Bi-objective Optimization Model for Determining Shelter Location-allocation in Humanitarian Relief Logistics

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Abstract: Shelter location-allocation is very important since it affects victims' security and the performance of the relief supply chain. This paper proposes a bi-objective optimization model for justifying locations of shelters and allocating appropriate shelters to all affected areas efficiently and effectively. The first objective seeks to minimize the total cost, and the second objective attempts to minimize the average victim evacuation time. The Epsilon Constraint method is employed to deal with the bi-objective function. To avoid the inefficient solutions problem, which is likely generated by the Epsilon Constraint approach, the transformed constraint is augmented by the positive constant value of allowance time. A case study of the flood in Phun Phin, Surat Thani, Thailand is used to demonstrate the application of the proposed model. The results obtained from this study could help decision-makers to determine an effective shelter location-allocation plan as well as, more broadly, to develop a disaster management strategy.

1 INTRODUCTION

In 2019, natural disasters were frequent and impacted people and economic systems across the world. According to statistical data from the Centre for Research on the Epidemiology of Disaster, there were 396 natural catastrophes, leading to 11,755 deaths, 95 million affected people, and \$103 billion in economic losses. The Natural Disaster 2019 report reveals that flooding was the most frequent disaster and the main cause of death (CRED, 2019). Humanitarian logistics plays an important role in evacuating victims from the affected areas to safe zones, as well as in distributing the necessary relief supplies to victims efficiently, to the right place, and in the right quantity (Manopiniwes and Irohara, 2014; Thomas, A.; Kopczak, 2005). Furthermore, determining the location of relief facilities such as shelters, distribution centers, and medical centers is a critical decision that should be taken by humanitarian logisticians as well as related relief authorities (Maharjan and Hanaoka, 2018). In this regard, seeking proper shelters to serve victims is the most important issue to be decided prior to the disaster (Ozbay et al., 2019) since it affects victims' security and influences the success of disaster management more broadly (Balcik and Beamon, 2008; Verma and Gaukler, 2015; Kongsomsaksakul and Yang, 2005).

Considering several important criteria simultaneously could help related authorities to efficiently and effectively develop an appropriate shelter location-allocation plan. This research proposes a bi-objective optimization model for determining adequate shelter location-allocation. The considered criteria include 1) total cost combining fixed cost for opening shelters, victim evacuation cost, and service cost; and 2) victim evacuation time. The proposed model is tested with a case study of the 2011 flood in Phun Phin district, Surat Thani, Thailand (Surat Thani National Statistical Office, 2012). The remainder of this paper is organized as follows. Section 2 discusses related work in this field. Section 3 presents the proposed methodology, which encompasses parameters, model formulation, and solution method. Section 4 describes the flood case study. Section 5 provides the numerical experiment results. Finally, Section 6 outlines the conclusions made from this study.

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2 RELATED WORK

The selection of appropriate locations for relief facilities influences victims' lives and the flow of services and relief supplies. Furthermore, it has a long-term impact, affecting the success of disaster management (Boonmee et al., 2017; Haghani, 1996). Typical relief facilities include shelters, warehouses, distribution centers, medical centers, and prevention centers. The issue is not only to select the right locations but also to allocate the proper facilities to the affected areas (Boonmee et al., 2017).

A lot of research has been conducted related to facility location-allocation in the area of humanitarian logistics and disaster management. For the shelter location-allocation problem, the mathematical models are formulated as single objective, bi-objective, and multi-objective functions. The typical goal is to improve either the efficiency or effectiveness of the humanitarian logistics performances. The models aimed at improving effectiveness are developed to minimize evacuation time, the number of opened shelters, distance, and demand weighted distance (Kongsomsaksakul and Yang, 2005; Qin et al., 2018; Görmez et al., 2011; Ozbay et al., 2019; Chanta and Sangsawang, 2012), whereas the models aimed at improving efficiency are developed to minimize transportation cost, the cost of opening the shelters, and other operation costs (Horner and Downs, 2010; Praneetpholkrang and Huynh, 2020). A relatively small number of studies consider both effectiveness and efficiency simultaneously e.g. by maximizing demand coverage and minimizing operating cost (Hallak et al., 2019), minimizing distance and total cost (Rodríguez-Espíndola and Gaytán, 2015), minimizing distance together with minimizing cost of opening shelters (Hu et al., 2014), or minimizing maximum response time and minimizing total cost (Manopiniwes and Irohara, 2017). Several pieces of research related to other relief facilities—e.g. warehouse, distribution center, and healthcare—have also been conducted. Such models aim to maximize the demand coverage of the distribution center (Balcik and Beamon, 2008). Others attempt to maximize demand coverage, maximize the number of healthcare facilities, and minimize total cost (Miç and Koyuncu, 2019), or to minimize transportation time and unmet demand, and minimize operation cost for locating warehouses (Mete and Zabinsky, 2010). Determining both criteria simultaneously means that, when seeking to minimize cost, the responsiveness level would be lower and vice versa.

