Location-allocation model for earthquake shelter solved using MPSO algorithm

Xiujuan Zhao
Tsinghua University
xjzhao@mail.tsinghua.edu.cn

Jianguo Chen
Tsinghua University
chenjianguo@mail.tsinghua.edu.cn

Peng Du
Beijing Global Safety Technology Co., Ltd
dupeng@gsafety.com

Wei Xu
Beijing Normal University
xuwei@bnu.edu.cn

Ran Liu
Beijing Global Safety Technology Co., Ltd
Liuran@gsafety.com

Hongyong Yuan
Tsinghua University
hy-yuan@tsinghua.edu.cn

ABSTRACT

Constructing shelters in suitable quantities, with adequate capacities and at the right locations is essential for evacuees under earthquake disasters. As one of the disaster management methods, constructing shelters can help to significantly reduce disruption and devastation to affected population. Mathematical models have been used to solve this problem allied with a heuristic optimization algorithm. The optimization of evacuation efficiency, as one of the most important objectives, has many expressive forms, such as minimizing evacuation distance and evacuation time. This paper proposes a new model that aims to minimize evacuation time with a new calculation method and to maximize total evacuees' comfort level. The modified particle swarm optimization (MPSO) algorithm is employed to solve the model and the result is compared with a model that calculated evacuation time differently and a model without distance constraint, respectively.

Keywords

Earthquake shelter, location-allocation, evacuation time minimization, comfort level maximization, MPSO.

INTRODUCTION

Natural disasters have caused serious economic losses and casualties (Bilham, 2010; Norio et al., 2011; Yuan, 2008). Many engineering methods have been implemented to protect buildings and infrastructures against damages (Chen and Scawthorn, 2003). However, in some cases, these methods cannot protect people after an earthquake disaster that leaves many people homeless. Therefore, constructing emergency shelters with reasonable locations, sufficient assets and supplies is important to provide safe places to affected people at different phases of a disaster.

In this paper, a new bi-objective model is developed for determining locations of earthquake disaster emergency shelters as well as allocating affected population to specific shelters. Both evacuation time and comfort level of evacuees are considered. The evacuation time is obtained with consideration of evacuation route's width and the number of evacuees of each community. Also, an optimization approach named modified PSO (MPSO) algorithm derived from the work of Zhao et al. (2015) is used to solve the model. The MPSO algorithm incorporates simulated annealing (SA), thus allowing better solutions to be obtained for the earthquake shelter location-allocation problem. Furthermore, Chaoyang District, Beijing, China is selected for the case study and the presented results provide the local government with a solution to the earthquake shelter location-allocation problem.

RELATED WORK

In order to facilitate decision-making, many research have been carried out to help determine shelters' locations and population allocation. The methods used mostly includes spatial analysis of geographical information systems (Gall, 2004; Sanyal & Lu, 2009) and location-allocation mathematical models (Bayram, Tansel and Yaman, 2015; Gama, Scaparra and Santos, 2013; Kilci, Kara, & Bozkaya, 2015; Sherali, Carter, & Hobeika, 1991) that are derived from site selection models. The site selection models includes P-median model (Hakimi, 1964), P-center model (Hakimi, 1965), and covering model (Toregas, Swain, ReVelle, & Bergman, 1970) that have been modified to solve the disaster shelter location-allocation problem. According to the characteristics of the disaster shelter location-allocation problem that the evacuees should be evacuated to assigned shelters as soon as possible, the objective derived from P-median model is most commonly adopted. For example, the work of Sherali et al. (1991), one of the first research applied P-median model in solving disaster shelter location-allocation problem. This work developed a shelter location-allocation model with an objective to minimize the total evacuation time of all affected people to their assigned hurricane shelters. Based on these single-objective models, multi-objective models (Alçada-Almeida, Tralhão, Santos, & Coutinho-Rodrigues, 2009; Barzinpour & Esmaeili, 2014; Doerner, Gutjahr, & Nolz, 2009; Hu, Xu, & Li, 2012; Hu, Yang, & Xu, 2014; Zhao, Xu, Ma, & Hu, 2015) and hierarchical models have been proposed (Z. Chen, Chen, Li, & Chen, 2013; Ng, Park, & Waller, 2010; Widener & Horner, 2011). Multi-objective model is more popular as it can satisfy different requirements simultaneously, such as the objectives to minimise evacuation distance or time, to minimise construction cost and to minimise disaster risks. Among these objectives, the objective of evacuation time minimization is also widely used. Hu et al. (2014) proposed an earthquake shelter location-allocation model with two objectives for solving evacuees' allocation problem, i.e. to minimize total cost and to minimize total distance from communities to their assigned shelters. Similarly, Zhao et al. (2017; 2015), Xu et al. (2017) and Kongsomsaksakul et al. (2005) also developed their models with the objectives to minimize distance or time for evacuees to reach their assigned shelters, respectively. However, the definitions of evacuation time vary in these research. For flood and hurricane disasters, the evacuees are assumed to travel in vehicles and the evacuation time is defined with network model (Bayram et al., 2015; Sherali et al., 1991). Also, some researchers used evacuation distance to represent evacuation time (Alçada-Almeida et al., 2009; Doerner et al., 2009; Rodríguez-Espíndola & Gaytán, 2015). However, evacuees are expected to walk during and after earthquake disasters that cannot be calculated using the method of evacuation time calculation for hurricane and flood disasters. Although Zhao et al.(Zhao et al., 2017, 2015) proposed an earthquake shelter location-allocation model with an objective to minimize evacuation time, it is weighted evacuation time rather than real travel time for all members of a given community to reach their designated shelter. Furthermore, after a severe earthquake disaster, the evacuees may need to stay in shelters for prolonged periods of time. Thus, their comfort should be an important factor. However, the comfort level of evacuees is still not taken into account in current works.

