UNIVERSITY OF HONG KONG

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DEPARTMENT OF INDUSTRIAL AND MANUFACTURING SYSTEMS ENGINEERING

Coursework 2:

Application of OR in Evacuation Planning

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1. Introduction

Occasionally, there are some major disasters and accidents that seriously endanger the safety of people's lives and property. As an important part of post-disaster emergency response, evacuation plans are very important to reduce casualties.

In general, evacuation removes people or objects from a building or some affected area by assigning a limited number of routes to different evacuees in real time while maximizing the rate of success throughout the evacuation mission. JIANG (2021). It is found that the fundamental objectives for evacuation problems of sudden disasters are generally similar, but we also notice that different kinds of disasters have their own specific features. Table 1 shows examples of some public emergencies and its casualties. These emergencies could have been avoided, or the damage to which could have been alleviated if proper evacuation plannings are conducted.

Table 1: Examples of Public Emergency in Need of Proper Evacuations

Time	Place	Reason	Casulties
2014.12	The Bund, Huangpu District, Shanghai	A crowd hedge is generated on stairs, triggering a stampede	36 dead, 49 injured
2015.09	Mecca, Saudi Arabia	The pilgrims crowded each other, which led to stampede	1399 dead, 2000 injured
2015.10	Maimensin, Bangladesh	A stampede at a charity event	over 23 dead
2017.04	Penn Station, New York, America	Group Panic	many injured
2017.09	Bombay, India	Overpass collapse led to group panic	22 dead, 39 injured
2018.12	Ancona, Italy	Tear gas was used to spray the crowd, causing stampede	6 dead, 120 injured
2019.02	Port Harcourt, Nigeria	A stampede occurred during the break-up	over 15 dead, many injured
2019.03	Northern Ireland, England	A stampede in the Disco party, causing stampede	3 dead, many injured
2019.06	Antananarivo, Madagascar	Crowds rushed to the entrance to the stadium, causing a stampede.	15 dead, 75 injured

This essay focuses on solving a specific evacuation problem, the evacuation in Great East Japan earthquake.

The rest of this essay is organized as follows. A literature review of existing works on evacuation planning is given in section 2. Then section 3 gives the description of the specific evacuation problem and proposes the mathematical model. Afterwards, section 4 presents the numerical studies under experiments. Finally, section 5 concludes the essay and discuss the difficulties in solving the problem.

2. Literature Reivew

The main difficulty in studying evacuation planning is that we cannot make the pedestrians directly exposed to potentially dangerous real environments Haghani and Sarvi (2018), which violates ethics and morality. Therefore, in addition to observing historical evacuation videos to study evacuation behavior, computer simulation has become the main tool for evacuation research Tan et al. (2015) to test scientific theories and hypotheses and the rationality of architectural design. Ji et al. (2018) proposed a new triangular mesh cellular automata model to accurately simulate the evacuation process of high-density people. The simulation results show that the model has high computational efficiency; Bode and Codling (2019) uses a high degree of control, Safe and cheap virtual crowd evacuation experiments to analyze the environmental factors affecting evacuation time; Elmoussaoui et al. (2018) designed a mesoscopic probability model to simulate crowd evacuation in a bounded area based on dynamics and random game theory.

Currently, evacuation planning models are mainly divided into micro models Yuksel (2018); Hu et al. (2018), mesoscopic models Shi et al. (2018) and macro models Jiang et al. (2016). To put it simply, micro models view each person as single moving particles, wheras macro models see the crowd as a whole flow, and mesoscopic ones lie between micro and macro models. Obviously, the micro-evacuation model starts from the individual modeling, which can describe the micro-interactions between individuals in a complex dynamic evacuation environment, thus is more extensive in current research YU et al. (2021). In micro models, Social Force Model, Cellular Automata models are three prevlant models in current research.

