. After determining the positive and negative ideal solutions, the distance between the options should be calculated using Equations 16 and 17. These distances are denoted as d^{+} and d^{-}, respectively.

$$d^{+} = \sqrt{\sum_{j=1}^{J} (t_{ij} - s_j^{+})^2} \tag{16}$$

$$d^{-} = \sqrt{\sum_{j=1}^{J} (t_{ij} - s_j^{-})^2} \tag{17}$$

Where s_j^{+} and s_j^{-} are respectively positive and negative values of the ideal solution in the *j*th criterion. The next step is to calculate the relative proximity value for all options, which is done using Equation 18.

$$C_i = \frac{d^{-}}{d^{+} + d^{-}} \tag{18}$$

Where is the degree of relative closeness to the ideal solution for the *i*th option. This numerical index ranges from 0 to 1, with a higher value indicating a closer proximity to the ideal solution. Therefore, the options should be sorted in descending order based on their C_i value to rank them according to this index.

4- Results and discussion

4-1- Study area

The proposed method in this study has been implemented in a part of Tehran's District 12. Demographic block data, candidate ES, and the road network were used for this analysis. The calculation of the center of the polygon for each population block assumed that the population is concentrated at the center of each block. The demand centers were identified as these points. Figure 3 illustrates the study area and the data utilized in this study.

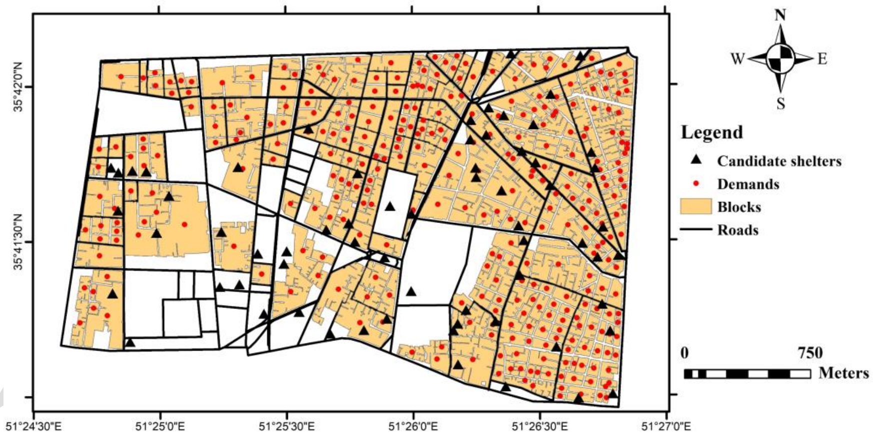


Figure 3 – Study area

According to Figure 3, 332 population centers with a population of 78,499 people have been considered, along with 65 candidate centers for ESs. The ESs were obtained from the Tehran Municipality website, which lists multiple ESs for each region. Various regional schools, mosques, and parking lots have been identified as potential locations for ESs. Various criteria have been considered when selecting ESs from potential centers. The criteria for determining location suitability include proximity to fault lines, fire stations, hospitals, main road networks, area of Ess, and population vulnerability, shown in Figure 4.

