Shelter Site Selection and Allocation Model for Efficient Response to Humanitarian Relief Logistics

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Abstract. Shelter sites selection and allocation is the most critical part of humanitarian relief logistics and affects the success of disaster management strategy. This paper presents shelter location allocation model to efficiently respond to relief logistics. The mathematical model is developed to minimize the total cost which combines fixed cost for establishing shelters, transportation cost, and service cost. The model is tested with two scenarios i.e. capacitated shelter and uncapacitated shelter, then compared with the existing location and allocation plan. The Genetic Algorithm is used to solve the model. The numerical experiment with the case study of the flood in Tha Uthae, Surat Thani, Thailand is employed to demonstrate the application of the proposed model. The results obtained from this proposed model clearly outperform the current plan. Moreover, the sensitivity analysis is conducted to observe how the cost structure changed when the parameter is adjusted. The obtained results are constructive for decisionmakers to determine the appropriate strategies for disaster management.

Keywords: Humanitarian logistics · Emergency logistics · Discrete facility location · Optimization · Cost structure · Disaster management

1 Introduction

In the past, disasters have caused enormous damage to humanity and have had a tremendous impact on the economy. According to a report by the Centre for Research on the Epidemiology of Disasters (CRED), natural disasters in 2018 resulted in 67,572 deaths, affected 198.8 million people, and caused $166.7 billion worth of economic losses worldwide. Floods had the most drastic effects on people when compared with other types of disasters, and the Asian continent was most affected by catastrophes [7]. Due to severely damaging effects, many academicians turned their attention to the study of which involves preparedness, mitigation and effective response to catastrophes in order to reduce

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its devastating impacts [15]. Furthermore, it leads to an increase in humanitarian relief logistics research. Humanitarian logistics aims to relieve the victims' suffering through the processes of evacuating the victims from affected areas to safe places by planning, and implementing and controlling the flow and storage of products with the given financial budget [2,6,23]. To achieve the purposes of humanitarian logistics, the optimization models are proposed to cope with diverse important criteria such as effectiveness, efficiency, or equity. These criteria are demonstrated through either single objective optimization or multi-objective optimization which incorporates various criteria simultaneously. For effectiveness view, the response time, transportation distance, coverage, and reliability are determined. Equity is considered according to fairness in accessing resources, while efficiency focuses on controlling the set of costs [21]. In this context, cost criteria cannot be ignored since it involves the investment of money, funds, as well as private donors [10].

Apart from helping the victims escape natural catastrophes, finding the necessary facilities, especially temporary shelters for victims who cannot stay at their homes, is important to consider before the disasters occur [19]. Without the appropriate methods required to determine the characteristics of the environment requiring relief, organizations may make ad-hoc decisions which lead to high costs, waste of resources, sluggish response, and failure to satisfy demands [2]. Therefore, decision-making regarding shelter sites selection and allocation is the most critical part of humanitarian relief logistics since it influences securement, equity, efficiency, effectiveness, and affects the success of the strategy [2,5,13,16,24]. Moreover, accommodation for victims should be provided adequately and according to the standards for evacuation shelters. The necessary resources should include portable restrooms, temporary kitchen, temporary warehouse, vehicles for mobilizing the victims, and staffs for assisting the victims during their stay in the shelters [13].

By considering the aforementioned issues, this research aims to propose mixed integer nonlinear programming to define the optimal number of shelters, to select the shelters for victims, and to assign the affected area to the appropriate shelters with the appropriate cost. The model corresponds to both capacitated and uncapacitated shelters. The obtained results from the model are compared with the current shelter site selection plan announced by the Department of Disaster Prevention and Mitigation. The repeatedly flooded areas in Tha Uthae Subdistrict, Surat Thani, Thailand is selected as the case study of shelter location and allocation problem.