Different kinds of optimization models have been proposed. Some are single objective models, and some are multiobjective ones. Mitchell and Radwan (2006) applied a microscopic assignment model aiming at optimizing the clearance time of the network, solving the problem with heuristic metods. Chien and Korikanthimath (2007) proposed an optimization model minimizing the evacuation duration and potential congestion delays simultaneously. Abdelgawad and Abdulhai (2010) put forward an optimization model to minimize the times for travelling and waiting of all the people getting evacuated. Chen and Zhan (2014) made simulation on the condition of the network and tried to obtain the best results for high-density areas. More recently, Bretschneider and Kimms (2012) developed a dynamic flow model based on traffic patterns and solve the model with bi-level heuristic apporach, which minimizes the clearance time. Li et al. (2012) designed a staging algorithm for evacuation planning to minimize the congestion occurs in an evacuation. Netflow models are also widely used, extending the previous model for multiple destinations (Xie et al. (2014); Li et al. (2018)). Escribano-

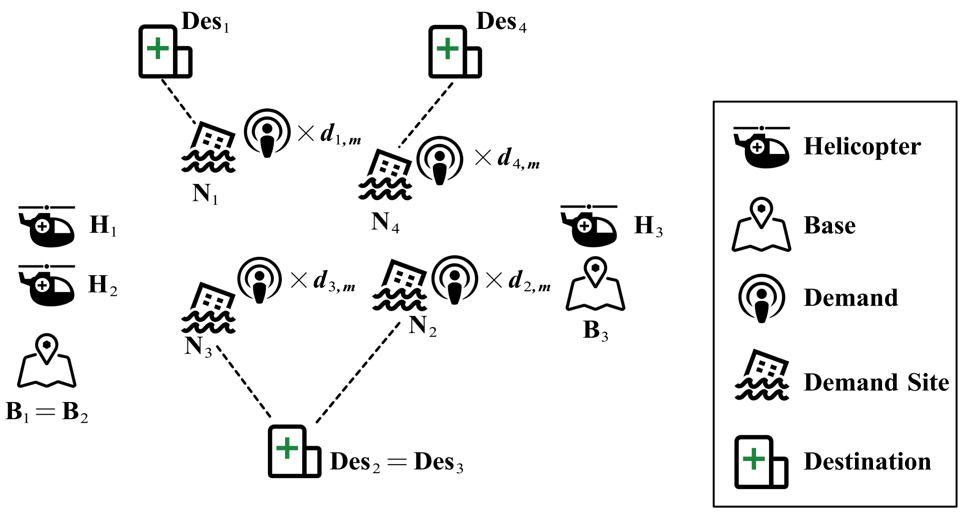

Figure 1: Problem Description

Macias et al. (2020) developed an evacuation decision model that simultaneously controls the evacuation and signal phasing strategy over a specified time horizon, which also acknowledges the ability of the evacuees to make independent route choices.

3. Problem and Formulation

This essay focuses on the same evacuation problem in a previous study Oh et al. (2017). This section briefs the evacuation problem, and then proposes a mathematical formulation.

3.1. Problem Description

The evacuation planning problem is considered under a natrual disaster, which consists of several helicopters carrying the victims, a certain amount of victims with various types of needs, some disaster areas as the place for pick-up, and some safe locations as place for delivery. The problem is illustrated in Figure 1.

Specifically, $|H|$ helicopters, denoted as $h_1, \ldots, h_{|H|}$ participate in the evacuation. These helicopters start from different bases, with some of which sharing same bases (e.g., h_1 and h_2 in Figure 1). There are also $|N|$ demanding places, denoted as n_i, each of which contains $d_{i,m}$ people categorized as type m, where $m \in M$ is the injured degree of the victim. Moreover, there are health-care sites, denoted as $r \in R = \{r_1, \ldots, r_{|R|}\}$. Different injury conditions determine different destination, as we should save the closer health-care destination $r \in R = \{r_1, \ldots, r_{|R|}\}$ for victims with higher urgency levels. The capacitied helicopters with limited fuel edurance are assigned to pick up the victims and deliver them to destonations, and the objective is to maximize the number of evacuees given limited rescue time.

3.2. Basic Assumptions

- Each helicopter h_i must start and end its tour at a fixed starting base b_i. All helicopters that reach the base should spend some time refueling, and the refueling time is denoted as T_{rf}^k. After the refueling, they depart from the base again.

