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Published by the Faculty of Engineering, Khon Kaen University, Thailand

Optimization for flood evacuation shelter location-allocation problems with different priority level constraints

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Received 14 October 2022
Revised 24 March 2023
Accepted 29 March 2023

Abstract

A natural disaster is a major adverse event. Flooding is a common natural disaster that damages the environment and causes economic losses, deaths, and homelessness. In recent years, floods have significantly impacted people in Asia. Although disasters cannot be avoided, we can develop plans to address their associated problems. However, resources for preparation, capital, time, and employees are limited. This paper aims to address the location-allocation problem in humanitarian aid during catastrophes by planning and managing evacuation of victims from flooded areas to safe locations. A mixed-integer programming model is used to determine the number of shelters needed and to assign the victims to appropriate shelters using a facility location and allocation model. The model considers the total population in each affected area, the travel distance, victim's priority score, shelter's priority score, shelter's capacity, fixed cost for transportation, cost for opening the shelter, and staff wages. To approach the real-world issues, we expand some constraints in the mathematical model concerning the priority level of victims and the capacity limit of facilities. An experiment comparing various scenarios at different problem scales was done to gauge the validity of the proposed approach. The outcomes demonstrated the applicability of the suggested strategy.

Keywords: Location-allocation problem, Optimization, Cost structure, Priority score

1. Introduction

Disasters have historically wreaked havoc on the economy and inflicted immeasurable harm on humanity every year. According to the Centre for Research on the Epidemiology of Disasters (CRED) [1], natural disasters killed 10,492 people, impacted 101.8 million people, and caused $252 billion in economic damages globally in 2021. As a continent, Asia was the most severely affected, experiencing 40% of all disaster events, accounting for 49% of all fatalities, and 66% of all affected individuals.

Flooding is an extreme weather event that is exacerbated by the current effects of climate change. It is the type of natural catastrophe that occurs most frequently, is geographically most prevalent, and is the most severe [2]. Flooding causes loss of life, damages the economic infrastructure, and affects the environment. This impacts the economic and social development of regions and countries, as funds must be spent to reconstruct the affected regions and assist victims [3, 4]. Compared to other types of disasters, floods have the greatest impact on people, and the Asia is the most affected. China is one of the most disaster-prone nations on Earth. In disaster response, it is critical to build an efficient and quick relief logistics system. Strategic prepositioning of emergency items, particularly selection of appropriate emergency warehouse locations, has a significant impact on rapid disaster response to ensure adequate relief supplies. A difficult decision must be made regarding emergency warehouse location [5]. After a natural disaster, efficient evacuation, stabilization, and rescue of the victims of large-scale disasters require various services. Infrastructure, including neighborhood pharmacies, hospitals, and other essential facilities, may be destroyed by a severe disaster. Establishment of temporary facilities that can offer trauma relief and temporary facilities for services, food, and drinking water is necessary for the affected regions [6, 7]. Therefore, transporting victims from impacted regions to safe locations as well as organizing and distributing relief materials for humanitarian logistics is an essential role in supporting disaster management operations. Optimally locating relief facilities such as shelters, hospitals, distribution facilities, warehouses, and disposal sites is another aspect of humanitarian logistics. Decisions about shelter location and allocation are more critical for disaster response than those about other services [8, 9]. Additionally, researchers are also focusing on effective natural disaster preparedness, mitigation, and responses to reduce the devastating effects of natural disasters. Humanitarian logistics alleviate victim suffering by planning, implementing, and regulating the movement of victims from impacted areas to safe locations within the limitations of budgetary constraints [10, 11].

This study aims to identify a model to minimize the total cost of humanitarian operations in flooding disasters using a programming method that includes fixed costs for transportation, opening shelters, and staff costs for serving victims in the location-allocation problem with different priority levels, as shown in Figure 1. The main constraint is a priority score for victim allocation and shelter selection, based on a comparison of the victim's and shelter's priority scores. These scores indicate the capability of a candidate shelter to thoroughly service victims' needs.