With respect to problem solving methods, geographical information system is employed to solve simple models (Kilci et al., 2015; Ye, Wang, Huang, Xu, & Chen, 2012) while complex models with different objectives and constraints are typically solved using heuristic optimization algorithms such as ant colony optimization (Colorni, Dorigo, & Maniezzo, 1991), genetic algorithms (GAs) (Goldberg, 1989), particle swarm optimization (PSO) (Kennedy & Eberhart, 1995) and simulated annealing (Kirkpatrick, Gelatt, & Vecchi, 1983). Compared with other heuristic optimization algorithms, PSO algorithm exhibits properties including straightforward calculation process, simple parameters, and fast convergence. Also, it has been modified with simulated annealing (SA) to avoid premature convergence (Hu et al., 2012; Zhao et al., 2015).

MATHEMATICAL MODEL, OPTIMIZATION METHODS AND CASE STUDY

In this section, a mathematical model for the earthquake shelter location-allocation problem is developed. Also, MPSO, the optimization heuristic algorithm employed to solve the location-allocation model is described. Furthermore, an overview of the case study designed to demonstrate the results of the model solved with the MPSO algorithm is presented.

This work makes four assumptions as described below:

1) All residents of a community will be allocated to the same shelter;

2) The residents queue to evacuate and each evacuee occupies 1 square meter;

3) Residents will go to their assigned shelters along the shortest route from their locations;

4) The residents of a given community will be assigned to only one shelter.

Shelter location-allocation model

The objective to minimize the total evacuation time is used widely to ensure the affected people can arrive to their shelters as soon as possible. Also, the comfort level is important as the evacuees would live in their shelters for a long time after a severe earthquake disaster. Non-utilized area of a shelter for each evacuees is one of the import factors to affect their comfort level. Thus in the preliminary study reported in this paper, a model with two objectives to minimize the total evacuation time and to maximize total comfort level are proposed with a distance constraint and a capacity constraint. In this paper, the comfort level is simplified to non-utilized area before a community coming.

The notation used in this paper is shown as below.

i: Index of objective, equal to 1, 2, …,I

j: Index of community equal to 1, 2, …, M

k: Index of candidate shelter, equal to 1, 2, …, N

t_{kj}: Travel time from community j to shelter k

B_{kj}: Whether or not community j is assigned to shelter k, equal to 1 or 0

L_{kj}: Non-utilized capacity of shelter k before community j coming

d_{kj}: Shortest evacuation route's distance from community j to shelter k

D_j: The maximum evacuation distance that community j can travel

P_j: The number of people within community j

C_k: Capacity of candidate shelter k

X_k: Whether or not candidate shelter k is selected, equal to 1 or 0

w_p: Path width of an evacuation occupies

W_{kj}: The weighted mean width of the evacuation paths that form the entire route taken by community j to candidate shelter k i

v_j: Evacuation speed of the people in community j

a_i: Weight of objective i

$$\min f_1 = \sum_{j=1}^{M}\sum_{k=1}^{N}\left(t_{kj} \times B_{kj}\right) \tag{1}$$

$$\min f_2 = \sum_{j=1}^{M}\sum_{k=1}^{N}\left(L_{kj} \times B_{kj}\right) \tag{2}$$

$$d_{kj} \times B_{kj} - D_j \le 0 \qquad \forall k = 1,2,\dots,N; \forall j = 1,2,\dots,M \tag{3}$$

$$\sum_{j=1}^{M}\left(P_j \times B_{kj} - C_k \times X_k\right) \le 0 \qquad \forall k = 1,2,\dots,N \tag{4}$$

$$\sum_{k=1}^{N}\left(B_{kj} \times X_k\right) = 1 \qquad \forall j = 1,2,\dots,M \tag{5}$$

Equation (1) is the objective to minimize total evacuation time of all communities where t_{kj} is the minimum evacuation time from community j to candidate shelter k that can be obtained using Equation (6).

$$t_{kj} = \frac{d_{kj} + \dfrac{P_j}{w_P \times W_{kj}}}{v_j} \tag{6}$$

In Equation (6), the evacuation time of a community is the time required for all residents of the community to reach their shelter. Here, the distance for the final evacuee of a community is adjusted by the number of evacuees of this community, the occupied width of an evacuee and the width of the evacuation route as shown in Figure 1.

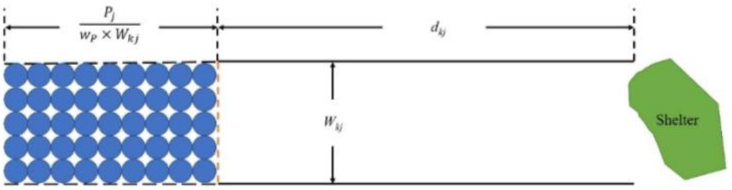


Figure 1 Evacuation distance adjustment

Parameter d_{kj} in Equation (6) is the shortest distance obtained using Dijkstra algorithm, P_j is the number of evacuees in community j, w_p indicates the width that an evacuee needs which in this paper is assumed to be 1 meter. W_{kj} is the average width of the shortest route from community j to shelter k and v_j is the average evacuation speed of community j calculated as:

$$v_j = (2 \times p_c \times v_c + (p_a - p_c) \times v_a + p_o \times v_o) \times \rho \tag{7}$$

where v_c, v_a and v_o represent the speed of a community's children, adults and elderly people that is defined by Gates et al. (2006), and p_c, p_a, and p_o are the proportions of these three categories of people respectively. The parameter ρ is an adjustment parameter of the evacuation speed relative to the ordinary speed that is set as 1 in this paper.