- The helicopters are not allowed to go directly from base to destination without picking up any victims, nor should they travel solely between two bases.

- If a helicoper moves to a victim site, it can only deliver the load the victims, with no delivery being allowed, and it should head for the desired destination directly with no detour. Similarly, when it arrives at a destination, only delivery is allowed and the next stop could only be another victim site or its base.

- The helicopters follow the orders of urgency level of the demands to provide evacuation service. In other words, the more urgent demand sites are served first.

- The effect of traffic congestion, bad weather influence is ignored. The vehicles are assumed to travel at a constant speed.

Definition 1 (trip of a helicopter)
A trip of a helicopter is defined as a direct flight from $p_1 \in B \cup D \cup R$ to $p_2 \in B \cup D \cup R$, $p_1 \neq p_2$.

Definition 2 (travel of a helicopter)
A travel of a helicopter is defined as a sequence of end-to-end trips, which satisfies the following:

- *The start location of a travel is base $b \in B$ or a health-care site $r \in R$ and the terminal location is $b' \in B, b' \neq b$ or $r' \in R, r' \neq r$.*

- *If a travel ends at $r \in R$, then it must include a trip ends at $d \in D$ before the last trip.*

Definition 3 (loop of a helicopter)
A loop of a helicopter is defined as a sequence of end-to-end travels, which satisfies the following:

- *The first node visited of the loop is the same as the last node visited of the loop.*

- *The first node and last node are the same base node.*

- *The base nodes are only allowed to be the first and last node visited in the loop.*

An example loop of a helicopter in evacuation planning is given in Figure 2. The loop starts from B_1, and the first travel is $B_1 \xrightarrow{1} N_3 \xrightarrow{2} Des_2$, and the second is $Des_2 \xrightarrow{3} N_3 \xrightarrow{4} Des_2$, and the third is $Des_2 \xrightarrow{5} N_2 \xrightarrow{6} Des_3$, and the last is $Des_3 \xrightarrow{7} B_1$. In Oh et al. (2017), the authors coped with the demand by treating a loop as the smallest unit, and constrained the maximum number of loops for each type of demand according to the latest tolerable time of that type.

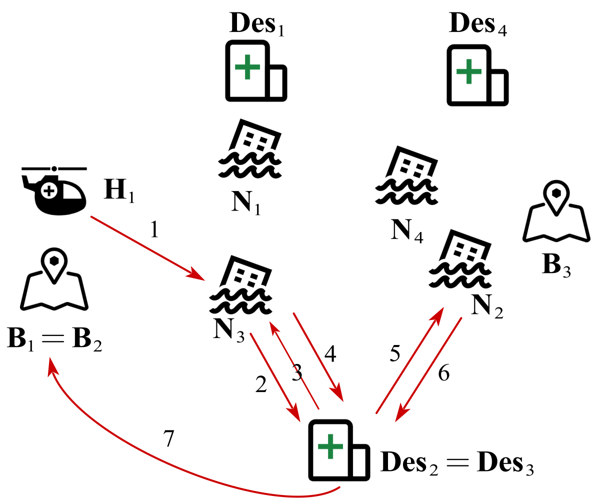

Figure 2: Example of the Route of a Helicopter in Evacuation Planning

3.3. Mathematical Formulation

Before we introduce the formulation, some symbols used in the models are given as follows.

3.3.1. Sets

H	the set of all helicopters
Des	the set of all safe destination nodes
B	the set of bases for the helicopters
N	the set of diaster affected nodes
M	the set of demand types corresponding to emergnecy level

3.3.2. Parameters

$M_i(i = 1, 2, 3)$	a very large number
$t^k_{i,j}$	the time for helicopter k to travel from node i to node j
t^k_{rf}	the time for refuling of helicopter k
C_k	the capacity of helicopter k
$d_{i,m}$	the number of demand for type m at node i
T^k_{max}	the maximum time for helicopter k to travel without refueling

3.3.3. Decision Variables

$x^{k,c}_{i,j,m}$	an integer variable that determine the number of travels for helicopter k satisfying demand m

$y_{i,m}$	an auxiliary variable used to control the value of serviced and unserved demand
$z_{i,m}$	an auxiliary variable used to control the value of serviced and unserved demand
$unsat_{i,m}$	the number of unsatisfied demand at node i for demand type m
$over_{i,m}$	the number of sapce left for all vehicles after serving all demands of type m

Moreover, we give some detailed derivation or introduction for some important variables.