2 Related Work

Facility location models are categorized into continuous facility location and discrete facility location. For continuous location, the facilities are allowed to be placed anywhere within the planning continuous area, whereas discrete location, also referred to as discrete space, permits the finite set of potential facilities that are predestined to be selected [3,4,18,20]. Facility, in humanitarian logistics, includes emergency medical centers, warehouse or distribution centers, and emergency shelters. Research related to site selection for placing emergency medical locations and warehouses has been widely conducted, but research on shelter site selection is still fairly unexplored [19].

To evaluate the relief effort, cost efficiency is the criteria that decision makers use to determine resource utilization. Moreover, significant factors such as capacity, budget, and transportation modes are also considered [21]. There are existing literature on facility location that were employed in the humanitarian logistics field. Horner et al. [11] present a GIS-based method for selecting the special needs shelter for elderly casualties during a hurricane, with the objective of minimizing transportation cost. In this regard, shelters' capacity and the desired number of shelters to be located are identified. Lin et al. [14] propose the location allocation model for placing the temporary depot around the earthquake-affected area. The purpose is to minimize transportation and penalty costs caused by unmet demand, delayed delivery, and service unfairness among demand points. Hu et al. [12] study shelter site selection for response to the earthquake in Beijing, China. In their research, the bi-objective model is used for minimizing the distance and total cost of shelter construction. The Nondominated Sorting Genetic Algorithm is employed to improve both effectiveness and efficiency performances. Ahmadi et al. [1] formulate the mixed integer nonlinear programming to determine the location of depots and define routing for last mile transportation. With regard to location decision, they aim to minimize the traveling time, the penalty cost of unmet demand, and the fixed cost of opening the depot. The proposed model is applied in the case study of the earthquake in San Francisco.

Aforementioned literature reveals that the facility location problem in the context of humanitarian relief logistics received attention from researchers and was applied to identify the appropriate location in preparation and response to various kinds of disasters. Other than efficiency-based facility location models which take into account the cost of operation, there are various research papers focused on the responsiveness and effectiveness criteria (i.e. time, coverage, and distance [5,9,17]). However, the study of efficient location allocation of shelter is still fairly unexplored when compared with other facilities. Cost efficiency is the noteworthy criteria that reflects the use of resources and is the indicator to measure how well limited resources are utilized. Moreover, cost criteria also helps decisionmakers to plan and allocate the budget for response and prepare sufficiently. Therefore, this study aims to present the shelter location allocation model to decide which shelters should be selected, and which affected areas should be assigned to the appropriate shelters.

3 Methodology

In this section, the mathematical model is proposed for shelter site selection and allocation. The objective of this model is to minimize the total cost which includes the fixed cost of opening the shelters, the transportation cost of victim mobilizing, and the service cost during the victims' stay in the shelter; this is calculated based on the cost of staff hiring. The shelter site selection and allocation are determined both in aspects of *"capacitated shelter"* and *"uncapacitated shelter"* for providing the alternative for decisionmakers. First, the candidate shelters are predetermined. The data that are used to formulate the model includes the number of victims in each affected area, traveling distance, shelters' capacity, fixed cost for opening shelters, transportation cost, and duration of the disaster. The model assumes that the victims in each affected area are mobilized as an entire unit and not separately assigned to different shelters, that all affected areas are faced with the disaster at the same time, that the number of victims and location of the candidate shelters are fixed, and that the vehicles used in evacuation process are homogenous. In this study, the Genetic Algorithm is employed to solve the proposed model since it avoids getting trapped with the local optimal solution, and successfully used to deal with many location and allocation problems.

