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Multi-objective location model of earthquake shelters

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ABSTRACT

Most cities around the world are in danger of disasters. Among disasters, the earthquake is the most dangerous and ruining one. Iran has been located in the Alpine-Himalayas seismic belt, and because of the significant frequency of severe earthquakes happening all over the country compare to other countries and the state of the unsecured residential and non-residential buildings in most of the areas, attention to the post-disaster phase is vital. This study aims to locate shelters in some districts and allocate at-risk people of all districts to these shelters. Also, another purpose of this study is the reduction of the allocated budget by the government and reduction of traveled distance by people considering the possibility of link failure due to the earthquake. Allocated budget by the government for shelter construction includes the fixed and marginal cost. Mixed Integer Linear Programming has been used for modeling the suggested method. This method has been applied to the Tehran network, and the Genetic Algorithm has been used for solving the proposed method. The results showed that the leading share of the imposed costs arose from the shelter construction budget. Furthermore, the probability of choosing a district for constructing a shelter has a direct relationship with the at-risk population and the cost of shelter construction in that district. Seven districts have chosen to build shelters with about 400 thousand people capacity. District 16 chosen for constructing the biggest shelter that should serve to up to 123 thousand people and District 5 chosen to construct the smallest shelter that should serve to up to 16 thousand people.

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INTRODUCTION

Most cities around the world are in danger of encountering natural disasters. Disasters can hurt people's life and ruin their properties and damage the economy of these societies. Even considering the number of economic losses due to natural disasters, it is not possible to ignore the emotional or physical damages (Boonmee *et al.,* 2017). Also, the lack of attention to at-risk people may intensify the losses (Edrisi and Askari, 2019a; Hugelius *et al.,* 2017; Martin, 2015). In most studies that have been done on natural disasters, the post-disaster phase, and providing temporary or permanent life condition for people has been neglected (Mirzapour, *et al.,* 2019). People need necessary facilities like shelter after losing their properties (Ahmadi-Javid *et al.,* 2017; Lin *et al.,* 2012; Rawls and Turnquist, 2010; Roh *et al.,* 2015; Soltani-Sobh, *et al.,* 2016; Verma and Gaukler, 2015). These shelters must be located in a district that

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most of the at-risk population can access them with the least movement and also their capacity could serve to all of them (Ghasemi *et al.,* 2019; Perez-Galarce *et al.,* 2017; Salman and Yucel, 2015). Iran has been located in the Alpine-Himalayas seismic belt. During recent years, devastating earthquakes have occurred, e.g., Bam and Rudbar and Manjil. Over the past 50 years, earthquakes cause more than 100000 fatalities. In the Rudbar and Manjil earthquake, more than 35000 people died and more than 100000 home has been destroyed (Akbari *et al.,* 2017). Despite the weak buildings of these cities, there was no plan to establish centralized shelters and at-risk populations only could use tent shelters that set beside the destroyed houses (Ghafory-Ashtiany and Hosseini, 2008). According to the seismic history of Tehran, a high-intensity earthquake has occurred every 150 years, and regarding the last high-intensity quake in 1830, it seems likely to occur an earthquake in years ahead. Several active faults have been threatened Tehran city, which Rey fault is one of the most dangerous that can cause 500000 home destructions and 400000 casualties (JICA, 2000). This paper addresses the question of how the best pattern for shelter positioning can achieve in a city considering the transportation network resiliency. Also, the study looks for the least movement of people after the disaster with attention to the government budget. The main contribution of this research is the integration of transportation network resiliency to the shelter location-allocation problem. The objective function of the proposed problem consists of two terms. The first term tries to minimize the shelter's construction budget, and the second term tries to convert the discomfort of people's movement to economic losses. An economic parameter introduced in this study that turns people's move to financial losses. This study includes five sections that the second section reviews the literature review and formulation and the problem-solving method has been presented in section three. In the fourth section, the suggested method tested on the Tehran network, and finally, the conclusion and some suggestions for future researches are presented in the fifth section. During recent years, some studies have been done on shelter locating, and some of them have been investigated this issue as a transportation point of view. Several studies that are more related to this study have been presented in this section. Some of these studies were looking for estimations of the number of at-risk populations and some others looking for presenting a model for different types of disaster (Casteel, 2018; Drakaki *et al.,* 2018; Paul and Zhang, 2019; Sherali *et al.,* 1991). Liu *et al.,* (2011) present a framework to select shelter sites in mountain areas. Their structure used a wide range of disciplines like seismology and engineering. Li *et al.,* (2012) seek to present a bi-level model considering the different types of storm incidents scenarios. The proposed model has been solved by the Lagrangian relaxation method and tested in North California. Results showed that the performance of the model increased by increasing the size of the network. Coutinho-Rodrigues *et al.,* (2012) seek a multi-objective model with six main objectives for shelter location and evacuation route. The Mixed Integer Linear Programming (MILP) model used and tested in fire scenarios in Coimbra, Portugal. Finally, ten ideal results gained by minimizing each object cost. Also, Alcada-Almeida *et al.,* (2009) have presented a multi-objective decision making GIS model, and the model tested in the fire scenario in Coimbra, Portugal. Li *et al.,* (2017) estimated the population that needs shelters in the first step and then by Hybrid cross-entropy method identified shelters locations and finally assigned at-risk people to shelters. Ozbay *et al.* (2019) proposed a three-stage model to locate shelters and assign at-risk people to them. This research investigated multi-hazard scenarios and emphasized on secondary disasters. In other types of studies, shelters located were the main objective, and in some of them, finding the best evacuation route and shelters capacity. Furthermore, some studies investigated both of them with equal priority (Kinay, *et al.,* 2018). Dalal and Mohaparta (2007) categories villages to find the number and capacity of shelters. They used the Elzinga-Hearn method as a reciprocal method. At first, the population divided into groups considering distance matrix and then shelters capacity determined. Chu and Su (2012) have presented an assessment system with three primary levels and nine secondary levels produced by the Analytic Hierarchy Process (AHP) and Entropy methods.