Decision Variables Different from the previous work, where the authors preassigned demand site D_i to R_i, we allow the demanded victims at d_i being delivered to r_j $(i \neq j)$. Therefore, the decision varible in this paper should also be modified. We have to adopt conventional VRP sequence-index based formulation, $x^{k,c}_{i,j,m}$ are treated as a binary variable. If the helicopter k in loop c for demand type m travels from node i to j, then it equals to 1, otherwise 0.

Maximum number of cycles Following the derivation in Oh et al. (2017), we still cope with the problem in unit of cycles. For each type of demand m, given a specific helicopter k, we first calculate the latest possible cycle flying time $T^{latest}_{k,m}$. We consider the extreme case that the helicoper delivers the victim at destination r before the latest survival time T_m, then come back to its base, as is given in (1).

$$T^{MAX}_{k,m} = T_m + \max_{i \in R_m} t^k_{i,B_k} \tag{1}$$

Here $R_m = \{r \in R \mid \sum_{i \in B \cup D} x_{i,j,k,m} \neq 0\}$ is the set of the destinations where non-zero victims are sent. Then suppose there are L loops for helicoper h to cope with demand type m, we get (2).

$$\sum_{l=1}^{L} TL^{k,l}_m + (L-1)T^k_{rf} \leq T^{MAX}_{k,m} \tag{2}$$

$\sum_{l=1}^{L} TL^{k,l}_m$ represents the pure time spent on loop flying without the refueling. We substitute it with $L\overline{TL^k_m}$, standing for number of loop times the average time. Then take it into (2), we could solve the constraint for L, as (3).

$$L \leq \frac{T^{MAX}_{k,m} + T^k_{rf}}{\overline{TL^k_m} + T^k_{rf}} \tag{3}$$

Further, as the average is greater and equal than the smallest. We get (4).

$$L \leq \frac{T_{k,m}^{MAX} + T_{rf}^{k}}{TL_{\min}^{k} + T_{rf}^{k}} \tag{4}$$

Finally, the minimum time for a loop flying is determined as the case where the helicopter starts from its base, travels to only one demand and destination, then directly comes back, calculated as (5).

$$TL_{\min}^{k} = \min_{d_i \in D, r_j \in R} t_{h_k,d_i}^{k} + t_{d_i,r_j}^{k} + t_{r_j,h_k}^{k} \tag{5}$$

Notice that L is an integer, so we use ceiling funtion to get the final result of L, as shown in (6).

$$L = \left\lceil \frac{T_{k,m}^{MAX} + T_{rf}^{k}}{TL_{\min}^{k} + T_{rf}^{k}} \right\rceil \tag{6}$$

3.4. Mathematical Model

The objective of our proposed model is to minimize the number of unserved demands, which is shown in (7).

$$\min \sum_{i \in D} \sum_{m \in M} unsat_{i,m} \tag{7}$$

s.t.

$$unsat_{i,m} - over_{i,m} = d_{i,m} - over_{i,(m-1)} - \sum_{k \in H} \sum_{l \in L_m^k} \sum_{j \in S_k} C_k x_{j,i,m}^{k,l}$$
$$\forall i \in D; m \in M; E_{i,0} = 0 \quad \forall i \in D_i \tag{8}$$

$$0 \leq unsat_{i,m} \leq M_1 y_{i,m} \qquad \forall i \in D; m \in M \tag{9}$$
$$0 \leq over_{i,m} \leq M_2 z_{i,m} \qquad \forall i \in D; m \in M \tag{10}$$
$$y_{i,m} + z_{i,m} = 1 \qquad \forall i \in D; m \in M \tag{11}$$

The above constraints (8) - (11) defines situation of over serving and short of service. Specifically, constraint (8) represents the iterative relations of demand for type m and $m-1$. If after the service of the previous step for type $m-1$, the helicopter still have space left, then certain amount of demand for m will be added to make the vehicle fully loaded, therefore the real demand in next step for type m will be calculated by deduction of these preserved demands. Constraint (9) to (11) ensure that either unsatisfaction number or the over served number is greater than 0, and the other one should be exactly 0.