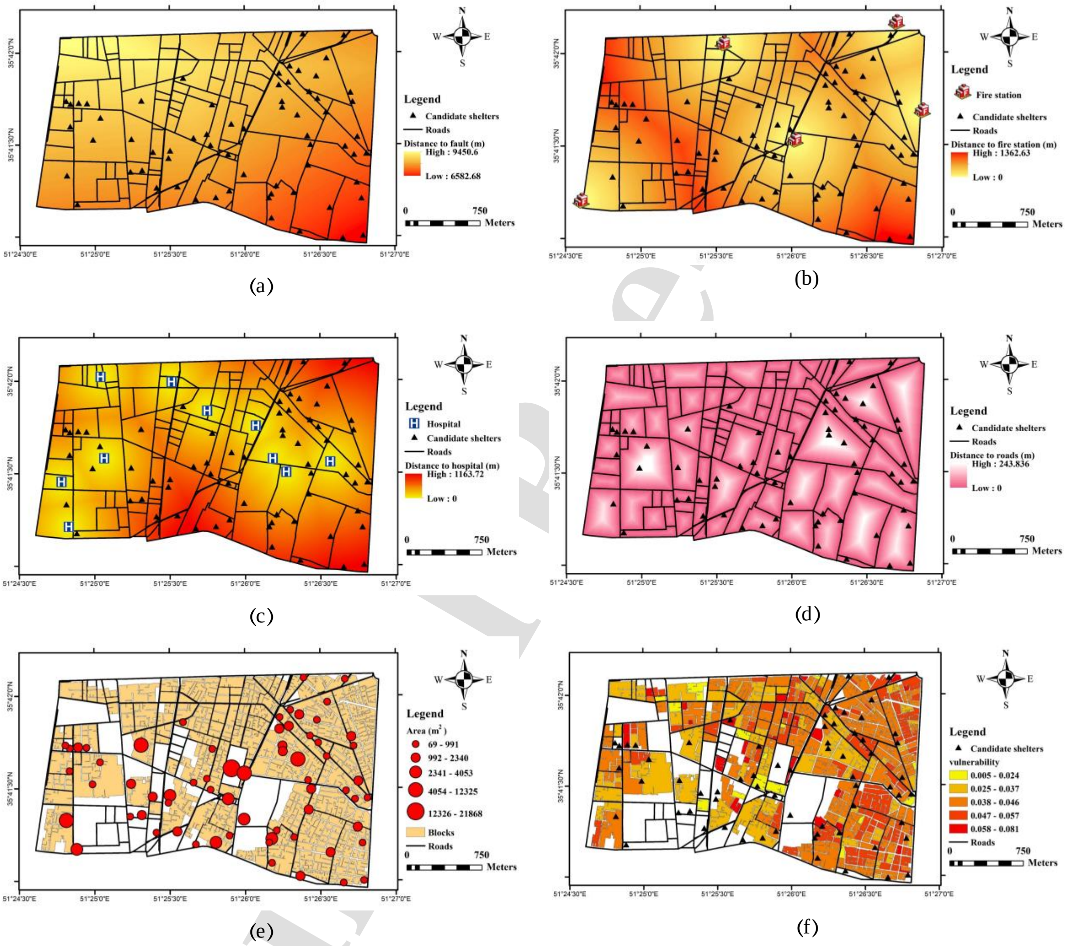


Figure 4 - The layers used include: (a) distance from the fault, (b) distance from fire stations, (c) distance from the hospital, (d) distance from the main roads, (e) area, and (f) Population vulnerability

4-2- Ranking of candidate centers

The TOPSIS method was used to rank the candidate centers. Before implementing this method, assessing the weight and importance of various criteria is essential. This study used a CRITIC to assign weights to the layers. According to the CRITIC, a weight value was obtained for each layer, as indicated in Table 2.

Table 2- The weight of different layers for ranking candidate centers for ESs

Layer name	Layer weight
Distance from the fault	0.18
Distance from fire stations	0.19
Distance from the hospital	0.19
Distance from the main roads	0.17
Area	0.12
Population vulnerability	0.15

After determining the weight values of the layers, the TOPSIS method was used to rank the potential centers. First, a decision matrix was created, and the values associated with each criterion were normalized. Positive and negative ideals were identified based on their influence on decision-making. The criteria for positive criteria include the distance from the fault, the area, and the vulnerable population. The most suitable ES is determined by selecting the highest value for each factor. Moreover, considering the minimum values for distance from the hospital, distance from the main road, and distance from the fire station, these are considered positive ideals. The negative ideal is approached similarly, with the lowest value considered for the first three layers and the highest value for the second three layers. The distance between each option and the positive and negative ideals was calculated as d^+ and d^-, respectively. Table 3 shows the distances and index C values used for the final ranking.