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doi: 10.14456/easr.2023.25

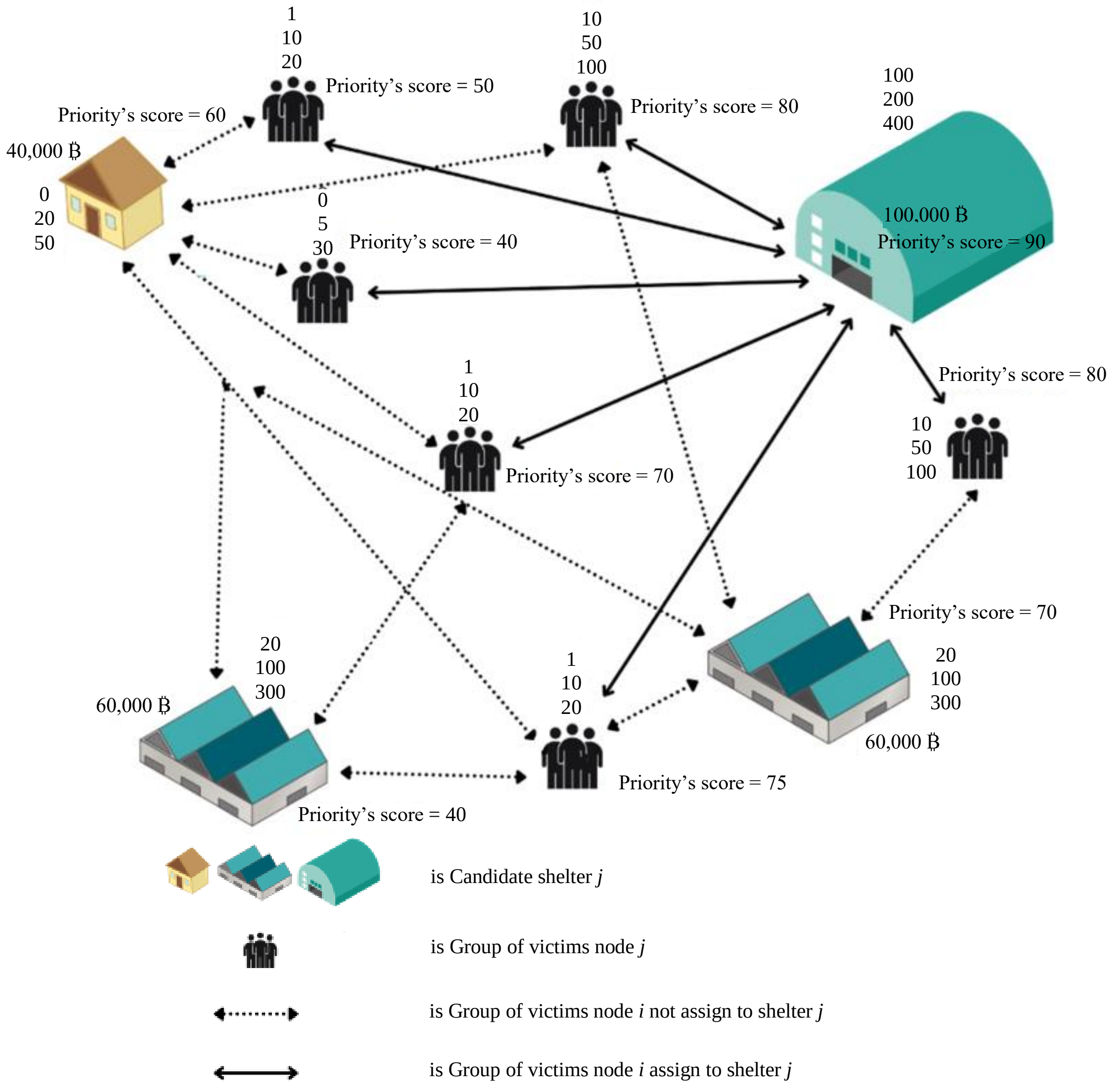

Figure 1 The problem statement of model formulation in the current study.

Facility location-allocation models (FLAM) are important for decision-making in selecting locations and allocating supplies to meet demand [12, 13]. Thus, in humanitarian relief, there is a set of potential facilities at predetermined locations that can be accessed. Each location includes temporary accommodations, supply warehouses, emergency medical centers, transportation centers and rescue teams [8, 11, 14]. Although many studies have been conducted on selecting locations for emergency medical facilities and shelters, research on allocating resources according to priority levels is still unexplored.