Set

I	Set of affected area i
J	Set of candidate shelter j

Parameters

d_{ij}	Distance between affected area i and candidate shelter j
c_j	Capacity of the candidate shelter j
h_i	Number of victims in area i
f_j	Fixed cost of opening the shelter j
M	Maximum acceptable distance between affected area and shelter
α	Constant coefficient of transportation cost per kilometer per person
β	Wage per person for hiring staff to work in the shelter
γ	Ratio of the required staff per victims
T	Duration of the disaster occurrence

Decision variable

X_j	1, if candidate shelter j is selected or otherwise 0
Y_{ij}	1, if affected area i is assigned to candidate shelter j or otherwise 0
Z_{ij}	The victim in area i is assigned to candidate shelter j

The model can be formulated as follows:

$$min \quad \sum_{j \in J} x_j f_j + \alpha \sum_{i \in I} \sum_{j \in J} d_{ij} y_{ij} h_i + \beta T \sum_{i \in I} \frac{Z_{ij}}{\gamma} \tag{1}$$

Subject to

$$\sum_{j\in J} y_{ij} = 1, \quad \forall_{\mathrm{i\in I}} \tag{2}$$

$$y_{ij} \leq x_j, \quad \forall_{i\in I, j\in J} \tag{3}$$

$$d_{ij} y_{ij} \leq M \quad \forall_{i\in I, j\in J} \tag{4}$$

$$\sum_{i\in I} z_{ij} \leq c_j x_j \quad \forall_{j\in J} \tag{5}$$

$$\sum_{j\in J} z_{ij} = h_i \quad \forall_{i\in I} \tag{6}$$

$$x_j \in \{0,1\} \quad \forall_{j\in J} \tag{7}$$

$$y_{ij} \in \{0,1\} \quad \forall_{i\in I, j\in J} \tag{8}$$

The objective function (1) is to select the shelter that generates minimum total cost which includes the fixed cost for opening the shelter, transportation cost, and service cost. Constraint (2) identifies that each affected area will be entirely assigned to only one shelter. Constraint (3) restricts each affected area to be allocated to only selected shelters. Constraint (4) ensures that the distance between affected area and selected shelter does not exceed the maximum acceptable distance. Constraint (5) ensures that the number of assigned victims does not exceed the capacity of selected shelter. Constraint (6) identifies the constraint of the number of victims in each affected area. Constraints (7) and (8) states the binary variable in the model.

4 Case Study

The flood case study in Tha Uthae, Surat Thani of Thailand is applied to the proposed model for selecting the shelters as well as assigning the victims to the shelter with the minimum total cost. The terrain of Tha Uthae is a lowland and repeatedly faces flooding during the rainy season. Normally, the Department of Disaster Prevention and Mitigation, Ministry of Interior is the agency that decides the evacuation shelters for each community based on their administrative area. A majority of the candidate shelters are schools, city halls, or temples. However, the assigned shelters are rather decentralizing than centralizing.

The historical data of the 2011 floods in Tha Uthae which was gathered by Surat Thani National Statistical Office [22] are used in this study. There were 10 affected areas, 20 potential shelters, and 5,076 victims that suffered due to the floods. The distance between affected areas and candidate shelters are estimated from the given coordinates using the Euclidean distance. In this study, the maximum acceptable distance for each route is assumed to be 10 km. The vehicles that are used for victim transportation belong to the Royal Thai Army. The truck capacity is 12 persons and the fuel consumption rate 8 km per liter.

For shelter capacity, the schools that are utilized as shelter can contain 2,000 victims, as suggested by JICA [9]; other shelters that are not the schools can accommodate 500 victims. Although there are no construction costs since existing facilities are used as shelter, related costs for opening the shelters still need to be included, such as costs for portable toilets, tents to use as a temporary kitchen, medical center, and warehouse [8], which hereafter are defined as the fixed cost.

To estimate the service cost that occurs when serving the victims during the time they reside in the shelter, the cost of staff hire is determined. Although assisting the victims is volunteer work, government staffs are still paid by their agencies. In this case, the standard wage of 380 Thai Baht per person per day is taken into account. The number of required staff is 1 staff per 50 victims [8]. The average duration of the disaster occurrence based on historical data is 6 days. Tables 1 and 2 are the parameters that are used in the numerical experiment.