In Equation (1), B_{kj} is a decision variable that indicates if the community j will be allocated to shelter k (1 allocated, 0 otherwise). Equation (2) is the objective to maximize the comfort level of all evacuees in their allocated shelters. The parameter L_{kj} indicates the non-utilized capacity of shelter k before community j coming. Equation (3) represents the distance constraint that a candidate shelter cannot be selected by a given community if the distance is greater than D_j, the farthest this community can reach. Equation (4) indicates the capacity constraint that the number of evacuees allocated to a shelter cannot exceed the capacity of the shelter. Here, C_k is the capacity of shelter k that can be obtained by total area of shelter k divided by smallest refuge area per person, i.e., 1 m^2 (Beijing Municipal Institute of City Planning & Design, 2007). X_k is a decision variable that indicates whether the candidate shelter k will be selected (1 selected, 0 otherwise). Equation (5) ensures that a community can only be allocated to one shelter.

Modified particle swarm optimization algorithm

The model proposed in this paper involves different two objectives. There are different approaches can be taken to solve models involving multiple objectives such as Pareto-based approach and converting the multi-objective problem to a single objective problem. This conversion can be achieved by summing the weighted values of each of the multiple objectives to be an average assessment index as shown in Equation (8). I is the number of objectives and a_i is the weighted value of objective function f_i. The weight assigned to each objective function can be determined according to the prior information on the relative importance of each one. Here, it should be noted that the units should keep consistent.

$$\min f = \sum_{i=1}^{I} (a_i \times f_i) \tag{8}$$

In the preliminary work reported in this paper, the weighted-based approach is used and the two objectives can be converted to a single one, to minimize average assessment index, as shown in Equation (9). In the preliminary work presented in this paper, both the two weights, a_1 and a_2 are set as 0.5. To eliminate the effect of the units, a normalization approach is employed as shown in Equation (9). $f_{1,\min}$ and $f_{2,\min}$ are the minimum values of function 1 and 2 respectively that are solved individually neglecting the other function. Similarly, $f_{1,\max}$ and $f_{2,\max}$ are the maximum values of function 1 and 2 respectively that are solved individually neglecting the other function.

$$\min f = \left(a_1 \times \frac{f_1 - f_{1,\min}}{f_{1,\max} - f_{1,\max}} \right) + \left(a_2 \times \frac{f_{2,\max} - f_2}{f_{2,\max} - f_{2,\min}} \right) \tag{9}$$

To solve the model proposed in this paper, MPSO algorithm is introduced by adding SA to PSO algorithm. The pseudo code for the MPSO algorithm is presented in Algorithm 1. MPSO algorithm begins with a population of size 100 that is generated randomly via the INITIALIZE function. The particle of swarm P is named u. After the first 100 iterations, the solution of each subsequent iteration will be compared with previous 100 solutions. If there is no difference between them, then a new particle swarm is generated using INITIALIZE function. The MPSO process executes until the convergence is met, i.e., the solution remains the same for 1,000 iterations.

Algorithm 1 MPSO

```
$P$ ← INITIALIZE($popSize$)
While (MPSO not converged) do
  COMPUTEOV($P$)
    for each particle in $P$
    if von Neumann topology then
      $v$ ← UPDATE_v($p$, $v$, $p_{best}$, $n_{best}$)        ▷ Update particle's velocity
    else
      $v$ ← UPDATE_v($p$, $v$, $p_{best}$, $g_{best}$)        ▷ Update particle's velocity
    $p$ ← UPDATE_p($p$, $v$)                                  ▷ Update particle's position
    if $p_{current} > p_{best}$
      $p_{best}$ ← $p_{current}$
    else
      $p_{best}$ ← apply SA($p_{current}$)                    ▷ Apply SA
    if von Neumann topology then
      for each particle in $P$
        $n_{best}$ ← UPDATE_n($p_n$, $n_{best}$)              ▷ Update best of neighbours
    else
      $g_{best}$ ← UPDATE_g($p_g$, $g_{best}$)                ▷ Update global best
    if PREMATURE($P$) then
      $P$ ← INITIALIZE($popSize$)
```

In algorithm 1, both von Neumann topology and global topology are used. More specifically, if using the von Neumann topology, each particle's velocity and position in iteration t+1, v_u^{t+1} and p_u^{t+1}, are updated using Equations (10) and (13) respectively. If using the global topology, each particle's velocity and position in iteration t+1, v_u^{t+1} and p_u^{t+1}, are updated using Equations (11) and (13) respectively.

$$v_u^{t+1} = \varphi(v_u^t + c_1\, r_1\, (p_{best,u}^t - p_u^t) + c_2\, r_2\, (g_{best}^t - p_u^t)) \tag{10}$$

$$v_u^{t+1} = \varphi(v_u^t + c_1\, r_1\, (p_{best,u}^t - p_u^t) + c_2\, r_2\, (g_{best}^t - p_u^t)) \tag{11}$$