In the past, various methods have been proposed for solving humanitarian relief management problems. There is existing literature on humanitarian relief management. Praneetpholkrang et al. [11] presented a shelter site selection and allocation model for disaster situations with the objective of minimizing the total cost using a genetic algorithm. Gao et al. [15] presented a method to solve the location allocation problem in temporary emergency medical centers for injured patients in the post-disaster phase. There were two objectives for the model, minimizing the total traveling time and the total mortality risks. Hallak et al. [8] proposed shelter locations in conflict areas with a case study in Syria having multiple objectives, including the maximum capacity of shelters, total cost, maximizing the number of people with vulnerability criteria, and maximizing the coverage of people with disabilities. Mollah et al. [16] studied humanitarian logistics and relief distributions during floods, prioritizing the most affected regions to reduce casualties. The objective aimed to minimize costs and improve performance using genetic algorithms. Wongloucha et al. [14] presented a route planning method for rescuing people from floods, considering urgency and victim types, and distributing relief bags to them. The authors solved a vehicle routing problem with mixed pickup and delivery (VRPMPD) using the "1-M-1/P-D/Min Cmax" case to minimize flood relief operation time and help victims in a timely and impartial manner. Mohamadi and Yaghoubi [17] presented a rapid medical supply distribution model, focusing on quickly transferring injured people from affected areas. They used bi-objective function stochastic optimization to develop a location plan for transfer points and medical supply distribution centers. After a disaster, Duhamel et al. [18] studied a mathematical model and heuristics for solving a multi-period location-allocation problem. Their objective function aimed to maximize the population size at the end of the period. Shavarani [19] studied the use of drone relief distribution vehicles to determine the best topology for both relief centers and recharge stations, covering a large-scale area while minimizing incurred costs and waiting times. Kilci et al. [20] presented a mixed integer linear programming-based methodology for selecting temporary shelter locations, with an objective function that maximizes the problem variables to select the best possible combination of shelter areas.

Table 1 Literature on humanitarian relief management.

Author	Problem type	Model	Objective function						Constraint	Method	Case study
			Total Cost	Total distance	Total time	Number of facilities	Mortality risk value	Number of victims			
Praneetpholkrang et al. [11]	LAP	Single	*						- Service distance limit	GA	F
Gao et al. [15]	LAP	Bi				*	*		- Travel speed limit - Life risk score	GA - M FCM	EMS
Hallak et al. [8]	LAP	Multi	*			*		*	- Type of victim - Type of facility	WGP	C
Mollah et al. [16]	LAP	Single	*						- Time window - Vehicle speed limit	GA	F
Wongloucha et al. [14]	VRPMPD	Single			*				- Travelling time - Time to evacuate - Vehicle capacity	EX	F
Mohamadi and Yaghoubi [17]	LARP	Bi	*		*				- Priority transportation victim - Medical supplier cover	EPS	EMS
Duhamel et al. [18]	LAP	Single						*	- Limits of supplies that can be distributed	VNS	Dis
Shavarani [19]	LAP	Multi	*	*	*				- Shortest paths from depot - Cover all demand	H-GA	Dis
Kilci et al. [20]	LAP	Single				*			- Travelling main road to shelter	EX	EQ
This Article	LAP	single	*						- Types of victims - Priority's victim	NNA	F

Remark: C: Conflict area, Dis: Disaster situation, EMS: Emergency medicine service center, EPS: Epsilon constraint method, EQ: Earthquake, EX: Exact method, F: Floods situation, GA: Genetic algorithm, NNA: Nearest neighbor algorithm, VNS: Variable neighborhood descent local search, WGP: Weighted-goal programming

Numerous studies on humanitarian relief logistics have helped identify optimal locations for disaster preparation and response. Many researchers have focused on managing humanitarian relief. Table 1 summarizes recent studies, including our own research and areas where further study is needed. Our study prioritizes assigning disaster victims to evacuation centers that can provide specialized care for groups with specific needs or conditions requiring specialized equipment. To achieve this, we use a scoring system to determine the level of crisis for each population group and direct people to the evacuation centers that are best equipped to care for them. However, providing all evacuation centers with the same level of capability is not feasible due to budget and personnel constraints. Therefore, we must consider the location allocation problem within the affected area, capacity of candidate shelters, transportation costs, fixed costs for opening shelters, victim priority scores and shelter priority scores. Our objective function minimizes the cost of operations using a mathematical model and the nearest neighbor algorithm to solve the problem.