Table 1. Affected area and number of victims

Affected area	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
No. of victims (person)	750	540	400	800	650	250	350	450	500	386

Table 2. Candidate shelters, capacity, and fixed cost

Candidate shelters	Capacity	Fixed cost (THB)
S1, S3, S5, S6, S8, S10, S11, S14, S15, S16, S17, S19, S20	500	114,000
S2, S4, S7, S9, S12, S13, S18	2,000	144,000

5 Results and Discussion

5.1 Computational Results

Table 3 shows the results generated by the proposed model. The number of selected shelters, shelter allocation, and total cost of both capacitated and uncapacitated shelters are compared with the current shelter assignment announced by the government agency. "Capacitated shelter" considers the restrictions of capacity and that the maximum acceptance distance does not exceed 10 km. There are 5 selected shelters—S7, S12, S18, S19, and S20—to serve the victims. The shelter utilization rates are 40%, 89.3%, 77%, 90%, and 100% respectively and the total cost is 899,471 Thai Baht.

For "uncapacitated shelter", the capacity in constraint 5 is ignored. It reveals that only small shelters which generate cheaper costs and are located within the acceptable distances of 10 km are chosen. There are 3 selected shelters include S3, S6, and S20. The number of selected shelters and the total cost are less than that of the capacitated shelters. Since the objective function is not bound by the capacity restriction, the model then seeks to select a few shelters which are located in the acceptable distance to minimize the total cost. The total cost of 3 selected shelters is 580,891 Thai Baht. However, uncapacitated shelters would be difficult to employ in a practical manner due to overabundantly assigning the victims to particular shelters, which leads to congestion and will eventually affect the victims' welfare.

Both capacitated and uncapacitated shelters are compared to the current shelter assignment planned by the government sector. The numerical experiment reveals that the service cost of all plans remain constant, as shown in Table 3, since the number of victims is not changed and all victims are rescued. Moreover, it is evident that the current plan fails to achieve cost efficiency because there are 10 shelters that are selected and allocated based on their administrative area. The shelter allocation is decentralized and causes the setup cost to be unavoidably higher. Likewise, the total cost obtained from the proposed model, both capacitated shelter and uncapacitated shelter is lower than the current plan as 40.02% and 61.26% respectively.

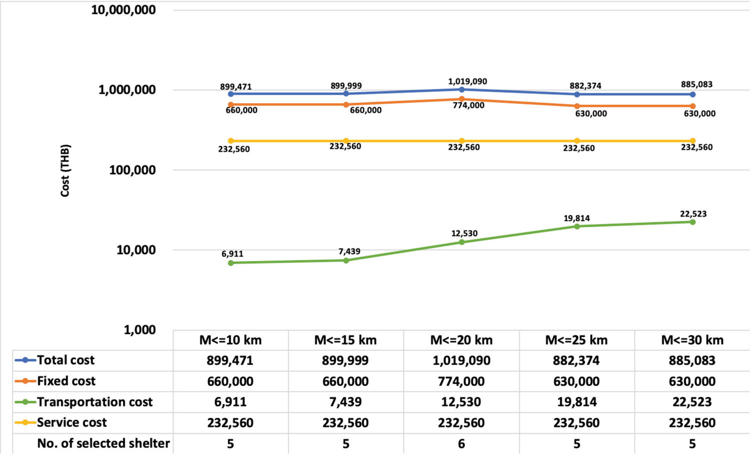
Table 3. The result of case study with acceptable distance not over 10 km

Affected area	Capacitated shelter	Uncapacitated shelter	Current plan
A1	S12	S20	S12
A2	S18	S6	S13
A3	S18	S6	S14
A4	S7	S6	S6
A5	S12	S20	S15
A6	S18	S20	S16
A7	S18	S20	S17
A8	S19	S3	S18
A9	S20	S20	S19
A10	S12	S20	S7
Setup cost (THB)	660,000	342,000	1,260,000
Transportation cost (THB)	6,911	6,331	7,036
Service cost (THB)	232,560	232,560	232,560
Total cost (THB)	899,471	580,891	1,499,596