Table 3- The weight of different layers for ranking candidate centers for ESs

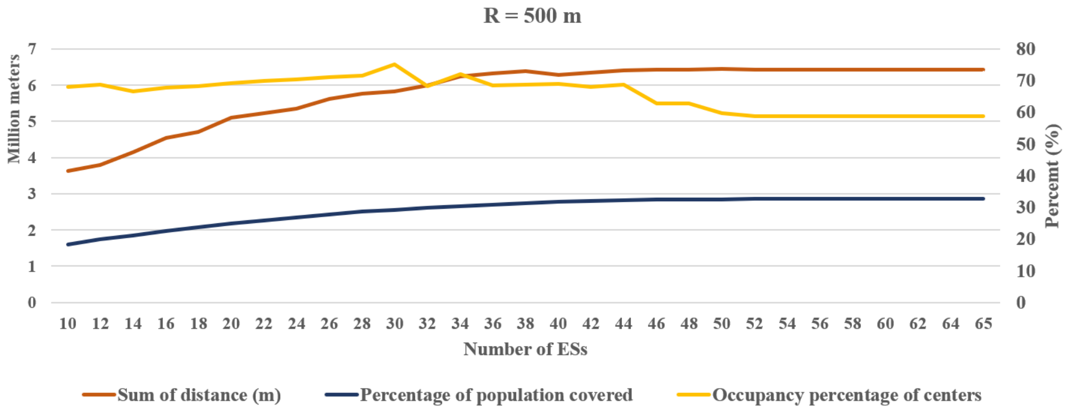
rank	d^+	d^-	C
1	0.000682	0.011469	0.943882
2	0.003817	0.007128	0.651266
3	0.003661	0.005286	0.590804
4	0.004069	0.004471	0.52351
⋮	⋮	⋮	⋮
63	0.010815	0.002185	0.168068
64	0.012161	0.001905	0.135431
65	0.010301	0.001256	0.108704

As indicated in the table, the highest value of C was associated with the first rank, indicating that it is the most similar to the positive ideal and the least similar to the negative ideal compared to the other options. The value of C decreased over time and reached its lowest point at rank 65. This ranking has been used to locate and allocate ESs.

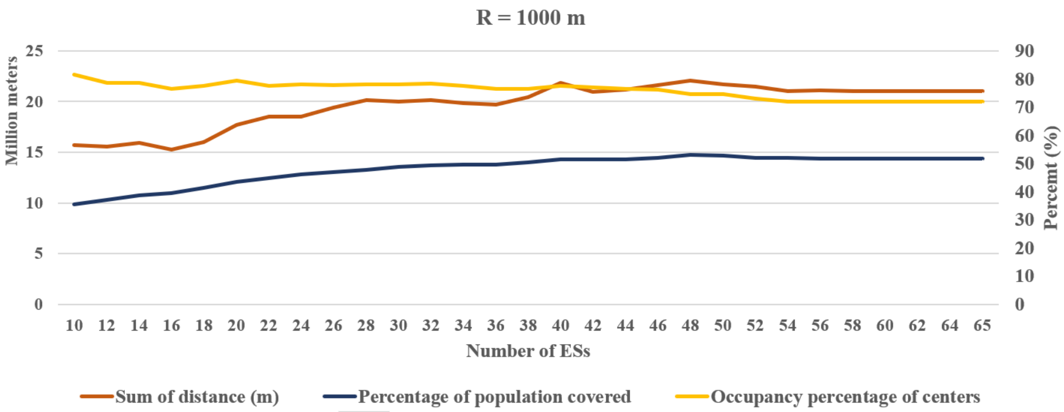
4-3- Location - Allocation of ESs

In the previous stage, the CRITIC and TOPSIS methods were utilized to rank the candidate ESs, resulting in a C value for each ES. In this section, which focuses on the location and allocation of ESs, C values are used as weights for each potential center. The higher the weight of a center, the more likely it is to be selected during the location process. For instance, the center with a rank of one had a C value of 0.943882, whereas the center with a rank of two had a C value of 0.651266. Therefore, the probability that rank one is chosen is 1.5 (0.943882/0.651266) times that of choosing rank 2.