The previous research is illustrated with case studies on floods, earthquakes, hurricanes, and conflict areas; they are usually solved using various methods such as the Exact Algorithm, Weighted Sum Method, Epsilon Constraint, and Weighted Goal Programming. The methods that involve the assignment of weights to indicate the relative importance of each objective are not suitable for solving multi-objective optimization models in the context of humanitarian logistics, as monetary and non-monetary objective functions are both involved. In these scenarios, victims' welfare is very important and cannot be ignored. On the other hand, the related authorities need to save costs and resources to prevent scarcity during unexpected situations. Therefore, the decision-makers are under pressure both in terms of victims' welfare and the related costs, so these must be balanced in the proposed model through the use of multi-objective methods.

3 PROPOSED METHODOLOGY

The necessary data—i.e. number of victims, shelter's capacity, vehicle's capacity, fixed cost for open shelter, ratio of required staff, and duration of disaster—are gathered to formulate the mathematical model. Unlike other prior works, this study considers the ideal minimum distance between the affected area and candidate shelter (m_{ij}) that would be safe from the disaster range. The m_{ij} is calculated based on the number of victims and population density. However, the locations of selected shelters should not be farther than the maximum acceptable distance (M_{ij}). The assumption of the model, model formulation, and the solution methods are outlined in the next section.

3.1 Model Formulation

The assumptions of the model are as follows:

- The number of victims in each affected area is known and constant
- The locations of all affected areas and candidate shelters are fixed
- The victims in each affected area will be allocated to the same shelter
- The vehicles used in the evacuation process are homogeneous
- The velocity of the vehicles is constant; the traffic conditions are not taken into account

Indices

I Set of affected areas

J Set of candidate shelters

Parameters

d_{ij} Distance between area i and shelter j
c_j Capacity of the shelter j
h_i Number of victims in area i
f_j Fixed cost for opening the shelter j
m_{ij} Minimum distance between area i and shelter j
C Capacity of vehicle
M_{ij} Maximum distance between area i and shelter j
N Number of vehicles for evacuation process
W Target time for evacuating the victims from area i to shelter j
α Constant coefficient of transportation cost per kilometer per person
β Wage per person per day for hiring staff to work in the shelter
γ Ratio of the required staff per victim
T Duration of the disaster occurrence
V Velocity of the vehicle that is used in evacuation process

Decision Variables

x_j 1, if shelter j is selected or otherwise 0
y_{ij} 1, if area i is assigned to shelter j or otherwise 0
z_{ij} Number of victims in area i that are assigned to shelter j

Objective Functions

Minimize

$$f_1 = \sum_{j\in J} x_j f_j + \alpha \sum_{i\in I}\sum_{j\in J} d_{ij} y_{ij} h_i + \beta T \sum_{i\in I} \frac{z_{ij}}{\gamma} \quad (1)$$

The first objectives function (1) seeks to minimize total cost, which combines fixed cost for opening shelters, victims' transportation cost, and service cost that is paid during the victims' stay.

Minimize

$$f_2 = \sum_{i\in I}\sum_{j\in J} \frac{d_{ij} y_{ij}}{V} \cdot \frac{h_i}{NC} \quad (2)$$

The second objective function (2) is to minimize victim evacuation time, the distance between affected areas and allocated shelters, the number of available vehicles, vehicle capacity, and the velocity of the vehicle during the flood.