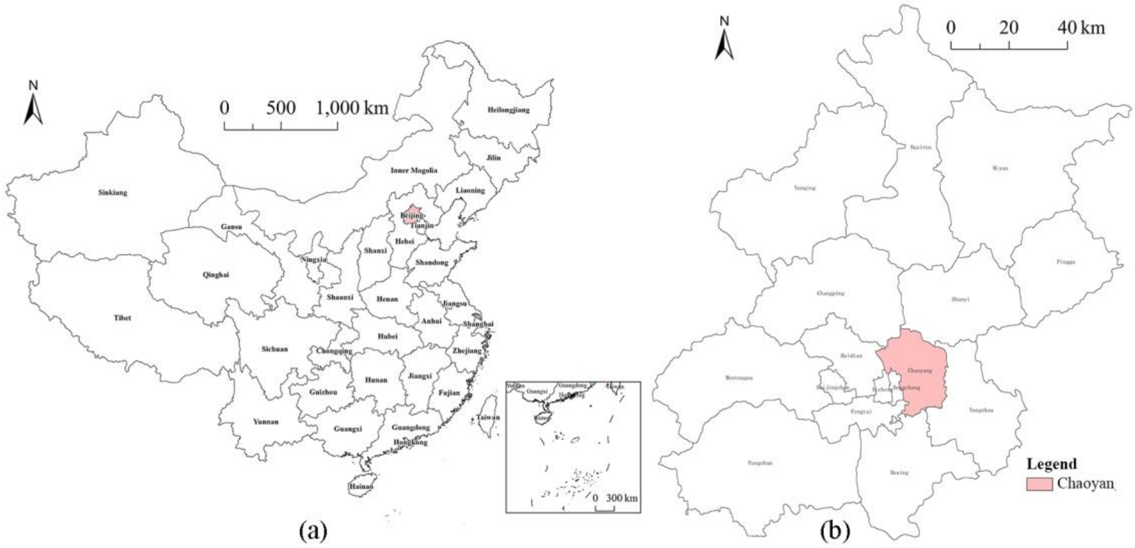
$$\varphi = \frac{2}{|\, 2 - (c_1 + c_2) - \sqrt{(c_1 + c_2)^2 - 4(c_1 + c_2)}\, |} \tag{12}$$

$$p_u^{t+1} = p_u^t + v_u^{t+1} \tag{13}$$

where φ is the constriction coefficient introduced by Clerc and Kennedy (2002) to guarantee convergence by avoiding the explosion of the particle swarm. It is a function of c_1 and c_2 as shown in Equation (10) that are the cognitive and social acceleration coefficients respectively where $c1$=2.8 and $c2$=1.3 leading to a value of φ=0.7298. In Equation (8) and (9), r_1 and r_2 are generated randomly in the range [0, 1]. For each particle, the fitness value of each particle can be calculated using COMPUTEOV function that is Equation (1). For each particle, its best position so far, $p_{best,}$ can be replaced by its current position, $p_{current}$, if $p_{current}$ is better. However, if $p_{current}$ is worse than $p_{best,}$ SA is applied such that a worse position can be accepted with a lower probability. When von Neumann topology is used, the best position among neighbouring particles, n_{best} is updated via the UPDATE_n function that compares the positions of neighbours of a particle, p_n. When using global topology, the best position among all particles, g_{best} is updated by comparing it with all other particles.

Case study

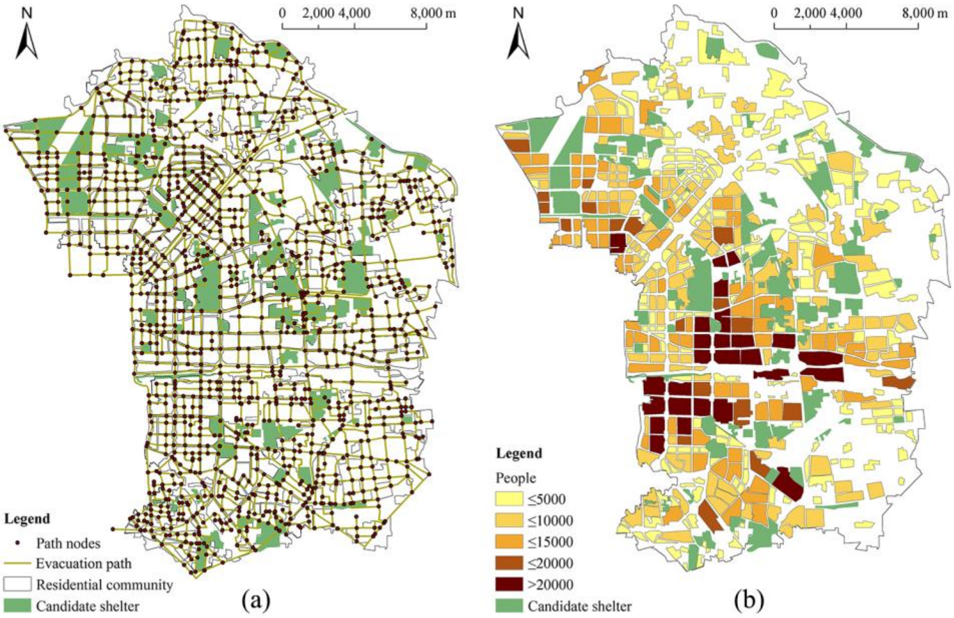
Figure 2 illustrates the location of the geographical area for case study in this paper, namely Chaoyang District, Beijing, China. More specifically, Figure 2(a) shows the location of Beijing in China and Figure 2(b) shows the location of Chaoyang in Beijing.



(a) (b)

Figure 2. Location of Jinzhan, Chaoyang, Beijing, China

Figure 3(a) presents a map of communities, shelters and evacuation path network, which was provided by the Key Laboratory of Environmental Change and Natural Disaster of Ministry of Education, Beijing Normal University. Figure 3(a) indicates the locations of 72 candidate shelters and 463 communities that need to be allocated to the designated shelters. All these 72 candidate shelters are more than 500m from the earthquake faults, have slopes less than 20^o, and covered by basic facilities in consideration of the safety requirement (Hu et al., 2014). The area of these 72 candidate shelters are shown in Table 1. The 463 communities in Chaoyang District are shown in Figure 3(b) that is provided by the Beijing Bureau of Civil Affairs. It shows that the population of Chaoyang is mainly concentrated in the central part of the district while the northwest and southeast look to be the most sparsely populated areas.