There are also some time constraints. The first is that the total flying time in a cycle should not exceed the endurance of a helicopter, which is given in constraint (12).

$$\sum_{i,j\in S_k} t^k_{i,j} x^{k,l}_{i,j,m} \le T^k_{max} \quad \forall k \in H; m \in M; l \in L^k_m \tag{12}$$

All the victims served of a certain type m should be delivered before the required time for this type, i.e., T_m. Since we are using cycle as the basic calculation unit, the last travel from the destination to base should be eliminated, as is shown in constraint (13).

$$\sum_{m=1}^{m_c} \left[\sum_{l\in L^k_m} \sum_{i,j\in S_k} t^k_{i,j} x^{k,l}_{i,j,m} + T^k_{rf}\left(N^k_m - 1\right) \right] - T^k_{f,m_c} \le T_{m_c}$$

$$\text{where } N^k_m = \sum_{l\in L^k_m} \sum_{j\in R} x^{k,l}_{B_k,j,m}, T^k_{f,m_c} = \sum_{i\in R} t^k_{i,B_k} x^{k,N^k_c}_{i,B_k,m_c} \quad \forall k \in H; m_c \in M \tag{13}$$

Moreover, there are some constraints which are common in basic routing problems. The first one is that given a helicopter, for every node it visits, the number of time that the vihecle come to this node is equal to the number out, as is shown in constraint (14).

$$\sum_{j\in S_k} x^{k,l}_{i,j,m} - \sum_{j\in S_k} x^{k,l}_{j,i,m} = 0 \quad \forall k \in H; i \in S_k; m \in M; l \in L^k_m \tag{14}$$

Also, all helicopters should start from the base and return to the base in a cycle, with no other visits to base, as is shown in constraint (15).

$$\sum_{i\in R} x^{k,l}_{i,B_k,m} = \sum_{j\in R} x^{k,l}_{B_k,j,m} \le 1 \quad \forall k \in H; m \in M; l \in L^k_m \tag{15}$$

Constraint (16) means that only if the helicopter leaves the base, would there be a cycle. M_3 here is a very large number, and if leaving is triggered, the RHS would be a very large value, and the LHS can be any non-negative value.

$$\sum_{i,j\in R} x^{k,l}_{i,j,m} \le M_3 \sum_{j\in R} x^{k,l}_{B_k,j,m} \quad \forall k \in H; m \in M; l \in L^k_m \tag{16}$$

Similarly, if the helicopter does leave the base, it should at least visit one demand site, then come back to the base again. Direct base-to-base visit is forbidden, as given in constraint (17).

$$x^{k,l}_{B_k,B_k,m} = 0 \quad \forall k \in H; m \in M; l \in L^k_m \tag{17}$$

Finally, we have to add the sub-tour elimination constraint in order to avoid cyclic visit at nodes inside a cycle, as shown in constraint (18). Note that $U^{k,l}_m$ here is any subset of S_k with more than one element.

$$\sum_{i,j \in U^{k,l}_m} x^{k,l}_{i,j,m} \leq \left|U^{k,l}_m\right| - 1 \quad \forall k \in H; m \in M; l \in L^k_m$$
$$\forall \left|U^{k,l}_m\right| = 2, 3, \cdots, \left(\sum_{i,j \in S_k} x^{k,l}_{i,j,m}\right) - 1 \tag{18}$$