Subject to

$$\sum_{j\in J} y_{ij} = 1, \quad \forall_{i\in I} \quad (3)$$

Constraint (3) defines that the affected area i must be entirely allocated to a single shelter

$$y_{ij} \leq x_j, \ \forall_{i\in I, j\in J} \quad (4)$$

Constraint (4) expresses that the affected area i must be assigned to the opened shelter j

$$d_{ij} y_{ij} \geq m_{ij}, \ \forall_{i\in I}, _{j\in J} \quad (5)$$

Constraint (5) defines that the distance between an affected area i to assigned shelter j must be farther than the minimum acceptable distance m_{ij}

$$d_{ij} y_{ij} \leq M_{ij}, \ \forall_{i\in I}, _{j\in J} \quad (6)$$

Constraint (6) limits the distance between an affected area i to assigned shelter j to the maximum acceptable distance M_{ij}

$$\frac{d_{ij} y_{ij}}{V} \cdot \frac{h_i}{NC} \leq W, \ \forall_{i\in I}, _{j\in J} \quad (7)$$

Constraint (7) restricts victim evacuation time to the target time for evacuation

$$\sum_{i\in I} z_{ij} \leq c_j x_j, \ \forall_{j\in J} \quad (8)$$

Constraint (8) ensures that the numbers of assigned victim do not exceed the capacity of shelter j

$$x_j \in \{0,1\}, \quad \forall_{j\in J} \quad (9)$$

Constraint (9) defines the binary variable; x_j is 1 if candidate shelter is selected, otherwise it is 0

$$y_{ij} \in \{0,1\}, \quad \forall_{i\in I}, _{j\in J} \quad (10)$$

Constraint (10) defines the binary variable; y_{ij} is 1 if affected area i is allocated to candidate shelter j, otherwise it is 0.

3.2 Solution Approach

In solving the multi-objective optimization with the Epsilon Constraint method, only one objective is assigned as the primary objective function, and the other objective functions become constraints. Employing the Epsilon Constraint method to solve the multi-objective problem is formulated as follows (Deb, 2008; Mavrotas, 2009):

Objective Function

$$Min \quad f_1 \quad (11)$$

Subject to

$$f_2(x) \leq \varepsilon_2 \tag{12}$$

$$f_3(x) \leq \varepsilon_3 \tag{13}$$

$$...$$

$$f_n(x) \leq \varepsilon_n \tag{14}$$

$$X \in S \tag{15}$$

Where x is the vector of decision variables, $f_1(x),...,f_n(x)$ and n is the objective function, and $n \geq 2$, S is the feasible region.

However, the Epsilon Constraint method requires intensive computational effort to obtain the Pareto solution and the obtained epsilon value is sometimes inappropriate for use as the constraint for the primary objective function (Mavrotas, 2009; Xiujuan and Zhongke, 2004). The objective function with a positive constant helps to avoid the inefficient solutions problem (Görmez et al., 2011). Therefore, the f_2 that seeks to minimize victim evacuation time is augmented by the allowance time, which encompasses personal needs (such as restroom or break times), fatigue, and delay. We take into account the fatigue allowance to account for the exhaustion of the physical and mental strength of the staff, while the delay allowance factors in delays during the transportation (Mital et al., 2016) for a total allowance time of 20% of the ordinary time. The augmented objective function is in Equation 17, where δ is the constant coefficient of allowance time for evacuating victims. Thus, solving bi-objective function problem with the Epsilon Constraint method can be formulated as follows:

Objective Function

$$Min \quad f_1 \tag{16}$$

Subject to

$$\delta \sum_{i \in I} \sum_{j \in J} \frac{d_{ij} y_{ij}}{V} \cdot \frac{h_i}{NC} \leq \varepsilon_{f_2} \tag{17}$$

(3) - (11)

The numerical experiment was conducted using the What'sBest LINDO Optimization tool on a Microsoft Windows 10 laptop with Intel(R) Core (TM) 1.51 GHz, RAM 4.0 GB.

4 CASE STUDY

The major flood in Phun Phin of Surat Thani, Thailand in 2011 is used as a case study to demonstrate the application of the proposed model. Phun Phin is located in the southern part of Thailand and experiences repeated floods, especially in rainy season. The international airport is located in this city and it is also the main agricultural area of the southern part of Thailand. According to the statistical data on flooding in the area in 2011, there were five neighborhoods that are henceforth defined as affected areas. The numbers of residents in these areas amounts to 1,965 people, while the total estimated numbers of victims who suffered from the flood were 1,434 people, as illustrated in Table 1.