(a) (b)

Figure 3. Location of communities, shelters, evacuation paths and distribution of population

Table 1. Area of candidate shelters

Index	Area (m^2)	Index of	Area (m^2)	Index	Area (m^2)	Index	Area (m^2)
1	4159154	19	913338	37	132689	55	760155
2	129008	20	1131302	38	557720	56	205123
3	1287289	21	1198171	39	1389666	57	225276
4	148632	22	151359	40	683912	58	101332
5	1054839	23	628007	41	1134819	59	185707
6	137168	24	435675	42	116883	60	154885
7	1747887	25	451206	43	182029	61	3259571
8	410019	26	1947589	44	209357	62	4025508
9	1965047	27	666949	45	151982	63	416397
10	444471	28	710093	46	1303315	64	632137
11	221256	29	458265	47	534468	65	1671783
12	1781155	30	211451	48	239690	66	104041
13	2351361	31	1281952	49	314890	67	170633
14	813119	32	336887	50	505944	68	1344011
15	708023	33	841863	51	512862	69	1852361
16	84579	34	966195	52	190563	70	232708
17	336393	35	562851	53	422104	71	244959
18	604975	36	547908	54	260175	72	217352

PRELIMINARY RESULTS AND DISCUSSION

As the location-allocation problem involves a large number of communities and candidate shelters, and different constraints, the aforementioned MPSO algorithm was adopted. The program executes 9 times in a laptop with 16GB memory and 2.2 Hz Intel Core i7. It needs average 5 minutes to obtain the result for each execution. In this section, the shelter selection and community allocation to the selected shelters are shown at first. Also, the average assessment index of each community is analyzed. Then, the result is compared with the result of the model with objective to minimize total evacuation time and the model without the distance constraint.

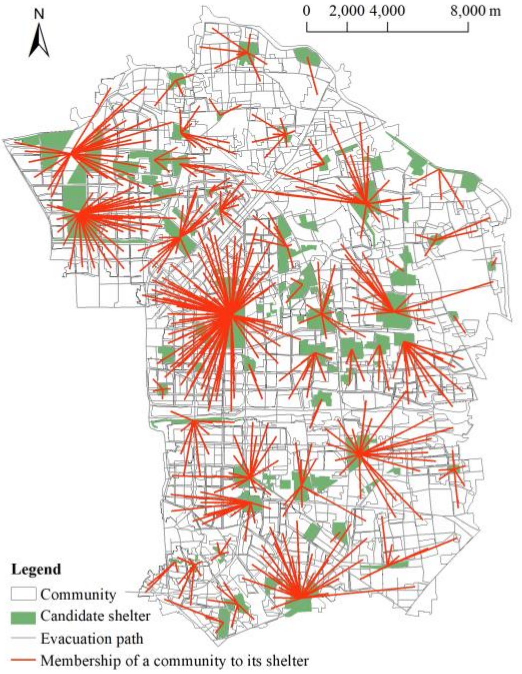


Figure 4. Location-allocation result

Figure 4 presents the result of shelter selection and how the 463 communities are allocated to them. A total of 47 shelters are being selected. The value of f , f_1, and f_2 are 0.2116, 5.47×10^5 and 2.83×10^8 respectively. It can be seen that shelters with larger capacity exhibit higher attractiveness that many relatively distant communities are allocated to them. In comparison, smaller shelters mainly serve communities more closely located.

Figure 5(a1) and (b1) shows the value of evacuation time of each community and non-utilized capacity before each community coming respectively. Also, the value ranges of them are shown in Figure 5(a2) and (b2) respectively. It illustrates that the value of evacuation time, for each community is less than 4,500 seconds, among which, even some of them are less than 500 seconds. The evacuation time for community 161 is the most that is 4,274 seconds while that for community 64 is the least. Most of the value for non-utilized capacity before a community coming is less than 4.2×10^6 m^2 and more than 4.3×10^4 m^2. Also, it can be seen that the value of evacuation time is more concentrated than the value of non-utilized capacity before communities coming.