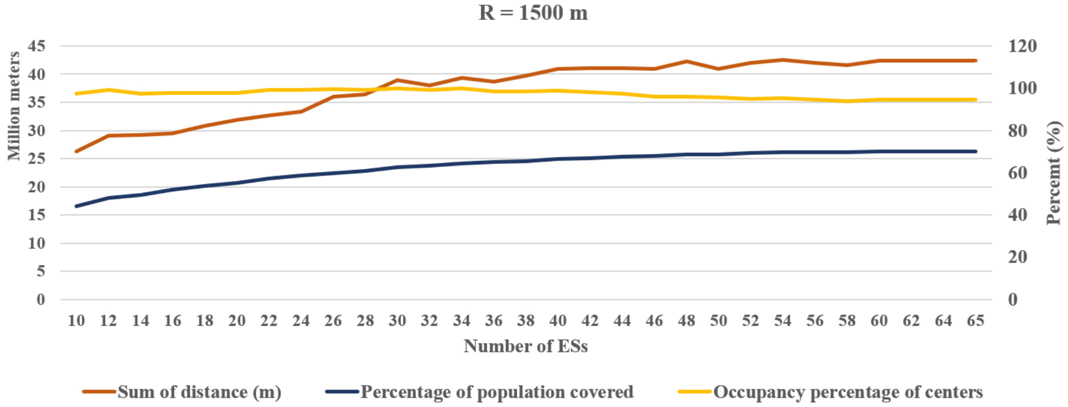
The modeling for the location-allocation problem considers two parameters: the neighborhood radius and the number of candidate ESs. To analyze the impact of these parameters on allocation results, three different neighborhood radius values (500, 1000, and 1500 meters) were considered for each candidate ES. It was assumed that only the population within each neighborhood could be relocated to the ES. Additionally, the model was evaluated using a range of 10 to 65 candidate ES as input. Figure 5 shows the changes in allocation percentage, total distance traveled by citizens, and average occupancy percentage of the selected ESs based on the radius of the neighborhood and the number of ESs.



(a)



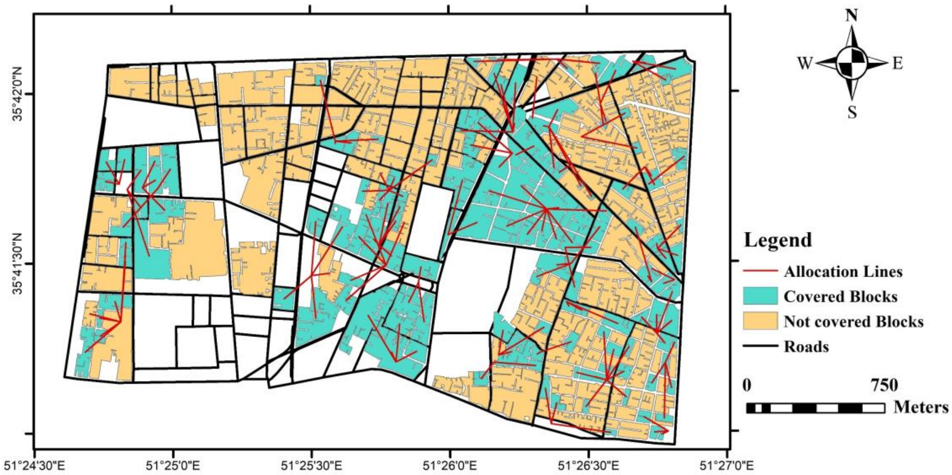
(b)



(c)

Figure 5- Chart of changes of different allocation statistics based on the number of different centers and for the coverage radius: (a) 500 meters, (b) 1000 meters, and (c) 1500 meters