5.2 Sensitivity Analysis

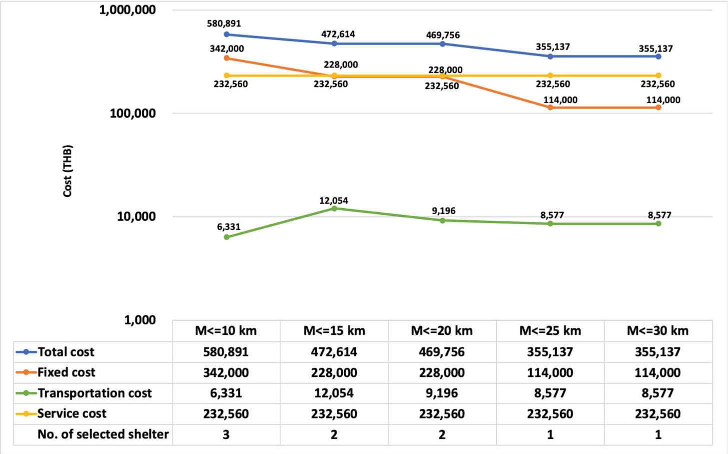
The sensitivity analysis is conducted to demonstrate how parameters influence the objective function and the model. Here, the maximum acceptable distances (constraint 4) are set between 10–30 km to allow the numerical experiment to be more flexible. In the case of capacitated shelter, it is the most cost efficient when the maximum acceptable distance does not exceed 25 km. It is required to select 5 shelters to serve the victims. Relaxing the maximum acceptable distance results in an increase in the transportation cost. On the contrary, the fixed cost of opening the shelter does not increase as the relaxed distance is extended. Meanwhile, the relaxation of distance will not significantly affect the service cost since the constraint strictly ensures that all victims are served thoroughly (see Fig. 1).

For uncapacitated shelter, it shows that, as the maximum acceptable distance is relaxed, the fixed cost of selected shelters decreases. This is because the relaxation of the acceptable distance means that the cheapest shelter can be found and selected without considering the limitation of the shelters' capacity. Since total cost is dominated by fixed cost, it leads the total cost to decrease as the maximum acceptable distance is relaxed (see Fig. 2).



	M<=10 km	M<=15 km	M<=20 km	M<=25 km	M<=30 km
Total cost	899,471	899,999	1,019,090	882,374	885,083
Fixed cost	660,000	660,000	774,000	630,000	630,000
Transportation cost	6,911	7,439	12,530	19,814	22,523
Service cost	232,560	232,560	232,560	232,560	232,560
No. of selected shelter	5	5	6	5	5

Fig. 1. Sensitivity analysis for capacitated shelter with distance 10–30 km



	M<=10 km	M<=15 km	M<=20 km	M<=25 km	M<=30 km
Total cost	580,891	472,614	469,756	355,137	355,137
Fixed cost	342,000	228,000	228,000	114,000	114,000
Transportation cost	6,331	12,054	9,196	8,577	8,577
Service cost	232,560	232,560	232,560	232,560	232,560
No. of selected shelter	3	2	2	1	1

Fig. 2. Sensitivity analysis for uncapacitated shelter with distance 10–30 km

6 Conclusion and Future Research

This study presents the mathematical model for shelter site selection and allocation for efficient response to relief logistics during the disaster. The model is formulated as mixed integer nonlinear programming and solved by Genetic Algorithm in order to achieve cost minimization. The proposed model is tested with the real world case study of the floods in Tha Uthae, Surat Thani, Thailand. The comparisons of the results obtained from this model (i.e. capacitated and uncapacitated shelter and current shelter allocation plan announced by the government) are shown. The comparison indicates that, when using the proposed model, the obtained results outperform the current shelter allocation plan. This study has positive implications for the decisionmakers to develop the appropriate strategies for future work, the model should be extended to large scale optimization. Additionally, uncertainty, such as demand uncertainty or transportation network disruption caused by the disaster, should be determined when formulating the model.

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