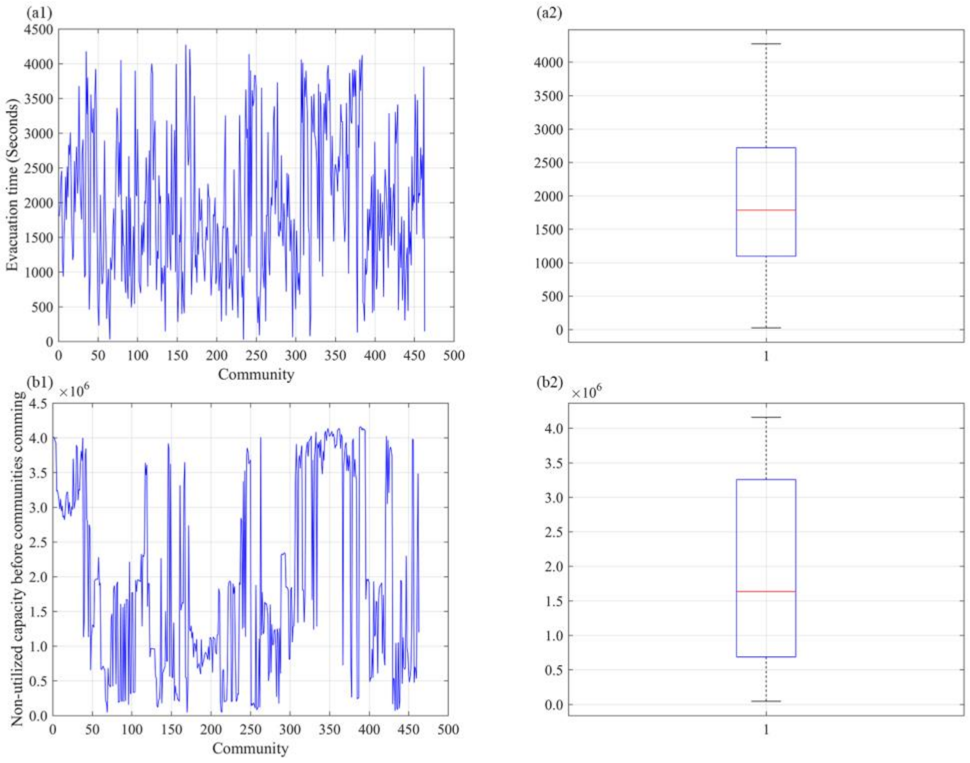


Figure 5 Evacuation time of each community and non-utilized shelter capacity before each community coming

The proportion of utilized and non-utilized area of 47 selected shelters are visualized in Figure 6. It presents that the utilized area is obviously less than the non-utilized area for all selected shelters. For shelter 43, the proportion of utilized area is the largest amongst all of 47 shelters with the value of 0.269. Thus, as the proportion of non-utilized area for all selected shelters is more than 0.5, each selected shelter has sufficient room to house relief workers and volunteers. Also, there is enough room for relief assets storage and movement of evacuees.

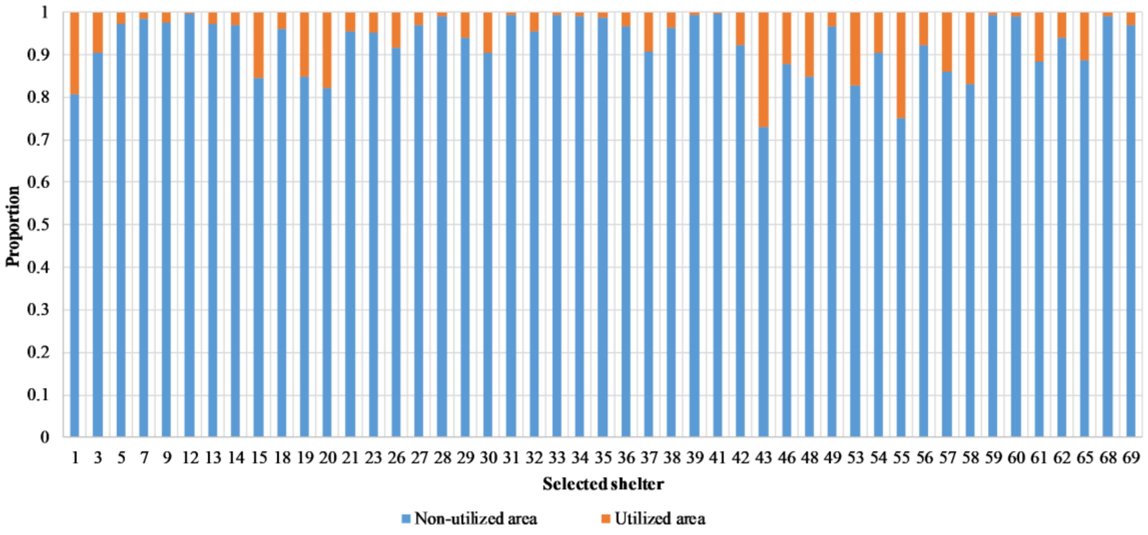


Figure 6 Proportion of utilized area and non-utilized area of each selected shelter

The result aforementioned is derived from solving the model with distance constraint described in subsection ‘Shelter location-allocation model’. However, if the evacuees are not sensitive to long distance, the result will be different. Also, if the evacuees only pay attention to evacuation time neglecting the comfor level, the objective will be the mere minimization of total evacuation time. To compare with the model proposed in this paper, a model without distance constraint and a model with the objective to minimize total weighted evacuation time as shown in Equation (14) are also solved using MPSO algorithm.

$$\min f_3 = \sum_{j=1}^{M}\sum_{k=1}^{N}\frac{d_{kj}}{v_j}\times\frac{P_j}{W_{kj}}\times B_{kj} \qquad \forall k=1,2,\ldots\ldots,N \quad \forall j=1,2,\ldots\ldots,M \tag{14}$$

The location of the candidate shelters selected and how the 463 communities are allocated to them obtained using the aforementioned two models are shown in Figure 7(a) and Figure 7(b) respectively. In Figure 7(a), it can be seen that there are 46 shelters being selected. It is less than 47 shelters obtained using the model with distance constraint as shown in Figure 4. However, some communities would be allocated to shelters that the distances are too long. Figure 7(b) presents locations of 65 selected shelters and the allocation of communities to them. It indicates that the number of shelters needed is more than that of the models with the two objectives proposed in this paper and the values of both f_1 and f_2 for this solution is more than those of the solution obtained by the bi-objective model.