As depicted in the graphs in Figure 5, the percentage of population coverage has increased in all scenarios with the increase in the number of ESs, which is expected. However, the changes were not linear, and the rate of increase was higher at the beginning of the chart than at the end. At the end of the corresponding diagram, there have been minor changes. Although the population is not fully covered, the expansion of medical centers at the end of the graph has not impacted the increase in coverage. The reason for this may be related to the size of the neighborhood. Specifically, as the radius of the neighborhood increases, the graph tends to converge more quickly. In a situation where convergence has occurred, the appropriate distribution of centers is much more important than the quantity of centers. This issue is consistent with the results of the study [42] so that the authors also concluded that the increase in the number of ESs is insufficient regardless of their distribution. Also, many studies have specifically addressed the importance of ESs distribution like [26, 30, 31] . This justification can also be considered for the distance-traveled graph. Regarding the chart depicting the average occupancy percentage of the centers, it can be observed that in all cases, there has been a decrease in value towards the end of the chart. This trend may be attributed to the size of the neighborhood. Even though there are still vacancies in the centers, the allocation has been prevented due to the neighborhood distance constraint, and the center still needs to be filled. With the expansion of the neighborhood radius, the occupancy rate has also risen, surpassing 90% when the radius reaches 1500 meters. Of course, it should be considered that in critical situations such as an earthquake, the emergency centers should be located close enough to ensure that citizens can access emergency services quickly. Assuming the selection of 40 ESs, maps related to the allocation and non-allocation for the studied area have been produced and evaluated. Figure 6 shows the allocation maps for the neighborhood distances of 500, 1000, and 1500 meters and the number of 40 ESs.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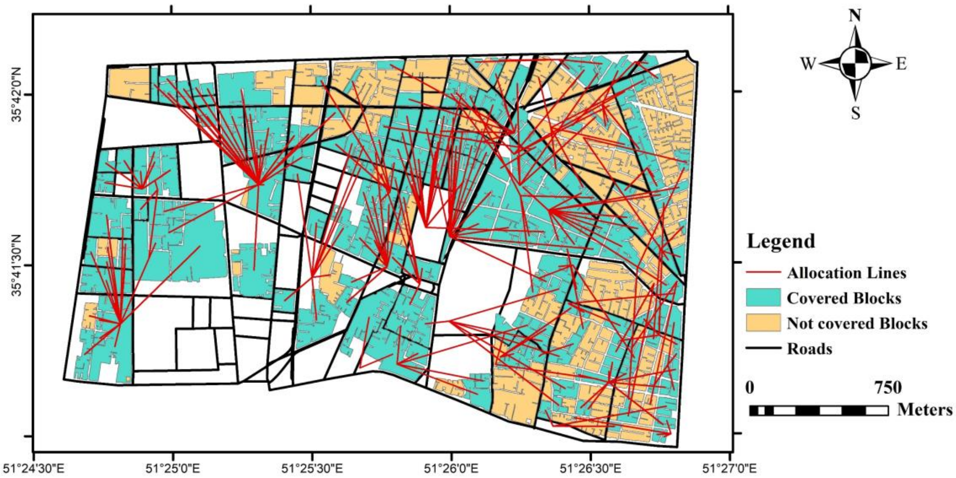
(a)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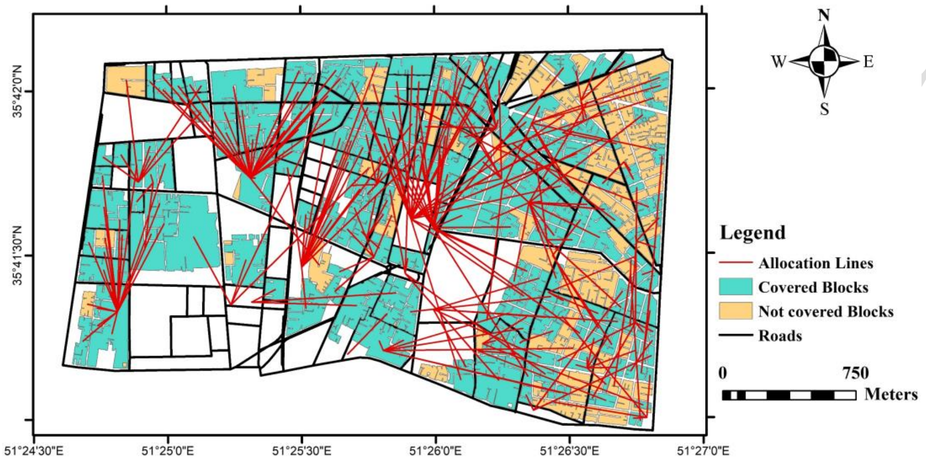
(b)