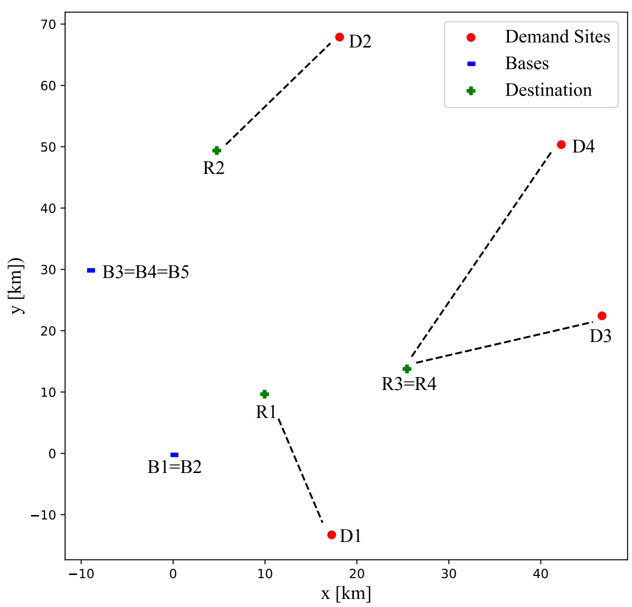

Figure 3: Demand sites and Destination Distribution of the Network

Table 2: Number of Demand at Each Site

	Coordinate (x, y)	Immediate	Delayed	Minimal	Total
D_1	(17.26, -13.30)	15	61	20	96
D_2	(18.12, 67.88)	25	42	112	179
D_3	(46.67, 22.42)	77	16	33	126
D_4	(42.24, 50.35)	92	42	13	147
Total	/	209	161	178	548

4. Numerical Studies

4.1. Data Process and Description

The data we are using in this essay is obtained from Oh et al. (2017). Although the authors proposed a coordinate figure like Figure 3, the detailed location point is not given. Therefore, this essay utilized the data extrator tool *WebPlotDigitizer-4.5* Rohatgi (2021) to extract the points in the figure.

Generally, there are 4 demand sites and 4 safe destinations, with 3 and 4 locating at the same place. Also, the severity is divided into 3 categories, corresponding to the 3 types of urgency level *Immediate, Delayed, Minimal* (in descending order) according to Surgery (2013). Different from the original problem, where the 4 demand sites are pre-assigned to the 4 safety destination, we here consider that such assignment does not exist. This would largely increase the complexity of the problem, but would definitely be more practical. The demand at each station is shown in Table 2.

The information of the helicopters are given in Table 3. There are 5 helicopters participating in this mission, and they are divided into 3 types with different capacity, flying speed and refueling time.

Table 3: The Information of the Helicopters

Helicopter Type	Helicopter Number	Capacity (people)	Endurance (hour)	Refuel Time (hour)	Speed (km/hour)	Base Location (x, y)
Heavy	1	25	3	0.5	240	(0.10, -0.30)
Medium	3	12	2.5	0.5	280	(-8.97, 29.78)
Light	1	5	2	0.5	240	(0.10, -0.30)

4.2. Results

The model is a Mix-Integer Programming problem, and it is solved with Gurobi Optimizer 9.1.2 coded with Python 3.8 via gurobipy package Gurobi Optimization, LLC (2021). The experiment is run on macOS monetery 12.0.1 with 2 GHz 4-core Intel Core i5 and 16 GB memory.

```
Root relaxation: objective 0.000000e+00, 637 iterations, 0.02 seconds

    Nodes    |    Current Node    |     Objective Bounds      |     Work
 Expl Unexpl |  Obj  Depth IntInf | Incumbent    BestBd   Gap | It/Node Time

     0     0    0.00000    0    6  361.00000    0.00000   100%     -    0s
H    0     0                     10.0000000    0.00000   100%     -    0s
H    0     0                      0.0000000    0.00000  0.00%     -    0s
     0     0    0.00000    0    6    0.00000    0.00000  0.00%     -    0s
|
Explored 1 nodes (2957 simplex iterations) in 0.32 seconds
Thread count was 8 (of 8 available processors)

Solution count 3: 0 10 361

Optimal solution found (tolerance 1.00e-04)
Best objective 0.000000000000e+00, best bound 0.000000000000e+00, gap 0.0000%
```