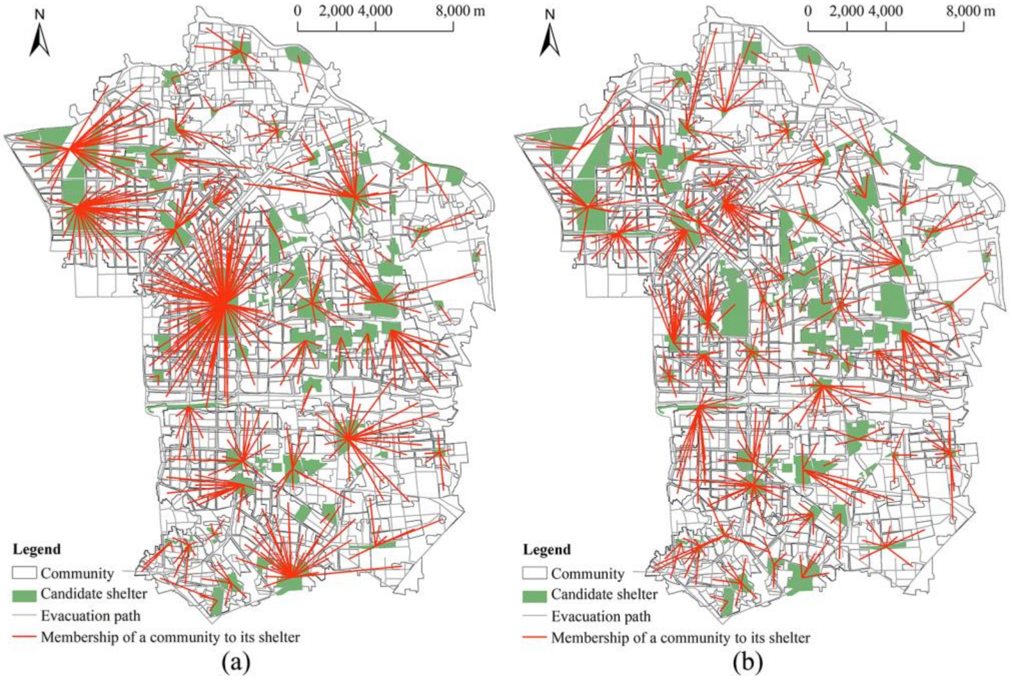


Figure 7 Location-allocation results of the model without distance constraint and the model to minimize total evacuation time

CONCLUSION

The aim of this paper is to present preliminary work in solving the proposed earthquake disaster shelter location-allocation problem. Findings in this work will facilitate future efforts for developing a more realistic mathematical model.

In this paper, a mathematical model with two objectives is proposed with capacity and distance constraints. The result obtained using this model is compared with a model without distance constraint and a model with objective to minimize total evacuation time, respectively. It is observed that the model proposed in this paper enables the balance between evacuation time and comfort level. In terms of further work, a number of improvements will be made to the mathematical model. For example, comfort level will be calculated dynamically rather than statically as in this paper. Also, other objectives can be considered in terms of the specifications of earthquake shelters such as construction cost and damage risk. Also, the changing situations of volume of evacuees and damages to road networks caused by an earthquake will be considered. Moreover, improvement of the heuristic optimization algorithm will be carried out for more rapid and accurate problem solving.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support provided by National Natural Science Foundation of China and Macau Science and Technology Development Joint Fund (NSFC-FDCT) (No. 71861167002).

REFERENCES

Alçada-Almeida, L., Tralhão, L., Santos, L., & Coutinho-Rodrigues, J. (2009). A multiobjective approach to locate emergency shelters and identify evacuation routes in urban areas. *Geographical Analysis*, *41*(1), 9–29. https://doi.org/10.1111/j.1538-4632.2009.00745.x

Barzinpour, F., & Esmaeili, V. (2014). A multi-objective relief chain location distribution model for urban disaster management. *International Journal of Advanced Manufacturing Technology*, *70*(5–8), 1291–1302. https://doi.org/10.1007/s00170-013-5379-x

Bayram, V., Tansel, B. T., & Yaman, H. (2015). Compromising system and user interests in shelter location and evacuation planning. *Transportation Research Part B: Methodological*, *72*, 146–163. https://doi.org/10.1016/j.trb.2014.11.010

Beijing Municipal Institute of City Planning & Design. (2007). Planning of earthquake and emergency shelters in Beijing central districts (outdoors). Retrieved from http://xch.bjghw.gov.cn/web/static/articles/catalog_84/article_7491/7491.html

Bilham, R. (2010). Lessons from the Haiti earthquake. *Nature*, *463*(7283), 878–879. https://doi.org/10.1038/463878a

Chen, W.-F., & Scawthorn, C. (2003). *Earthquake Engineering Handbook* (Vol. 332). https://doi.org/10.1126/science.332.6028.412

Chen, Z., Chen, X., Li, Q., & Chen, J. (2013). The temporal hierarchy of shelters: A hierarchical location model for earthquake-shelter planning. *International Journal of Geographical Information Science*, *27*(8), 1612–1630. https://doi.org/10.1080/13658816.2013.763944

Clerc, M., & Kennedy, J. (2002). The particle swarm - explosion, stability, and convergence in a\nmultidimensional complex space. *IEEE Transactions on Evolutionary Computation*, *6*(1), 58–73. https://doi.org/10.1109/4235.985692

Colorni, A., Dorigo, M., & Maniezzo, V. (1991). Distributed Optimization by Ant Colonies. In *Proceedings of the first European Conference on Artificial Life* (Vol. 142, pp. 134–142). https://doi.org/10.1016/S0303-2647(97)01708-5

Doerner, K. F., Gutjahr, W. J., & Nolz, P. C. (2009). Multi-criteria location planning for public facilities in tsunami-prone coastal areas. *OR Spectrum*, *31*(3), 651–678. https://doi.org/10.1007/s00291-008-0126-7

Gall, M. (2004). Where to Go? Strategic Modelling of Access to Emergency Shelters in Mozambique. *Disasters*, *28*(1), 82–97. https://doi.org/10.1111/j.0361-3666.2004.00244.x

Gama, M., Scaparra, M. P., & Santos, B. (2013). Optimal location of shelters for mitigating urban floods. In *EURO Working Group on Transportation* (Vol. 00).