There were four candidate shelters (S1-S4), consisting of existing facilities such as schools, temples, municipalities, or city halls, that were normally utilized to serve as temporary shelters during such disasters (Surat Thani National Statistical Office, 2012). Each shelter can accommodate 3,000 victims; there was no construction cost since they were all existing infrastructure. Nevertheless, a fixed cost for opening the shelters was still required for installing portable toilets, temporary kitchens, medical centers, and warehouses, at an estimated 144,000 Thai Baht per shelter.

As the locations of both the affected areas and candidate shelters are known, the road network distance can be obtained through the Google Maps Distance Matrix API. The vehicles that were used in the evacuation process could transport 12 victims per trip. The fuel consumption rate was 8 kilometers per liter. During the flood, the vehicles' speed was 24 kilometer per hour, based on the estimated function of flood depth and vehicle speed (Pregnolato et al., 2017); this was assumed to be constant. Furthermore, the government authorities had to pay the service cost required for the duration of the victims' stays. This cost was estimated based on the number of required staff i.e. one staff per 50 victims (Department of Disaster Prevention and Mitigation, Ministry of Interior, 2011). The staff's wage was 380 Thai Baht per person per day. The length of time for accomplishing the victim evacuation process was set at no longer than 72 hours, which aligns with the standard time accepted in the disaster management field (Ahmadi et al., 2015).

Table 1: Number of victims in each affected area.

Affected area	No. of victims
A1	325
A2	310
A3	320
A4	230
A5	249

5 NUMERICAL EXPERIMENT RESULTS

The numerical experiment commences by solving each objective function individually, as illustrated in the payoff table (Table 2). The individual optimal solution was found to be is 214,547 Thai Baht, which leads to an evacuation time of 2.67 hours. For the second objective function, which attempts to minimize the victim evacuation time, the optimal solution is 2.57 hours with a total cost of 504,637 Thai Baht. Based on Table 2, the lower and upper limit of the total cost is 214,547 Thai Baht and 504,637 Thai Baht. Meanwhile, the lower and upper limit of the victims' evacuation time is 2.57 hours and 2.67 hours, respectively.

Table 2: Payoff table illustrating the individual optimal solution.

Criteria	Optimal solution	
	Min f_1	Min f_2
Total cost (Thai Baht)	214,547	504,637
Evacuation time (Hours)	2.67	2.57

Table 3: Shelter location-allocation generated by individual optimal solution.

Objective function	Shelter location-allocation
Min f_1	S2: A1, A2, A3, A4, A5
Min f_2	S1: A4 S2: A2, A5 S4: A1, A3

If decision-makers seek to minimize the total cost, there is only one shelter that services all affected areas. If decision-makers prioritize minimizing victim evacuation time, several shelters are required to open in order to reduce the evacuation time between the affected areas and assigned shelters. The numerical experiment results shown in Table 2 and Table 3 reveal the conflict in terms of cost, but the total evacuation time does not vary much. However, simultaneously considering both objective functions to find a compromising solution is a necessity in determining shelter location-allocation, so further steps are required.

Table 4: Total cost, average evacuation time, and shelter location-allocation results.

ε_{f_2}	Total Cost (THB)	Evacuation time (hours)	Shelter-Allocation
2.57	358,609	2.26	S2: A1, A2, A3, A4 S4: A5
2.58	358,688	2.29	S2: A2, A4, A5 S4: A1, A3
2.59	358,688	2.29	S2: A2, A4, A5 S4: A1, A3
2.60	361,281	2.47	S1: A4 S4: A1, A2, A3, A5
2.61	361,281	2.47	S1: A4 S4: A1, A2, A3, A5
2.62	361,281	2.47	S1: A4 S4: A1, A2, A3, A5
2.63	359,120	2.49	S2: A1, A2 S4: A3, A4, A5
2.64	359,189	2.55	S2: A3, A4, A5 S4: A1, A2
2.65	359,189	2.55	S2: A3, A4, A5 S4: A1, A2
2.66	361,550	2.59	S2: A1, A4 S4: A2, A3, A5
2.67	361,550	2.59	S2: A1, A4 S4: A2, A3, A5