2. Materials and methods

This study develops a mathematical model for selecting shelters and allocating resources to move victims from flooded areas to safe places. The goal of this model is to minimize overall expenses, including staff costs, fixed costs related to opening shelters, and transportation. First, representative shelters are predetermined. The data used to formulate the model includes the number of victims and each level of victimhood in the affected area, candidate shelter capacity, travel distance, transportation costs, fixed fees for establishing shelters, victim priority scores, and shelter priority scores. The model is based on the idea that victims from each area are not separately assigned to various shelters for each level of victimhood. A disaster occurs simultaneously in all affected areas and a fixed number of victims and potential shelters are available. Evacuation vehicles are homogenous, and that the victim priority scores are not greater than the candidate shelter priority scores. The study uses priority scores to categorize flood victims into three subgroups based on their need for assistance: (1) those who cannot help themselves, (2) those who can help themselves but require support, and (3) those who are self-sufficient. Evacuation centers are evaluated based on these scores, with the highest priority given to the first subgroup. Victims are allocated to centers based on a comparison of their priority scores and the quality of services provided by the centers. This ensures that centers with the highest scores have the necessary resources to provide the best possible care. Priority scores can be applied to other emergencies and are based on factors such as danger level, property damage, vulnerable family members, pre-existing medical conditions, and available housing. Priority scores should not be influenced by wealth or social status. Victim priority scores were determined by the Department of Disaster Prevention and Mitigation using information from their household database. The nearest neighbor algorithm is used in this study to solve a large model, as it has been successfully used to deal with various location and allocation problems with priority scores.

2.1 Mathematical model

Sets

I : Set of victims affected node *i*
J : Set of candidate shelters *j*
K : Set of victim's score type *k*

Indices

I : Index of victim affected node $i \in I$
j : Index of candidate shelters $j \in J$
k : Index of victim score types $k = 1,2,3$

Parameters

h_{ik}	group of victims *i* each *k* type
d_{ij}	Distance between the victims affected node *i* to candidate shelter *j*. (kilometers)
CS_{jk}	Candidate shelter capacity *j* each *k* type
f_j	Cost-fixed for establishing the shelter *j* (Baht)
LC	Wage per person for hiring to service victims in shelters (Baht/person)
θ	Ratio of the staff service per victim
B	Constant per-kilometer transportation cost coefficient (baht/kilometer)
VP_i	Priority's score of victims *i*
SP_j	Priority's score of opening shelter *j*

Decision variables

$$x_j = \begin{cases} 1, candidate\ shelter\ j\ is\ opened \\ 0, otherwise \end{cases}$$

$$y_{ij} = \begin{cases} 1, victims\ affected\ node\ i\ assign\ to\ shelter\ j \\ 0, otherwise \end{cases}$$

$$z_{ijk} = \begin{cases} 1, victims\ affected\ node\ i\ type\ k \\ \quad assign\ to\ shelter\ j\ type\ k \\ 0, otherwise \end{cases}$$

A mathematical model can be formulated as follows:

$$min \sum_{j\epsilon J} x_J f_j + B \sum_{i\epsilon I}\sum_{j\epsilon J} d_{ij} y_{ij} + LC \sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K} \frac{z_{ijk}}{\theta} \quad (1)$$

Subject to

$$y_{ij} \le x_j \qquad \forall_{i\in I}, \forall_{j\in J} \quad (2)$$

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

$$\sum_{j\in J} z_{ijk} = h_{ik} \qquad \forall_{i\in I}, \forall_{k\in K} \quad (4)$$

$$\sum_{i\in I} z_{ijk} \le CS_{jk} \times x_j \qquad \forall_{j\in J}, \forall_{k\in K} \quad (5)$$

$$VP_i \times y_{ij} \le SP_j \times x_j \qquad \forall_{i\in I}, \forall_{j\in J} \quad (6)$$

$$z_{ijk} = h_{ik} \times y_{ij} \qquad \forall_{i\in I}, \forall_{j\in J}, \forall_{k\in K} \quad (7)$$

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

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

The objective function (1) aims to minimize the total cost of operation for selecting shelters. It includes the fixed cost of establishing the shelter, transportation costs, and staff service costs. Constraint (2) restricts each victim's affected node so that it can only be allocated to open shelters. Constraint (3) ensures that every victim's affected node shall be assigned to only one shelter. Constraint (4) limits the number of victims in each impacted node. Constraint (5) ensures that the quantity of victims allocated to shelters does not exceed the capacity limit of each shelter. Constraint (6) ensures that the priority scores of victims' affected nodes are not greater than the shelter priority scores. Constraint (7) ensure each victim node does not split each k each i assign to j. Constraints (8) and (9) specify the binary variables used in the model.