Also, the shelter location has been selected by Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). In another study, Xu *et al.* (2016) have presented seven principles for shelter location. They offered a multi-objective model for shelter location by developing a P-median model. Kilci *et al.* (2015) improved the Turkish red cross organization shelter locating method. They did it by weight criteria and formed it by the MILP model. Amideo *et al.* (2019) evaluate the recent studies in shelter locating and evacuation routing. Furthermore, the required research in the future and gaps is defined by this study. As it was shown, most of the studies used different methods to find shelters location. People's access to the shelter is one of the essential parameters for shelter location. The limited amount of budget compels the decision-makers to choose the projects with higher efficiency. This study tries to consider the effect of network resiliency on shelter location and people allocation, which is the main contribution of this study. The resiliency of the transportation network affects the access route of people who lost their homes to the shelters in which their access time participates as imposed cost due to discomfort in the objective function. The current study estimates the cost of settling the allocated people In addition to the fixed cost of building shelters that is considered in most of the previous studies. The current study has been carried out in Tehran in 2019 due to the large population and high seismicity of Tehran. Part of the data of this research extracted from Tehran Atlas (2014) and Edrissi *et al.* (2015) and another part of that like the information about the cost of building and equipping a shelter is extracted from interviews with civil engineers and disaster management experts. However, the extraction of the exact data of constructing and building Tehran shelters may need some comprehensive studies independently.

MATERIALS AND METHODS

The primary purpose of this section is the minimization of the shelter construction budget and people's movement, which makes a tradeoff between government cost and people comfort. Also, this model evaluates the effect of transportation network resiliency on the shelter location. The MILP model has been used for formulating the suggested method, and the Genetic Algorithm (GA) has been used for solving the proposed model (Samani and Hosseini-Motlagh, 2017). Consider a city with I districts that when an earthquake with specified intensity strikes the town, qi share of the population of district i is at-risk Pi and need to move to the closest shelter. In this study, it is assumed that when an earthquake occurs in a district, a set of different scenarios may happen in the evaluated city. If it is believed that any link may be available or fail after the earthquake, the number of all scenarios is $2^{|L|}$.