Since there is no single optimal solution that can optimize the bi-objective concurrently, the f_1 is set to minimize the total cost, while f_2 is augmented by the 20% allowance time for victims' evacuation and altered to act as an additional constraint (17). Hereafter, ε_{f_2} refers to the values between 2.57 and 2.67 hours that will be used to restrict f_2. Thus, f_1 is solved with 10 sub-problems regarding the value of ε_{f_2} = 2.57, 2.58, ..., 2.67 and bounded by constraints (3)-(10). The Pareto optimal generates the highest and lowest total cost of 358,609 and 361,550 Thai Baht, respectively. The shortest average time for victim evacuation is 2.26 hours and the highest is 2.59 hours. For shelter location-allocation in each period of ε_{f_2}, there are only two shelters that are required to open to serve the victims (Table 4). This reveals that, when the f_2 values are loosened and allowed to increase according to ε_{f_2}, the evacuation time and total cost increase as well. However, relaxing the time restriction to the highest acceptable value of 2.67 does not help to reduce the total cost (Figure 1).

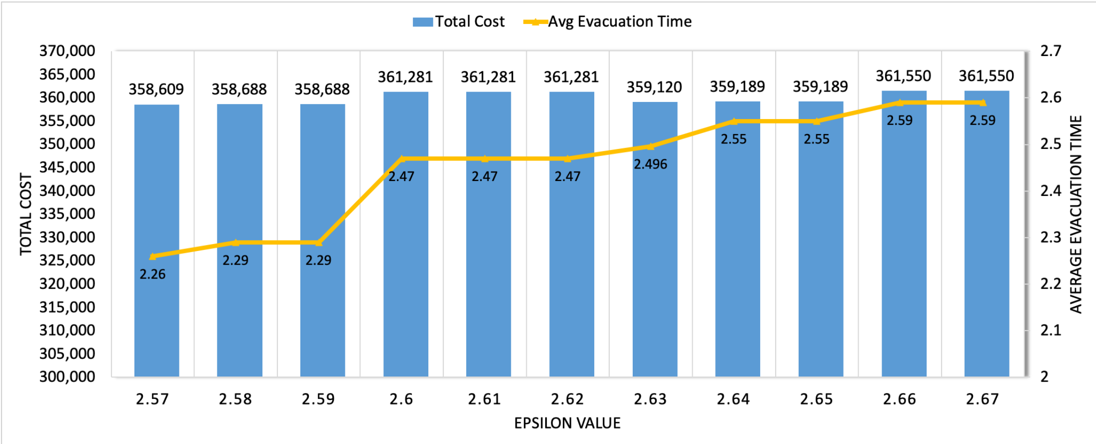

Figure 1: Pareto optimal generated by Epsilon Constraint method.

6 CONCLUSIONS

This study proposes the bi-objective optimization model for determining the appropriate shelter location-allocation in response to a natural disaster. In this case, the proposed model aims at improving the efficiency criterion through minimizing the total cost—which combines the fixed cost for opening shelters, victim evacuation cost, and service cost—while effectiveness is enhanced by minimizing victim evacuation time—which is calculated based on the number of available vehicles, speed, and capacity of the vehicles. The Epsilon Constraint method is selected to solve the bi-objective optimization problem since allocating a weight coefficient to identify the importance of monetary and non-monetary terms is inappropriate for making comparisons in this field. The first objective function—i.e. minimizing the total cost—is assigned as the primary objective function, whereas the second objective—i.e. minimizing victim evacuation time—is altered to be an additional constraint. Although the Epsilon Constraint method is suitable for solving the problem in this study, this method occasionally generates inefficient solutions caused by inappropriate definition of the value of the hard constraint. To avoid generating inefficient solutions, the second objective function is augmented with the positive constant value in which the additional allowance time is determined. Therein, the allowance time is justified based on personal, delay, and fatigue allowances. The application of the proposed model is demonstrated through the real-world case study of the 2011 flood in Phun Phin district, Surat Thani province, Thailand. The numerical experiment results reveal that, when focused on individual solving the first objective function, only one shelter is required to open since minimizing the total cost is the target. On the other hand, when individual solving the second objective function, the total cost is very high due three shelters being required to open to minimize the evacuation time. Hence, efforts are made to determine both objective functions simultaneously. The optimal solution obtained by solving the bi-objective function generates the compromise solution in determining shelter location-allocation, which is that only two shelters are required to open to serve the victims. The results found by this study can assist decision-makers to design appropriate measures for responding to shelter location-allocation during flooding events. Future studies could incorporate disaster risk levels in the proposed model as well as implement it on larger and multiple case studies to demonstrate its broader applicability.

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