2.2 Heuristic algorithm

The nearest neighbor algorithm (NNA) used in this paper applies a mechanistic approach to the location-allocation problem. First, the victim's priority score should not be lower than the candidate shelter's priority score. Second, if the shelter passes the qualifying list, the distance between the victim's node and the shelter is sorted in ascending order. Finally, the nearest member of the shelters is selected. However, if the capacity limit is exceeded, the next nearest shelter is selected and the process is repeated until all victims are assigned to shelters.

Nearest Neighbor Algorithm Pseudo code:

```
input data parameter
  for i = (1, size of VPi member)
  for j = (1, size of SPj member)
     if VPi <= SPj
        write j in the set of members
    elseif VPi > SPj
          reject j
    for l = (1, size of member's set)
    if CSjk – hik > 0 each k
       write j in allocate members set
    for q = (1, size allocate members set)
    sort data dij (j = position in q)
        write min number dij and j to assign set
compute the objective function
output objective function and j with i to j member
```

We applied the proposed model, which chooses shelters and allocates victim nodes to shelters with the minimized objective function, to a randomly generated dataset from a pilot study. In the model, the constant coefficient for transportation costs was set at 8 baht per kilometer, the staff-to-victim service ratio was set at 1:50, and the cost per person for hiring personnel to service victims in shelters was set at 380 baht per person.

The design of the experiment is three scales which include small, medium, and large. Small scale (S) is $10i5j$, $20i10j$. Medium scale (M) is $50i20j$, $100i20j$ and large scale (L) is $150i20j$, $160i20j$, $165i20j$. Opening evacuation centers (j) is often limited to the maximum resources of the Department of Disaster Prevention and Mitigation. Typically, there are a maximum of 20 centers available for each occurrence. Furthermore, financial resources and personnel are also limited by the resources of the Department of Disaster Prevention and Mitigation. Sample victim node data (h_{ik}) in Table 2 and sample candidate shelter data (CS_{jk}) in Table 3 are shown below.

Table 2 Sample data of groups of victims i of each k type and priority scores of victims (h_{ik})

i	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
k=1	4	4	2	4	4	4	2	4	2	1
k=2	10	10	10	10	10	30	50	20	10	20
k=3	50	50	50	50	50	120	200	100	120	60
VP_i	20	10	50	30	25	60	90	90	40	50

Table 3 Sample data of candidate shelters j of each k type, fixed cost of shelters, and priority scores of shelters (CS_{jk})

Candidate shelter	**1**	**2**	**3**	**4**	**5**
k=1	5	50	30	20	30
k=2	100	200	400	200	120
k=3	200	260	200	300	260
Fixed cost	20000	30000	14000	30000	5000
SP_j	10	100	90	50	80

3. Results

The mathematical model was solved using IBM CPLEX Studio v20.1 and the nearest neighborhood algorithm was solved using MATLAB R2021a on a Windows 10 laptop with 8 GB of memory and a 3.1 GHz Dual-Core Intel Core i5 processor. The results for the $20i10j$ problem from the model are shown in Table 4. Five shelters were used to assign victims based on the capacity of the shelter and priority level constraints. The optimal solution resulted in total costs of 84,286 baht, which included fixed costs for opening the shelters (70,200 baht), transportation costs (1,432 baht), and victim service costs (12,654 baht). This problem took 3.30 seconds of

CPU time to solve. Table 4 presents the sample results from the mathematical model applied to a $20i10j$ problem. This is a small problem with 20 victim groups and 10 shelter evacuation centers, each with a certain certification value. For instance, 'Shelter Center 1(85)' means that shelter center number 1 has a certification rating of 85, and each group of victims has a different priority within each center. In victim node 1, the assigned groups were 1(60), 6(15), 18(50), 19(80), and 20(20). Victim node 11 has a significance value of 60 points, and so on. The obtained results are correct and meet all specified conditions.

Table 4 Sample results from the mathematical model with $20i10j$.

Problem	Opened shelter (*j*), (Response Score)	Victim node (*i*) (Priority Score)	Capacity of shelter (*j*)	Sum victim assign	Total cost (Baht)	Time to solve the problem
$20i10j$	1(85)	1(60), 6(15), 18(50), 19(80), 20(20)	10 100 500	10 51 384	84,286	3.30 sec.
	2(65)	2(30), 7(45), 8(50), 13(50)	10 100 500	10 57 310		
	4(90)	3(65), 4(90), 9(20), 10(80), 11(40), 15(50), 17(80)	20 200 1000	16 72 301		
	5(90)	5(40), 12(40), 14(30), 16(50)	12 120 600	10 40 186		

Table 5 A comparison of the time to compute an objective between the mathematical model and the Nearest Algorithm (NNA).