(c)

Figure 6- Allocation maps based on 40 ESs and per neighborhood radius: (a) 500 meters, (b) 1000 meters, and (c) 1500 meters.

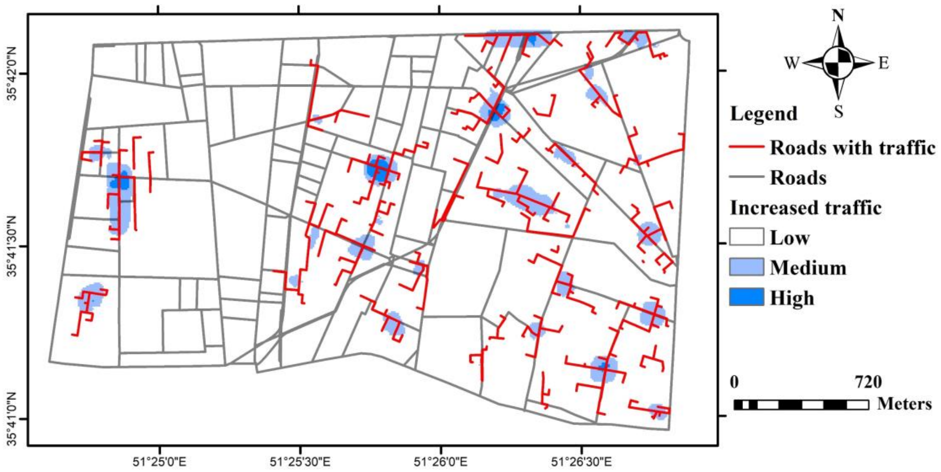
The allocation statistics for different age groups are presented in Table 4. This includes children under six, men and women between 6 and 65, and men and women over 65. The statistics are based on neighborhoods with a 500, 1000, and 1500 meter radius. Based on this, the age groups under six and over 65, who are highly vulnerable, have been prioritized for service when considering a larger neighborhood radius. In addition, women received higher services (in percentage terms) than men.

Table 4 - Allocation statistics for different age and gender groups

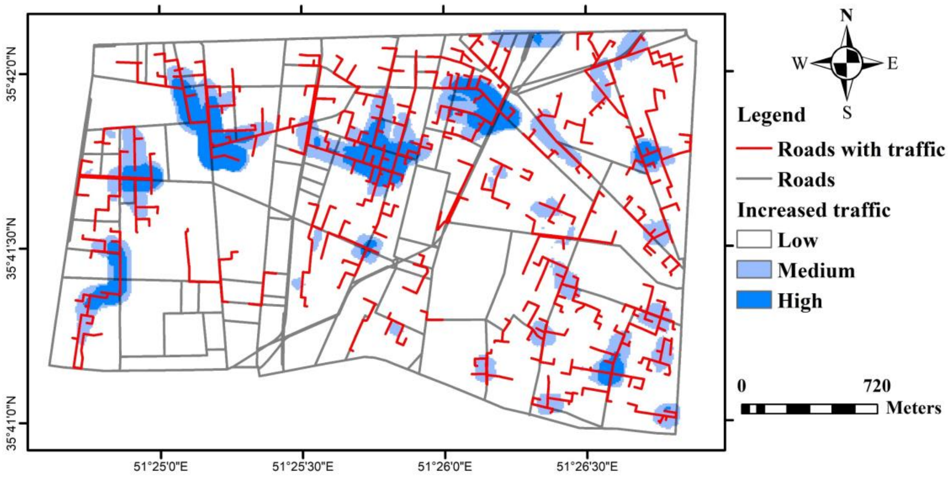
coverage radius		Boy under six years old	girl under six years old	men between 6 and 65 years old	women between 6 and 65 years old	men over 65 years old	women over 65 years old
500 m	person	993	952	9950	10246	1075	1088
	Percent	32.24	32.29	30.54	31.81	32.13	32.82
1000 m	person	1602	1552	15991	16086	1816	1812
	Percent	51.99	52.66	49.08	49.94	54.26	54.63
1500 m	person	2066	1992	20598	20457	2359	2304
	Percent	67.06	67.54	63.22	63.51	70.52	69.48