Figure 4: Output of the Solution to the Proposed Model

The result shows that we could get an unserved amount of 0 and the gap is 0, which indicates we get an exact solution. The output of gurobi is shown in Figure 4.
This is better than the previous work, with 92 out of 548 people left unserviced at last. Actually, this indicates that our model outperforms the previous one by eliminating the constraint of preassignment of the demand to destination.
Furthermore, in our experiment, the subtour elimination is conducted using Miller-Tucker-Zemlin subtour elimination Desrochers and Laporte (1991), which largely improve the calculation performance. We defined a set of auxiliary variables, denoted as $vmtz_{i,m,n,k}$, and the constraint is given as (19). The calculation time of the model is 0.32 seconds.

$$vmtz_{i,m,n,k} - vmtz_{j,m,n,k} + Mx_{i,j,k,m,n} \leq M - 1, \quad \forall i, j \in S_k, i, j \neq B_k, \forall k \in H, \forall m \in M, \forall n \in L, i \neq j \tag{19}$$

Finally, we give the schedule of the 5 helicopters, as shown in Table 4.

5. Conclusion and Discussion

This essay tried to address a specific evacuation problem of the Great East Japan earthquake and tsunami. The model is enhanced compared to the original one by eliminating the pre-assignment of the demand site to the destination, which enables the complete service of all the victims. The code of the model can be found at https://github.com/rqhu1995/evacuation_imse_7034.

Table 4: Routes of the Helicopters

route	helicopter number	demand type	loop
B_1-D_1-R_1-D_4-R_2-D_3-R_3-B_1	1	1	2
B_1-D_3-R_1-B_1	1	1	3
B_1-D_1-R_1-B_1	1	2	1
B_1-D_3-R_1-D_2-R_3-D_3-B_1	1	2	3
B_2-D_4-R_2-D_3-R_1-D_2-3	2	1	1
B_2-D_4-R_3-B_2	2	1	3
B_2-D_4-R_2-D_2-R_1-B_2	2	2	2
B_2-D_2-R_1-B_2	2	2	5
B_2-D_4-R_1-B_2	2	3	2
B_2-D_2-R_1-B_2	2	3	4
B_2-R_1-D_1-R_2-B_2	2	3	7
B_2-D_1-R_3-D_4-R_2-D_3-R_1-B_2	3	1	1
B_2-D_4-R_3-B_2	3	1	4
B_2-D_4-R_1-B_2	3	2	2
B_2-R_1-R_3-D_2-R_2-B_2	3	2	6
B_2-D_4-R_3-D_2-R_1-B_2	3	3	2
B_2-D_4-R_3-D_1-R_2-B_2	3	3	5
B_2-D_4-R_3-D_3-R_2-B_2	4	1	1
B_2-D_2-R_2-D_1-B_2	4	1	2
B_2-D_2-R_3-B_2	4	2	1
B_2-D_3-R_2-B_2	4	3	4
B_1-D_4-R_1-B_1	5	1	2
B_1-D_4-R_2-D_2-R_3-B_1	5	1	3
B_1-D_4-R_1-B_1	5	2	3
B_1-D_4-R_1-D_1-R_2-B_1	5	2	5
B_1-D_1-R_2-B_1	5	3	7
B_1-D_2-R_1-B_1	5	3	9

Although we extrated data directly from another paper, the original paper claimed that such data is not easy to obtain, as is put forward Andreeva-Mori et al. (2015):
One of the main issues related with disaster relief mission planning is the insufficient amount of data and/or their unavailability. Because of privacy issues, information on the exact location and number of evacuees, for example, is rarely released. Therefore, building a complete database from sporadic information is extremely difficult. Local authorities might have data about the missions performed during disaster relief, but such information is only released in summary reports such as Zenkoku-koukuu-shoubou-bousai kyougikai (2013).
Moreover, we actually omit the time for loading and unloading the victims onto the helicopter. This information also needs further reference and would definitely have

impact to the result.
We left some further improvement in the current model for future research. Firstly, the objective here is single one. In fact, from the result we found that sometimes the helicopter would leave some early loops to be idle. Although still not violating the time limit, this shows that the timeliness is not considered in the model, which is quite an important issue in a disaster evacuation. Secondly, the cost of evacuation is not investigated. Experiments on the optimal number of helicopters should be further conducted in order to avoid some redundant helicopter configurations.

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