Size	Math model CPU time (sec)	Total cost (baht)	NNA CPU time (sec)	Total cost (baht)
$10i5j$	3.67	87,551	0.86	87,551
$20i10j$	3.30	84,286	1	84,286
$50i20j$	4.68	382,568	2.43	457,552
$100i20j$	7.49	417,035.6	1.82	469,795
$150i20j$	8.2	524,173.6	1.52	534,991
$160i20j$	12.5	521,768.4	2.85	522,232
$165i20j$	>15 hrs.	NaN	2.2	694,690

The current study compares the performance of two algorithms, the mathematical model and the nearest neighbor algorithm, in solving problems related to departmental prevention and mitigation. Specifically, the study evaluates the optimal solutions obtained by each algorithm for small, medium, and large problems. Table 5 shows the results for small models (*i.e.*, those with 10 or 20 nodes). Both algorithms were able to identify the optimal solution. However, the nearest neighbor algorithm was more efficient in terms of CPU time. In contrast, for medium models (*i.e.*, those with 50, 100, 150, or 160 nodes), the mathematical model took longer to compute but yielded an optimal solution. The nearest neighbor algorithm, on the other hand, was faster but may not have produced the optimal solution. For the large model (*i.e.*, ones with 165 nodes), the mathematical model failed to generate the optimal solution. In such cases, the nearest neighbor algorithm was used and produced a solution in less than three seconds. This suggests that the nearest neighbor algorithm may be a suitable option for large-scale problems that require rapid solutions. However, it should be noted that this algorithm may not always provide the optimal solution. It is noteworthy that the number of shelters in the problem remained constant for medium and large models, representing the maximum number of shelters in accordance with government practice.

4. Discussion

This paper presents solutions to flood evacuation shelter location-allocation problems with different priority level constraints that are NP-hard and complex to solve. Mathematical and heuristic models were developed to be solved with expanded constraints in the mathematical model using the priority level of victims and the capacity limit of facilities. Various studies have considered logistics for humanitarian relief, but no research has considered priority score level constraints. For example, Praneetpholkrang *et al.* [11] presented a shelter site selection and allocation for flood disaster situations with an objective of minimizing the total cost using a genetic algorithm that highlights the service distance limit constraint. Krirk W. *et al.* [14] presented a vehicle routing problem with mixed pickup and delivery (VRPMPD) with travelling time, evacuation time, vehicle capacity, and types of victims. However, the current study proposes a mathematical model for selection and allocation of shelters during flooding disasters. A priority score system is used to identify victims who are in greater danger and require more assistance and allocate them to shelters based on their needs. This ensures that resources are allocated efficiently and effectively. The priority scores consider factors such as the extent of harm to the victims, their level of vulnerability, and their need for specific services. The aim is to assign victims to shelters that can respond to their needs and provide satisfactory assistance. Thus, we used the proposed mathematical model for identifying an optimal solution with priority level constraints and the nearest neighbor algorithm. These obtained acceptable solutions compared to the optimal solutions for solving large-sized problems. It is used in this scale and computation time is less than three seconds because it is not complex and obtains a solution. Furthermore, this approach can prove beneficial for other various scale evacuations in Thailand by decreasing costs for the transportation management system.

5. Conclusions

This study presents a mathematical model for selecting and allocating shelters during flooding disasters, using a priority score system for victims. The model is formulated as a mathematical program and solved using the nearest neighbor algorithm to minimize costs. While the mathematical model may not be suitable for solving large problems, the nearest neighbor algorithm can handle such problems. Comparing the results of both methods, the mathematical model produces better results when the objective function is computed, while the nearest neighbor algorithm may be a suitable option for large-scale problems that require rapid solutions. However, it should be noted that this algorithm may not always provide the optimal solution. Future research could extend the constraints of the model to cover other problems such as time limits, vehicle routing concepts, and supply management. However, this study focuses on allocation by priority level. The proposed model is applied to a real-world case using a metaheuristic approach to minimize the total costs. Overall, this study provides a valuable contribution to disaster management planning by offering an effective approach to shelter selection and allocation.

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