4-4- Prediction of increased traffic

After solving the allocation problem for coverage distances of 500, 1000, and 1500 meters, the allocation lines were used as network routes to predict the increase in traffic level after the earthquake caused by the transfer of residents to ESs. Line density analysis was utilized to generate the traffic map. This analysis focuses on the distribution of allocation lines on the road network, particularly in areas with high residential properties. The results of the analysis provide a general idea of areas with traffic. Figure 7 displays maps illustrating the traffic ranges for coverage distances of 500, 1000, and 1500 meters.



(a)



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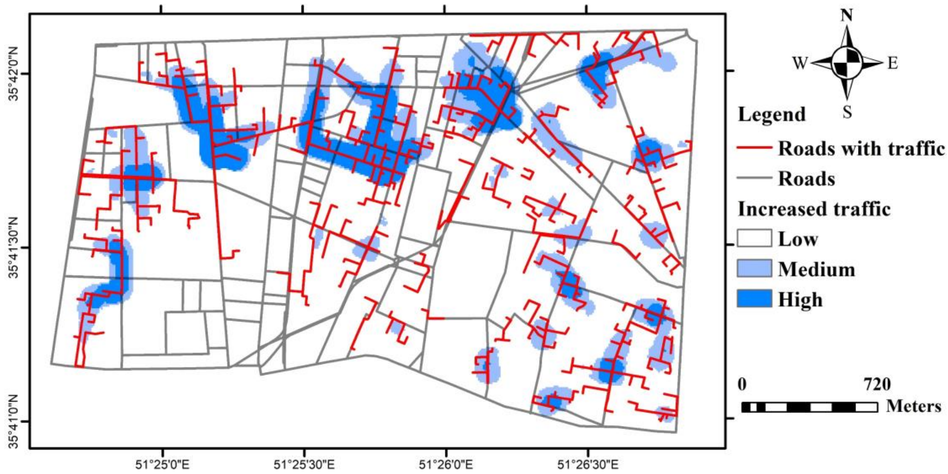

(c)

Figure 7- Prediction maps of areas with increased traffic for coverage distances: (a) 500 meters, (b) 1000 meters, and (c) 1500 meters

The traffic situation becomes more intense as the coverage distance for ESs increases, as shown in Figure 7. It is expected that there will be minimal traffic near the ESs within a 500-meter distance, while heavy traffic is not expected on the city's main roads. Additionally, traffic will disperse quickly because these centers are situated close to their designated areas. The traffic is heavier at distances of 1000 and 1500 meters. The transportation network includes sections of main roads serving other essential service departments, such as emergency and fire departments. This can cause disruptions, especially since the operations of these services should not be disturbed during that time.