Gates, B. T. J., Noyce, D. A., Bill, A. R., Van Ee, N., & Gates, T. J. (2006). Recommended Walking Speeds for Pedestrian Clearance Timing Based on Pedestrian Characteristics. *Transportation Research Record: Journal of the Transportation Research Board*, (Volume 1982 / 2006), 38–47. https://doi.org/10.3141/1982-07

Goldberg, D. (n.d.). AG-1-David E. Goldberg Genetic Algorithms in Search, Optimization, and Machine Learning.pdf.

Hakimi, S. L. (1964). Optimum locations of switching centers and the absolute centers and medians of a graph. *Operations Research*, *12*(3), 450–459. https://doi.org/10.1287/opre.12.3.450

Hakimi, S. L. (1965). Optimum Distribution of Switching Centers in a Communication Network and Some Related Graph Theoretic Problems. *Operations Research*. https://doi.org/10.1287/opre.13.3.462

Hu, F., Xu, W., & Li, X. (2012). A modified particle swarm optimization algorithm for optimal allocation of earthquake emergency shelters. *International Journal of Geographical Information Science*, *26*(9), 1643–1666. https://doi.org/10.1080/13658816.2011.643802

Hu, F., Yang, S., & Xu, W. (2014). A non-dominated sorting genetic algorithm for the location and districting planning of earthquake shelters. *International Journal of Geographical Information Science*, *28*(7), 1482–1501. https://doi.org/10.1080/13658816.2014.894638

Kennedy, J., & Eberhart, R. (1995). Particle Swarm Optimization. In *Proc. of IEEE International Conference on Neural Networks* (Vol. 5, pp. 1942–1948).

Kilci, F., Kara, B. Y., & Bozkaya, B. (2015). Locating temporary shelter areas after an earthquake: A case for Turkey. *European Journal of Operational Research*, *243*(1), 323–332. https://doi.org/10.1016/j.ejor.2014.11.035

Kirkpatrick, S., Gelatt, C. D., & Vecchi, M. P. (1983). Optimization by Simulated Annealing. *Science*, *220*(4598), 671–680. https://doi.org/10.1126/science.220.4598.671

Kongsomsaksakul, S., Yang, C., & Chen, A. (2005). Shelter location-allocation model for flood evacuation planning. *Journal of the Eastern Asia Society for Transportation Studies*, *6*(1981), 4237–4252. https://doi.org/10.11175/easts.6.4237

Ng, M. W., Park, J., & Waller, S. T. (2010). A Hybrid Bilevel Model for the Optimal Shelter Assignment in Emergency Evacuations. *Computer-Aided Civil and Infrastructure Engineering*, *25*(8), 547–556. https://doi.org/10.1111/j.1467-8667.2010.00669.x

Norio, O., Ye, T., Kajitani, Y., Shi, P., & Tatano, H. (2011). The 2011 eastern Japan great earthquake disaster: Overview and comments. *International Journal of Disaster Risk Science*, *2*(1), 34–42. https://doi.org/10.1007/s13753-011-0004-9

Rodríguez-Espíndola, O., & Gaytán, J. (2015). Scenario-based preparedness plan for floods. *Natural Hazards*, *76*(2), 1241–1262. https://doi.org/10.1007/s11069-014-1544-2

Sanyal, J., & Lu, X. X. (2009). Ideal location for flood shelter: A geographic information system approach. *Journal of Flood Risk Management*, *2*(4), 262–271. https://doi.org/10.1111/j.1753-318X.2009.01043.x

Sherali, H. D., Carter, T. B., & Hobeika, A. G. (1991). A location-allocation model and algorithm for evacuation planning under hurricane/flood conditions. *Transportation Research Part B*, *25*(6), 439–452. https://doi.org/10.1016/0191-2615(91)90037-J

Toregas, C., Swain, R., ReVelle, C., & Bergman, L. (1970). The Location of Emergency Service Facilities. *Operations Research*, *19*(6), 1363–1373. https://doi.org/10.1287/opre.19.6.1363

Widener, M. J., & Horner, M. W. (2011). A hierarchical approach to modeling hurricane disaster relief goods distribution. *Journal of Transport Geography*, *19*(4), 821–828. https://doi.org/10.1016/j.jtrangeo.2010.10.006

Xu, W., Ma, Y., Zhao, X., Li, Y., Qin, L., & Du, J. (2017). A comparison of scenario-based hybrid bilevel and multi-objective location-allocation models for earthquake emergency shelters: a case study in the central area of Beijing, China. *International Journal of Geographical Science*. https://doi.org/10.1080/13658816.2017.1395882.

Ye, M., Wang, J., Huang, J., Xu, S., & Chen, Z. (2012). Methodology and its application for community-scale evacuation planning against earthquake disaster. *Natural Hazards*, *61*(3), 881–892. https://doi.org/10.1007/s11069-011-9803-y

Yuan, Y. (2008). Impact of intensity and loss assessment following the great Wenchuan Earthquake. *Earthquake Engineering and Engineering Vibration*, *7*(3), 247–254. https://doi.org/10.1007/s11803-008-0893-9

Zhao, X., Coates, G., & Xu, W. (2017). Solving the earthquake disaster shelter location-allocation problem using optimization heuristics.

Zhao, X., Xu, W., Ma, Y., & Hu, F. (2015). Scenario-based multi-objective optimum allocation model for earthquake emergency shelters using a modified particle swarm optimization algorithm: A case study in Chaoyang District, Beijing, China. *PLoS ONE*, *10*(12), 1–16. https://doi.org/10.1371/journal.pone.0144455