Mathematical model

In this problem, two types of costs have been considered, and Eqs. 1 to 5 are presented to minimize cost values and people's movement considering network scenarios.

$$\min \sum_{S}\sum_{J} B_j^s I_j^s + \left(\sum_{S}\sum_{I}\sum_{J} x_{ij}^s t_{ij}^s\right)\alpha \quad (1)$$

$$\sum_{I} x_{ij} = P_i \qquad \forall s \quad (2)$$

$$\sum_{J} x_{ij} \le I_j C_j \qquad \forall s \quad (3)$$

$$B_j^s = F_j + R_j \sum_{I} x_{ij}^s \qquad \forall s \quad (4)$$

$$x_{ij} \ge 0 \quad (5)$$

In the presented model, Eq. 1 minimizes the objective function. The first term of the objective function indicates the shelter construction costs, and the second term shows the value of people's movement discomfort. Additionally, the "a" is an economic parameter that converts the people's movement discomfort to the monetary costs. Eq. 2 restricts the number of people who moved from each district to at-risk people in that district. Eq. 3 limits the number of people in each shelter to the predetermined capacity of that shelter. Eq. 4 estimates the shelter construction cost in each district regarding that the district was chosen for building shelter and the number of entrance people to each district's shelter. Finally, Eq. 5 controls the non-negativity of the people flows. A nomenclature is presented in the appendix to facilitate the perception of the mathematical model.

Fig. 1 has shown a diagram of the proposed approach. In the first step, shelters have been located in random districts. The next step estimated the new network incidence matrix regarding earthquake scenarios. Regarding the network configuration, people allocated to the located shelters in the next step. After that, construction cost has estimated

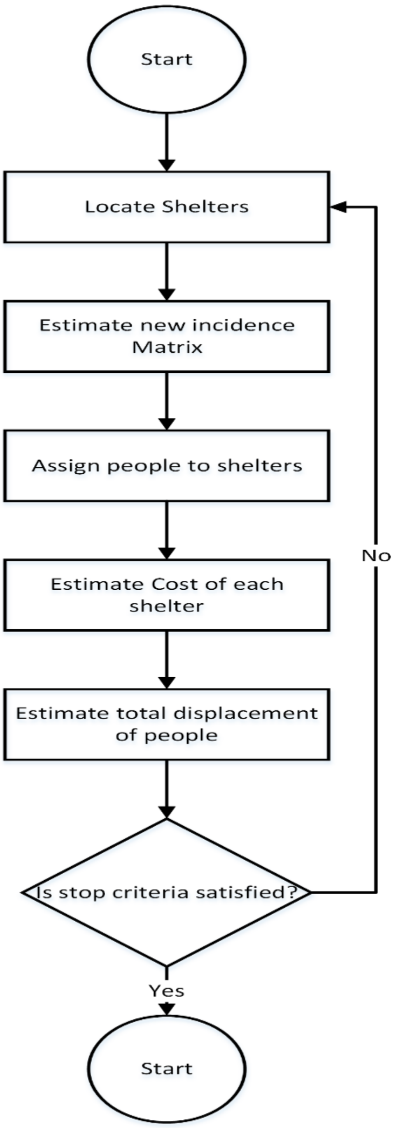

Fig. 1: Flowchart of the suggested method

considering shelter location and number of people assigned to each shelter. The discomfort of people in the next step determined by the movement time of at-risk people. The final step controls the stop criteria for the Genetic Algorithm and if it does not meet the criteria, the algorithm repeats until reaching the preset Number of Function Evaluation (NFE).

Numerical example

Tehran is known as the most populous city in West Asia. Many active faults threaten Tehran and this city needs more attention in disaster management. Regarding this, this study investigates the importance of disaster management, particularly shelter location in Tehran. The required and extracted information about the case study presented in Tables 1 and 2. Table 1 presents the population, district vulnerability, fixed and marginal costs for shelters constructing in each district and Table 2 shows link specification, including travel time and the failure probability of each link (Tehran Atlas, 2014; Edrissi, *et al.,* 2015). Fixed Cost includes land and primary requirements purchase for shelter construction and the marginal cost shows the cost for developing shelter for each person. The high-risk individuals in each district are shown in Fig. 2, in which most of the at-risk people are in District 15 and the least are in Districts 1, 21, and 22. The existing of old buildings in District 15 and Districts around it and recently built buildings in Districts 1, 21 and 22 can justify Fig. 2. Furthermore, the location of faults and population intensity can explain this issue.

RESULTS AND DISCUSSION

For solving the presented method, the GA has been used with 50 populations and up to 100 iterations. The paper uses the GA algorithm because of the integer nature of variables. This Algorithm belongs to population-based algorithms presented by Goldberg and Holland (1988). This algorithm uses the random numbers in the start step and this algorithm continues until meeting the iteration number 100 or meeting the stop criteria. This algorithm includes 1) Initialization, 2) Fitness, 3) New population, 4) Update, and 5) Stop criterion. To compute the objective function, the time value "a" in this problem considered equals to 650 Rials per minute in objective function regarding time value in Iran. Different network scenarios after the disaster have been analyzed regarding problem purposes. To reduce the calculation cost, only cases with no, one, or two collapsed link(s) investigated in which the number of these cases has determined using Eq. 6 (Edrisi and Askari, 2019b; Li and Silvester, 1984).

$$|S| = \binom{|L|}{0} + \binom{|L|}{1} + \binom{|L|}{2} \qquad (6)$$

Results that include shelters locations, capacity, and total imposed cost to the society are shown in

Table 1: District information of Tehran (Edrissi, *et al.,* 2015)

District	Population (10^3)	District Vulnerability Ratio (qi)	Fixed cost (Fi) (IRR) (10^{15})	Marginal cost (Mi) (IRR) (10^{12})
1	439	0.01	1000	100
2	632	0.01	700	70
3	314	0.02	810	81
4	861	0.01	500	50
5	793	0.01	550	55
6	229	0.03	610	61
7	309	0.04	450	45
8	378	0.04	480	48
9	158	0.06	270	27
10	302	0.07	300	30
11	288	0.11	310	31
12	240	0.15	305	30.5
13	276	0.04	410	41
14	484	0.05	390	39
15	638	0.08	290	29
16	287	0.10	270	27
17	248	0.12	250	25
18	391	0.06	230	23
19	244	0.067	260	26
20	340	0.09	255	25.5
21	162	0.03	308	30.8
22	128	0.01	430	43

Table 2: Link information of Tehran (Edrissi, *et al,* 2015)

Start District	End District	Travel Time (minutes)	Failure Probability	Start District	End District	Travel Time (minutes)	Failure Probability
1	3	12	0.00	9	21	21	0.30
1	2	15	0.10	9	10	16	0.10
1	4	20	0.30	9	17	21	0.30
2	5	9	0.00	9	18	17	0.10
2	6	13	0.00	10	11	13	0.00
3	4	15	0.10	11	12	10	0.00
3	7	17	0.20	11	17	8	0.00
3	6	16	0.20	12	13	15	0.10
4	8	8	0.00	12	14	15	0.10
5	22	15	0.10	13	14	11	0.00
5	21	23	0.30	14	15	13	0.00
5	9	17	0.20	15	16	11	0.00
6	7	16	0.20	16	19	10	0.00
6	11	12	0.00	16	20	14	0.10
6	12	22	0.30	17	18	19	0.20
7	8	6	0.00	17	19	15	0.10
7	13	7	0.00	18	21	23	0.30
7	12	19	0.20	19	20	19	0.20
8	13	5	0.00	21	22	25	0.30
9	21	21	0.30				

Table 3. As shown, the leading share of the expenses imposed is related to construction that this shows the importance of this parameter compares to people movement in locating shelters. The number of allocated people to shelters shown in Table 4 in which increased by decreasing construction or development costs in that district. Also, more shelters with high capacities needed in the districts with more at-risk people based on Fig. 2 Low prices of construction and development in districts with top at-risk people

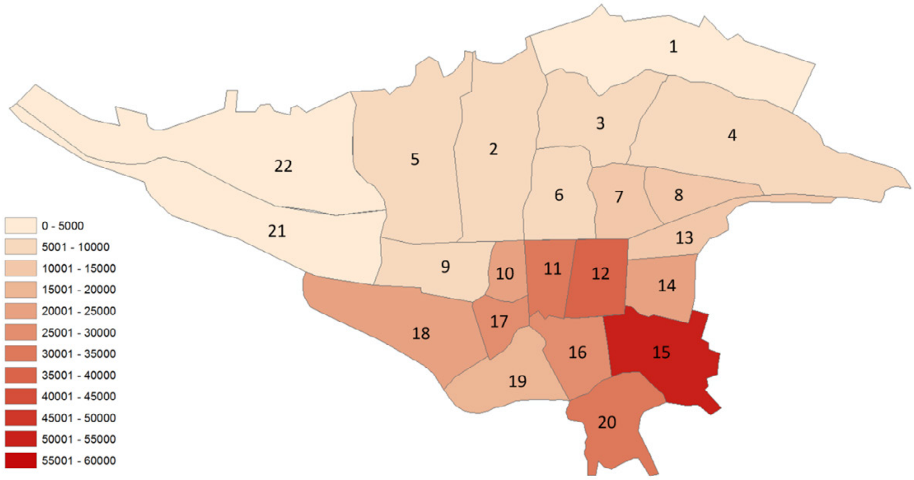

Fig. 2: Vulnerable population, , of the 22 districts of Tehran (Edrissi, *et al.,* 2015)

Table 3: The final result of the objective function

Components of the objective function	Value(IRR)
$\sum_{S}\sum_{J} B_j^s I_j^s$	$6.74*10^{12}$
$\sum_{S}\sum_{I}\sum_{J} x_{ij}^s t_{ij}^s$	$3.75*10^{6}$
Total Cost	$6.74*10^{12}$
Selected Districts for Shelter Construction	3-5-7-9-13-16-17

Table 4: Allocated people to shelters

Shelter	3	5	7	9	13	16	17
Number of allocated people (10^3)	21	16	40	43	64	123	81

are one of the issues that decrease the objective function. The main share of shelters capacity belongs to the southern districts of the city in which the capacity of shelter in the district 16 is more than the total capacity of shelters in the Districts 3, 5, 7 and 9 that are among the more resistant districts. The smallest shelter belongs to the district five because it is among the more resistant districts against the earthquake and its neighbor districts are the same. Also, the results show that because of the low cost of people's movement, it is better to locate shelters in districts with a lower amount of fixed or marginal shelter costs. This issue is observed in Districts 15, 16, and 17 that, despite a large number of at-risk people in District 15, the at-risk people of this district should go to one of the shelters in Districts 16 or 17.

CONCLUSION

In this study, the effect of network resiliency on shelter location has been analyzed. A mathematic model suggested, and GA has solved different network scenarios that have no, one, or two collapsed links. Regarding the population and high seismicity of Tehran, this study used Tehran as a case study. Results showed that the effect of construction cost is a more critical parameter compare to distances between at-risk people and the closest shelter. Furthermore, the number of at-risk people in each district is one of the essential metrics in selecting shelters location. The results may be very insightful for the policy-makers. For example, it is better to locate shelters in districts with high at-risk populations and low construction costs. Also, policy-makers can give loans in districts with small at-risk populations to prevent building a shelter in those districts with high fixed costs. This study has some gaps that can be the aim of future studies in which some of them are as; 1) The time of purchasing perishable foods regarding the uncertainty in earthquake time; 2) Other parameters, such as shelters maintenance costs can add to this problem; 3) The prioritization of building the shelters regarding the scarce financial resources; 4) This problem can be investigated concurrently with the building rehabilitation problem.

AUTHOR CONTRIBUTIONS

Ali Edrisi performed the literature review, analyzed and interpreted the results and finally edited the manuscript. Moein Askari presented and performed the methodology, prepared the manuscript text and other remained activities.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

ABBREVIATIONS

Nomenclature

Set	Definition
S	Set of scenarios
I	Set of origins
J	Set of destinations
L	Set of links
Parameters	
α	Conversion parameter of people's discomfort to the monetary unit
C_j	Maximum capacity of shelter in district *j*
t_{ij}^{s}	Travel time between districts *i* and *j* in scenario *s*
P_i	At-risk people in district *i*
F_j	Fixed cost of building a shelter in district *j*
R_j	The marginal cost of shelter in district *j*
Decision variables	
B_j^s	Shelter cost in district *j* in scenario *s*
x_{ij}^{s}	Number of moved at-risk people from district *i* to district *j* in scenario *s*
I_j^s	Dummy variable that 1 shows the construction of a shelter in district *j* and vice versa

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