5- Conclusion

ESs are essential for promoting peace and ensuring the safety of individuals during earthquakes and potential aftershocks. These centers' locating and coverage areas should be optimized to prioritize citizen safety and maximize accessibility. This study aimed to identify and allocate ESs in a part of Tehran's 12th district. Potential ESs were initially selected based on specific criteria, including their proximity to fault lines, fire stations, hospitals, main roads, ES areas, and population vulnerability. The criteria were weighted, and the centers were ranked using the CRITIC and TOPSIS methods.

According to the results obtained using the CRITIC method, the criteria of distance from the hospital and fire department had the highest weight (0.19). In contrast, the area criteria had the lowest weight (0.12). The TOPSIS method has been used to rank the ESs by assigning weights to the criteria. The ranked centers were utilized to address the issue of location and allocation. In the location problem, priority was given to centers with higher ratings. The location and allocation issues have been resolved for different numbers of ESs. Based on the results, the service delivery radius is assumed to remain constant. Simply increasing the number of centers does not guarantee better service delivery. The distribution is crucial. When the coverage radius was set to 500 meters, increasing the number of ESs decreased the occupancy percentage of the centers. This indicates that the centers were not fully utilized because they were more than 500 meters away from the residents. If the coverage radius is small, the distribution of centers becomes more significant. This requires considering multiple centers in different locations. In cases where the radius was set at 1000 and 1500 meters, there was an increase in the percentage of service delivery and occupancy of ESs. The service coverage percentage within a 1500-meter radius was only about 60%, well below the desired value of 80%. It is possible to expand the distance to increase this case's coverage. It is important to note that as the distance from centers increases, quick and easy access becomes more complex, which is crucial during times of crisis.

Line density analysis has been used to evaluate traffic conditions and predict areas with high traffic volume caused by the transfer of residents to ESs in the studied area. According to this analysis, reducing the service radius leads to decreased traffic, suggesting that services can be conducted more efficiently. Emergency response after an earthquake is crucial. Another reason expanding the coverage radius is not a viable solution for improving service delivery is the possibility of traffic and disruptions that may occur when relocating emergency services during crises. Therefore, this research introduces the conflict between the number of people served and the increase in traffic, which should be appropriately evaluated in the decision-making process because although the increase in the radius of the neighborhood increases the service to citizens, it can disrupt other services such as fire department, emergency, etc.

In this research, it is assumed that the population is concentrated in the center of population blocks, and perhaps higher-resolution information can lead to better planning. However, due to the unavailability of building data separately, it has not been possible to implement. Also, due to the unavailability of information on other urban uses, this study only considered residential use, therefore it is assumed that the earthquake occurred at night when most of the residents were in residential use. Also, if there is time information about the population in different blocks, it is possible to simulate the population flow and solve the location-allocation problem based on that. In this research, the types of structures related to ESs and their resistance to earthquakes are not considered as a weight component due to the unavailability of this information. Also, despite the availability of structural information, it is possible to simulate the destruction of buildings and the blocking of roads and the simultaneous evaluation of the effect of traffic and blocking of the road network after an earthquake.

In future studies, researchers can address the problem by exploring different assumptions. For instance, let us consider a situation where an earthquake strikes during the day, causing residents to be scattered in various locations. Other techniques, like VIseKriterijumska Optimizacija I Kompromisno Resenje(VIKOR), can be used to weigh and rank ESs and compare their results with the method used in this study. Additionally, considering time factors when determining location and allocation can result in a more accurate simulation of crisis conditions. This enables better decision-making in the location and allocation of ESs. It is also essential to consider other aspects of crisis management, such as allocating medical centers, firefighting, and rescue centers, as these tasks and services are interconnected. This would help achieve the study's objectives.

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Highlights

- Present an integrated multi-criteria decision-making and network-based model to solve the location-allocation problem.
- Consider population vulnerability based on age, gender and marital status in order to weigh emergency shelters.
- Solve the location-allocation problem by considering weights for emergency shelters
- Study the relationship between the coverage radius of emergency shelters and the number of citizens served.
- Investigate the possibility of blockage and traffic in case of increasing coverage radius of the emergency shelters.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: