Fast Solution for Evacuation Shelter Closing Problem

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Abstract

In the post-disaster recovery phase, evacuation shelters for evacuees who lost their homes by a disaster need to be closed at an appropriate time as the number of evacuees decreases. To handle this situation, we propose "Evacuation Shelter Closing Problem (ESCP)" for efficiently determining when to close evacuation shelters. In the ESCP, the sum of the relocation cost and the operation cost is minimized by considering the burden of those who will be relocated to other shelters due to the closure. Existing studies have formulated a similar problem, the Evacuation Shelter Scheduling Problem (ESSP), but since the number of variables in ESSP is proportional to the number of evacuees, it requires enormous computational resources when accommodating many evacuees. ESCP is inspired by the integer linear programming formulation of the multi-agent pathfinding problem, and treats evacuees who are initially in the same shelter and return home at the same time as the same group. Although the ESCP is limited to operations after the evacuation to the shelter, it can be calculated more efficiently with fewer variables than the ESSP. We experimentally confirmed that ESCP can be optimized for approximately 30,000 evacuees of the whole city and is at least 12 times faster than the ESSP formulation. We also proposed two simple heuristic methods for ESCP, and showed that our methods could reduce the computation time by 85%, although the value of the objective function increased by 16%.

Introduction

Evacuation shelters provide temporary lodging and safety for the survivors of natural disasters. After the Great East Japan Earthquake (March 2011),[1] which forced the evacuation of over 470,000 people, many evacuation shelters have been added in various Japanese cities. In Japan, the number of shelters increased by 65% from 48,014 to 79,281 between 2014 and 2020.[2]

However, operating shelters also levies a secondary burden. For example, when a school is used as a shelter, educational activities are hindered if evacuees stay even after classes have resumed. The burden of shelter operation can be translated into monetary terms. Otsuka and Koshiyama estimated that, based on the rental expense of the facilities occupied during the Kobe earthquake (Great Hanshin-Awaji Earthquake, January 1995),[3] the operation cost of its shelters was about 106 million dollars (10.66 billion yen) (Otsuka and Koshiyama 2016). Although the evacuees could have been gathered into fewer shelters to reduce operational costs, Nakahira reported that relocating the remaining evacuees was difficult because of the burden of leaving the shelters close to their homes (Nakahira 2018).

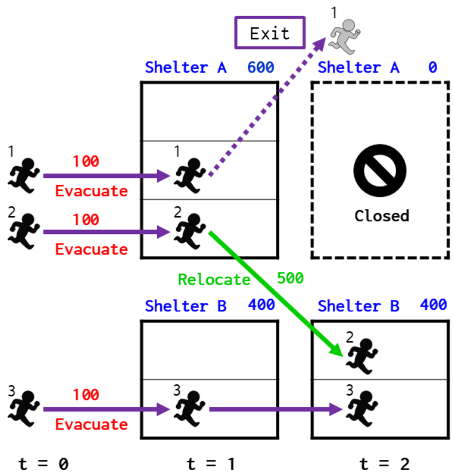
To find an acceptable solution for both evacuees and the other residents under these circumstances, we must consider the cumulative cost until they are all recovered. Shimizu et al. extended the Facility Location Problem (FLP) (Weber 1929; Hotelling 1929; Cornuéjols, Nemhauser, and Wolsey 1983; Daskin 2008; Wu, Zhang, and Zhang 2006) into time and formulated an Evacuation Shelter Scheduling Problem (ESSP) that minimizes the operation cost of shelters and the movement cost of evacuees until every evacuee has returned home (Shimizu et al. 2022). By solving ESSP, we can determine which shelters should be closed and to which other shelters the remaining evacuees should be relocated to minimize costs as evacuees gradually return home.

Figure 1(a) shows an example of ESSP. Shelter A has capacity for three people, and shelter B has capacity for two. Their operation costs are 600 and 400, respectively. The maximum value of a time step is $T = 2$. Evacuees 1 and 2 can evacuate to shelter A at a cost of 100, and evacuee 3 can evacuate to shelter B at a cost of 100 when a disaster occurs at $t = 0$. We assume that evacuees move to the nearest shelter, and ignore evacuation to any other shelters. As a result of the evacuation, at $t = 1$, both shelters A and B need to be open at a total operation cost of 1000. Evacuee 1, whose return time is $\tau_1 = 1$, will not need a shelter at $t = 2$. In addition, shelters A and B have an opening. Therefore, by $t = 2$, evacuee 2 can be relocated to shelter B, and evac-

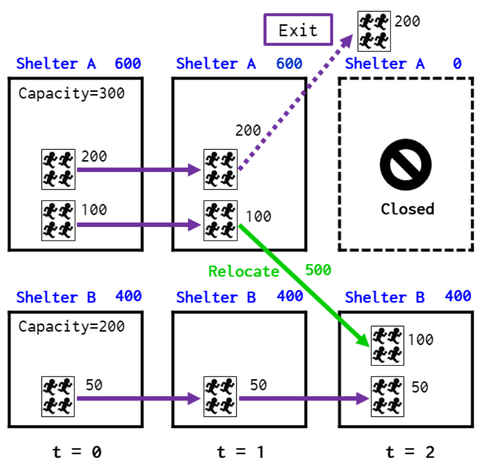
[1] https://en.wikipedia.org/wiki/2011_T%C5%8Dhoku_earthquake_and_tsunami (accessed Jan 13, 2022)

[2] http://www.bousai.go.jp/kaigirep/hakusho/index.html (accessed Jan 13, 2022)

[3] https://en.wikipedia.org/wiki/Great_Hanshin_earthquake (accessed Jan 13, 2022)



(a) ESSP



(b) ESCP

Figure 1: Example of ESSP and ESCP. In (a) ESSP, any location other than the shelters can be set as initial location of evacuees. In (b) ESCP, initial location of evacuees is limited to location of shelters.

uee 3 can be relocated to shelter A. However, the relocation cost is 500. If evacuee 2 is relocated to shelter B, shelter A can be closed, which minimizes the operation and relocation costs. In ESSP, since both evacuation and relocation can be considered simultaneously, it is possible to determine which shelter should be open when a disaster occurs.

However, since ESSP uses a binary variable representing the evacuees' location and movement, the number of variables is proportional to the number of evacuees. When so many people are being evacuated, ESSP take vast computational space to calculate. Therefore, we propose the Evacuation Shelter Closing Problem (ESCP) shown in Fig. 1(b). ESCP is inspired by the integer linear programming (ILP) formulation of the multi-agent pathfinding problem (MAPF), ESCP does not take the evacuation phase into account so that everyone is already in a shelter at $t = 0$ and the operating shelters at $t = 0$ are given. By separating the problems in this way, we can apply a fast solution method. In Fig. 1(b) at $t = 0$, shelter A has 200 people who will return home at $t = 1$ and 100 people who will return home at $t = 2$, for a total of 300 evacuees. In shelter B, there are 50 evacuees who will return home at $t = 2$. ESCP uses integer variables, instead of binary ones in ESSP, representing the number of people in a group of evacuees with a common return time. Consequently, the number of variables does not depend on the number of evacuees but on the number of groups. Although the number of evacuees is about 100 times larger than Fig. 1(a), ESCP can represent the problem with almost the same number of variables as in ESSP in Fig. 1(a). Thus, ESCP can obtain the optimal schedule of shelters even when there are many evacuees.

ESCP has a feature that it can be solved quickly when the closing times of the shelters are fixed. Therefore, we also propose two heuristic solution methods to solve the ESCP quickly. We experimentally confirmed that ESCP is more efficient than ESSP with binary variables for evacuees. We also experimentally evaluated the fast heuristic solution methods.

The following are the contributions of this paper:

- We formulated ESCP as a special version of ESSP.
- We showed that the ESCP is at least 12 times faster than ESSP by simulation experiments.
- We proposed a fast heuristic method for solving ESCP, and experiments show that the computation time can be reduced by 85%, although the objective function increases by 16%.

Related Work

Multi-Agent PathFinding

Multi-agent pathfinding (MAPF) is the task of moving multiple agents in a directed graph from their respective starting points to the goal point in a collision-free manner (Li et al. 2021; Stern et al. 2019). It aims to minimize one of the following four objective functions among the feasible solutions: maximum/average travel time and maximum/average travel distance. In general, multi-agent optimization problems can be transformed into integer linear programming (ILP) problems. For the MAPF problem, a method (Yu and LaValle 2016) was proposed by transforming it into an ILP. Their method uses a flow algorithm on a time-expanded directed graph.

Although the objective function of MAPF is different from that of ESSP, MAPF has a solution space similar to that of ESSP with a fixed shelter capacity of one person. Therefore, we considered applying their method to ESSP. When we try to apply their method (Yu and LaValle 2016) to ESSP, there are two challenges. First, although the flow algorithm they used is efficient, it cannot be applied directly to ESSP because the availability of nodes in the graph is not determined in advance. Secondly, if each person is treated as a different flow, the number of variables becomes huge and the computation becomes impossible. In this study, we have formulated ESCP to overcome these problems.

Evacuation Shelter Scheduling Problem

The facility location problem (FLP) (Weber 1929; Hotelling 1929; Cornuéjols, Nemhauser, and Wolsey 1983; Daskin 2008; Wu, Zhang, and Zhang 2006) has been studied to minimize total movement and operation costs. By extending FLP in time (Van Roy and Erlenkotter 1982; Owen and Daskin 1998; Kochetov 2011; Correia and Saldanha-da Gama 2019; Nickel and Saldanha-da Gama 2019), the problem of finding shelter allocation was formulated with minimum cumulative cost when the return time is known (Shimizu et al. 2022). ESSP extended a three-stage hierarchical location model (Chen et al. 2013) to consider the decrease of the number of evacuees and automatically resolved the trade-off between evacuation efficiency and operation cost by estimating the movement cost. In this section, we explain ESSP based on an existing study (Shimizu et al. 2022). The symbols are defined in Table 1.

Consider a situation where N evacuees are located at one of M locations. The M locations include the location at the time of the disaster and the location of the evacuation shelter. Evacuee n is assumed to return home after staying for τ_n steps. In this paper, τ_n is referred to as the return time. Although τ_n is generally difficult to know immediately after a disaster, here we assume that it is a known value. Let $T = \max_n \tau_n$. The time is expressed as discretized integer $t \in \{0, \dots, T\}$ where $t = 0$ is the beginning of the disaster (Fig. 1(a)). After a disaster occurs at $t = 0$, the evacuees move to a shelter and stay there by $t = 1$. After that, evacuee n with $\tau_n = 1$ goes home, and the others, if necessary, move to another shelter and stay there by $t = 2$. These procedures are assumed to be repeated. The location of evacuee n at time t is denoted by $\tilde{m}_t(n)$. If an evacuation shelter can be established at location m, it can accommodate C_m evacuees at most. Otherwise, $C_m = 0$ is set for locations that are not candidates to be evacuation shelters. $\sum_{m \in M} C_m \geq |N|$ is assumed so that all the evacuees can be accommodated in the evacuation shelters.

The movement from location m to m' at time t incurs movement cost $d_{tmm'}$, and the movement between any two locations is assumed to be completed in one time step. The movement cost at $t = 0$ is refered to as the evacuation cost, and the movement cost at $t > 0$ as the relocation cost. Here, as in FLP, ESSP introduces variable x_{tmn}, which indicates whether evacuee n will be accommodated in shelter m at time t, and variable y_{tm}, which indicates whether shelter m will be operated at time t. In the above setting, the problem can be expressed as a 0-1 integer linear programming problem by introducing variable $z_{tmm'n}$, which indicates whether evacuee n moves from location m at t to m' at time $t + 1$.

$$\text{Minimize} \quad \sum_{t=1}^{T} \left(\sum_{m \in M} \sum_{m' \in M} d_{tmm'} \sum_{n \in N} z_{tmm'n} + \sum_{m \in M} f_m y_{tm} \right) \tag{1}$$

$$\text{Subject to} \quad \sum_{n \in N} x_{tmn} \leq C_m y_{tm}, \forall m, \forall t \geq 1 \tag{2}$$

$$\sum_{m \in M} x_{tmn} = 1, \forall t \leq \tau_n, \forall n \tag{3}$$

$$\sum_{m \in M} x_{tmn} = 0, \forall t > \tau_n, \forall n \tag{4}$$

$$x_{t=0,mn} = \begin{cases} 1, & m = \tilde{m}_0(n) \\ 0, & m \neq \tilde{m}_0(n) \end{cases}, \forall n \tag{5}$$

$$y_{tm} \leq y_{(t-1)m}, \forall t \geq 1, \forall m \tag{6}$$

$$z_{tmm'n} \geq x_{(t-1)mn} + x_{tm'n} - 1 \quad \forall t \geq 1, \forall m, \forall m', \forall n \tag{7}$$

$$z_{tmm'n} \leq x_{(t-1)mn}, \forall t \geq 1, \forall m, \forall m', \forall n \tag{8}$$

$$z_{tmm'n} \leq x_{tm'n}, \forall t \geq 1, \forall m, \forall m', \forall n \tag{9}$$

$$x_{tmn}, y_{tm}, z_{tmm'n} \in \{0, 1\} \quad \forall t \geq 1, \forall m, \forall m', \forall n \tag{10}$$

$$\text{Given} \quad \tilde{m}_0(n), \forall n. \tag{11}$$

Equation (1) is an objective function that minimizes the sum of the costs of moving the evacuees and operating the shelters. Note that while it may be more convenient to stay in a shelter closer to home, this objective function does not include a term that prioritizes staying in a shelter closer to home. Note also that the operating costs of the shelter are assumed to be the fixed costs of occupying the facility and do not depend on the number of evacuees. If operating costs vary over time, the formulation can be naturally extended. Eq. (2) is a condition under which no evacuees can stay in the closed shelters and the number of evacuees in the open shelters does not exceed capacity. However, at the time of the disaster ($t = 0$), this constraint is not applied because the evacuees have not yet been accommodated in the shelters. Eqs. (3) and (4) are the conditions under which the evacuees live in a shelter until they return home. Eq. (5) is the condition where evacuee n is at given location $\tilde{m}_0(n)$ when the disaster occurs. Eqs. (7), (8), and (9) are the conditions for a movement from the source to the destination if and only if one is at the source before the movement and at the destination after the movement, i.e., $z_{tmm'n} = x_{(t-1)mn} \times x_{tm'n}$. Eq. (6) denotes a condition where once a shelter is closed, it will not be reopened.

This formulation creates a shelter management plan that minimizes the movement and operation costs. This formulation is refered as ESSP.

Proposed Method

Formulation

When the number of evacuees is large, the computational complexity of ESSP also grows. The number of variables x_{tmn}, y_{tm}, and $z_{tmm'n}$ are $T|M||N|, T|M|$, and $T|M|^2|N|$, respectively. The number of x_{tmn} and $z_{tmm'n}$ are proportional to $|N|$. Furthermore, since M includes not only the shelters' locations but also the locations of $|N|$ evacuees at the time of the disaster, $|M| > |N|$ if they are all

Table 1: Notation

Symbols	Definitions
N	Set of indexes of evacuees: $n \in \{1, \cdots, \|N\|\}$
N_t	Set of indexes of evacuees in a shelter at time t
N_m^t	Number of people remaining at time t among evacuees whose initial position is m
M	Set of indexes of locations: $m \in \{1, \cdots, \|M\|\}$
M_t	Set of indexes of shelters that can be operated at time t.
$\tilde{m}_t(n)$	Location of evacuee n at time t
C_m	Capacity of shelter m
T	Maximum value of time to be considered: $t \in \{0, \cdots, T\}$
τ^m	Time when shelter m to be closed
τ_n	Time when evacuee n returns home
f_m	Operation cost for one time step of shelter m.
$d_{tmm'}$	Movement cost of evacuee from location m at time $t-1$ to m' at time t.
x_{tmn}	Indicator that location of evacuee n at time t is location m.
$\bar{x}_{tm}$	Number of evacuees in location m at time t.
$\bar{x}_{tm}^{\tau}$	Number of evacuees in location m at time t who are to return home at time τ.
y_{tm}	Indicator for operating shelter m at time t.
$z_{tmm'n}$	Indicator for movement of evacuee n from location m at time $t-1$ to m' at time t.
$\bar{z}_{tmm'}$	Number of evacuees moving from location m at time $t-1$ to m' at time t.
$\bar{z}_{tmm'}^{\tau}$	Number of evacuees moving from location m at time $t-1$ to m' at time t who are to return home at time τ.

in different locations. These facts particularly make spatial complexity problematic.

Therefore, we first consider a special case in which the initial location of the evacuees is one of the shelters. This is a reasonable assumption since it is generally considered that people evacuate to the pre-defined shelter when a disaster occurs. This assumption corresponds to the fact that $\tilde{m}_0(n)$ takes only a limited number of values, and $|M|$ becomes smaller, but the formula remains the same. Therefore, this assumption significantly reduces the number of variables at $t = 1$ when $|M| \ll |N|$. Then, we transformed the formulation by introducing integer variables $\bar{x}$ and $\bar{z}$ that respectively denote the number of evacuees in the shelters and the number moving among them:

$$\bar{x}_{tm}^{\tau} = \sum_{n \in N} \left(x_{tmn} \times \mathbb{I}(\tau_n = \tau) \right) \tag{12}$$

$$\bar{z}_{tmm'}^{\tau} = \sum_{n \in N} \left(z_{tmm'n} \times \mathbb{I}(\tau_n = \tau) \right). \tag{13}$$

Note that $\bar{x}_{tm}^{\tau}$ and $\bar{z}_{tmm'}^{\tau}$ denote the number of evacuees whose return time is τ, but it is possible for evacuees with the same return time to split and stay in different shelters. By summing for τ, (12) and (13) are corresponding to x_{tmn} and $z_{tmm'n}$.

$$\sum_{\tau=1}^{T} \bar{x}_{tm}^{\tau} = \sum_{n \in N} x_{tmn} \tag{14}$$

$$\sum_{\tau=1}^{T} \bar{z}_{tmm'}^{\tau} = \sum_{n \in N} z_{tmm'n}. \tag{15}$$

Because $z_{tmm'n} = x_{(t-1)mn} \times x_{tm'n}$,

$$\bar{z}_{tmm'}^{\tau} = \sum_{n \in N} \left(x_{(t-1)mn} \times x_{tm'n} \times \mathbb{I}(\tau_n = \tau) \right) \tag{16}$$

$$\sum_{m \in M} \bar{z}_{tmm'}^{\tau} = \sum_{n \in N} \left(x_{tm'n} \times \mathbb{I}(\tau_n = \tau) \right) = \bar{x}_{tm'}^{\tau} \tag{17}$$

$$\sum_{m' \in M} \bar{z}_{tmm'}^{\tau} = \sum_{n \in N} \left(x_{(t-1)mn} \times \mathbb{I}(\tau_n = \tau) \right) = \bar{x}_{(t-1)m}^{\tau}. \tag{18}$$

Using Eqs. (12) and (13), we rewrite Eqs. (1) - (11) as follows:

$$\text{Minimize} \quad \sum_{t=1}^{T} \left(\sum_{m \in M} \sum_{m' \in M} d_{tmm'} \sum_{\tau=t}^{T} \bar{z}_{tmm'}^{\tau} + \sum_{m \in M} f_m y_{tm} \right) \tag{19}$$

$$\text{Subject to} \quad \sum_{\tau=t}^{T} \bar{x}_{tm}^{\tau} \leq C_m y_{tm}, \forall t \geq 1, \forall m \tag{20}$$

$$\sum_{m \in M} \bar{z}_{tmm'}^{\tau} = \bar{x}_{tm'}^{\tau}, \forall t < \tau, \forall \tau, \forall m' \tag{21}$$

$$\sum_{m' \in M} \bar{z}_{tmm'}^{\tau} = \bar{x}_{(t-1)m}^{\tau}, \forall t < \tau, \forall \tau, \forall m \tag{22}$$

$$y_{tm} \leq y_{(t-1)m}, \forall t \geq 1, \forall m \tag{23}$$

$$\bar{x}_{tm}^{\tau}, \bar{z}_{tmm'}^{\tau} \in \mathbf{Z}_{\geq 0}, \forall t \geq 1, \forall m, \forall m', \forall \tau \tag{24}$$

$$y_{tm} \in \{0, 1\}, \forall t \geq 0, \forall m \tag{25}$$

$$\text{Given} \quad \bar{x}_{t=0,m}^{\tau}, \forall m. \tag{26}$$

Equation (19) is an objective function that minimizes the costs of relocating the evacuees and operating the shelters. Eq. (20) is a condition under which no evacuees can remain in closed shelters and the number of evacuees in the open shelters does not exceed the capacity. However, at the time of the disaster ($t = 0$), this constraint is not applied because the amount of arrivals will probably exceed the capacity. Note that the solution space is equivalent to ESSP, since the shelters to be opened are determined at $t > 0$. Eq. (21) is the constraint that evacuees who have not yet returned home will be moved to one of the shelters. Eq. (22) is the constraint that the number of evacuees in the destination shelter is equal to the sum of incoming evacuees. Both Eqs. (21) and (22) together impose the condition that the number of evacuees does not change before and after the relocation. Eq. (23) denotes a condition where once a shelter is closed, it is not reopened. This is a necessary constraint to align conditions with ESSP. Eq. (26) is the condition where the number, location, and return time of the evacuees are given when a disaster occurs.

The number of variables $\bar{x}^{\tau}_{tm}$ and $\bar{z}^{\tau}_{tmm'}$ are reduced to $T^2|M|$, and $T^2|M|^2$ for x^{τ}_{tm}, and $z^{\tau}_{tmm'}$, respectively. If $T < |N|$, the number of variables is reduced. Although $|M|$ is smaller because the initial location of the evacuees is limited to shelters, the search space and optimal solution are equivalent to those of ESSP. This formulation can also be solved by an integer linear programming solver. This formulation is called ESCP: Evacuation Shelter Closing Problem.

Fast Solution

Although the number of variables is reduced, it takes time to obtain the exact solution for ESCP. However, in the formulation of ESCP, when y_{tm} is fixed, the efficient method of minimum-cost multicommodity network flows (Tomlin 1966) can be applied and the solution can be obtained fast. Also, if we determine the closure time of the shelter $0 < \tau^m \leq T$, y is uniquely determined by the following equation:

$$y_{tm} = \begin{cases} 1 & (t < \tau^m) \\ 0 & (t \geq \tau^m) \end{cases} \tag{27}$$

Therefore, the open and closed states of all shelters can be represented by an m-dimensional vector of τ^m. So we propose two heuristic solution methods, namely Greedy method shown in Algorithm 1 and FastGreedy method shown in Algorithm 2, both of which improve the solution by repeating the procedure of finding the optimal solution for $\bar{x}_{tm}$ with y_{tm} fixed.

Both Greedy and FastGreedy start with a solution where all shelters are open at all times (line 1 in Greedy and FastGreedy), and then search the solution space by decreasing the closure time of the selected shelters by one (line 5 in Greedy, line 6 in FastGreedy). When the solution does not improve by closing any shelter, the algorithm terminates. The difference between Greedy and FastGreedy is that Greedy calculates and selects which of all the shelters to close to reduce the cost the most (line 8), while FastGreedy selects a shelter at random (line 5) and closes it if it reduces the cost. FastGreedy is faster than Greedy because there is no procedure to find the shelter which reduce the cost the most.

Experiments

Dataset: IKOMA

In the experiments, we evaluated the effectiveness of our proposed method in a setting that resembled an actual disaster by creating a dataset based on an earthquake scenario

Algorithm 1 Greedy Solution for ESCP

Input: $N^m_t, C_m, \bar{x}_{t=0,m}, f_m, d_{mm'}$
1: $\tau^m \leftarrow T, \forall m$
2: Obj$^* \leftarrow \infty$
3: **while** True **do**
4:   **for** $m \in M$ **do**
5:     $\tau^m \leftarrow \tau^m - 1$
6:     Get Obj^m, $\bar{x}^m_{tm}$ by optimize ESCP with y_{tm} fixed
7:   **end for**
8:   $m \leftarrow \arg\min_m \mathrm{Obj}^m$
9:   Obj $\leftarrow \min \mathrm{Obj}^m$
10:   **if** Obj $<$ Obj* **then**
11:     Obj$^* \leftarrow$ Obj
12:     $\bar{x}^*_{tm} \leftarrow \bar{x}_{tm}$
13:   **else**
14:     **break**
15:   **end if**
16: **end while**
17: **return** $\bar{x}^*_{tm}, \tau^m$

Algorithm 2 Fast Greedy Solution for ESCP

Input: $N^m_t, C_m, \bar{x}_{t=0,m}, f_m, d_{mm'}$
1: $\tau^m \leftarrow T, \forall m$
2: Obj$^* \leftarrow \infty$
3: tabuList $\leftarrow \varnothing$
4: **while** length(tabuList) $< M$ **do**
5:   Choice a shelter m not in tabuList randomly
6:   $\tau^m \leftarrow \tau^m - 1$
7:   Get Obj, $\bar{x}_{tm}$ by optimize ESCP with y_{tm} fixed
8:   **if** Obj $<$ Obj* **then**
9:     Obj$^* \leftarrow$ Obj
10:     $\bar{x}^*_{tm} \leftarrow \bar{x}_{tm}$
11:   **else**
12:     tabuList.$append(m)$
13:   **end if**
14: **end while**
15: **return** $\bar{x}^*_{tm}, \tau^m$

(worst case) for Ikoma City. The locations of its 27 shelters are shown in Fig. 2. The operation costs of the shelters based on a previous work (Otsuka and Koshiyama 2016) are also shown in Table 2. We set a legal capacity ($160 \leq C_m \leq 2260$) for them. The total number of evacuees is $32,707$ and their return times were set to decrease in proportion to the actual number of people staying in the shelters of the Kobe earthquake (Kobe City Civil Service Bureau 1996; Kumagai 1995). We set $T = 8$ and the time step to one month. N^t_m represents the number of people remaining at time t among the evacuees whose initial position is m. The conditions for the initial position are $x^{\tau}_{t=0,m} = N^{\tau}_m - N^{\tau+1}_m$. The data for N evacuees was created by sampling N people with a probability proportional to the above $x^{\tau}_{t=0,m}$. For each N, ten data were generated.

Relocation costs were assumed to be proportional to the distance among shelters:

$$d_{tmm'} = \lambda\, ||\boldsymbol{p}_m - \boldsymbol{p}_{m'}||, \forall t > 0, \tag{28}$$

Table 2: Settings of simulation experiment: Left side shows operating cost f_m and capacity C_m of shelter shown in Fig. 2, and right side shows remaining evacuees at each time point who were initially in the corresponding shelter. Operating costs are based on a previous work.

							N_m^t					
m	Facility type	f_m	C_m	$t=0$	1	2	3	4	5	6	7	8
1	Elementary schools	54900	1530	1682	883	522	354	261	182	142	74	0
2	Public facilities (medium)	57300	760	397	209	124	85	64	46	37	21	0
3	Elementary schools	54900	1550	1292	679	402	273	202	142	111	59	0
4	Junior high schools	52800	1530	1292	679	402	273	202	142	111	59	0
5	Public facilities (small)	13500	160	161	85	51	35	27	20	17	11	0
6	Elementary schools	54900	1840	764	402	238	162	120	85	67	36	0
7	Junior high schools	52800	2260	622	327	194	132	98	69	55	30	0
8	Public facilities (large)	89400	2170	895	470	278	189	140	98	77	41	0
9	Elementary schools	54900	1540	1103	579	342	232	171	120	94	49	0
10	Elementary schools	54900	1730	2247	1180	697	472	348	243	190	99	0
11	Junior high schools	52800	1530	1522	799	472	320	236	165	129	67	0
12	Elementary schools	54900	1900	1204	632	374	254	188	132	104	55	0
13	Junior high schools	52800	2040	2026	1064	629	426	314	219	171	89	0
14	Elementary schools	54900	1580	1619	850	502	340	251	175	137	71	0
15	Public facilities (large)	89400	1030	719	378	224	152	113	80	63	34	0
16	Elementary schools	54900	2240	2481	1303	770	522	385	269	210	109	0
17	Public facilities (medium)	57300	980	908	477	282	191	141	99	78	41	0
18	Public facilities (large)	89400	1120	691	363	215	146	108	76	60	32	0
19	Public facilities (small)	13500	310	644	339	201	137	102	72	57	31	0
20	Elementary schools	54900	1670	1853	973	575	390	288	201	157	82	0
21	Junior high schools	52800	1950	2284	1199	708	479	353	246	192	99	0
22	Elementary schools	54900	1580	1474	774	458	311	230	161	126	66	0
23	Junior high schools	52800	1730	1026	539	319	217	161	113	89	48	0
24	Elementary schools	54900	1480	1002	526	311	211	156	109	85	45	0
25	Junior high schools	52800	1520	1007	529	313	212	157	110	86	45	0
26	Public facilities (large)	89400	1270	1233	648	383	260	192	134	105	55	0
27	Elementary schools	54900	1400	559	294	174	118	88	62	49	27	0
Total	-	1527600	40400	32707	17180	10160	6893	5096	3570	2799	1475	0

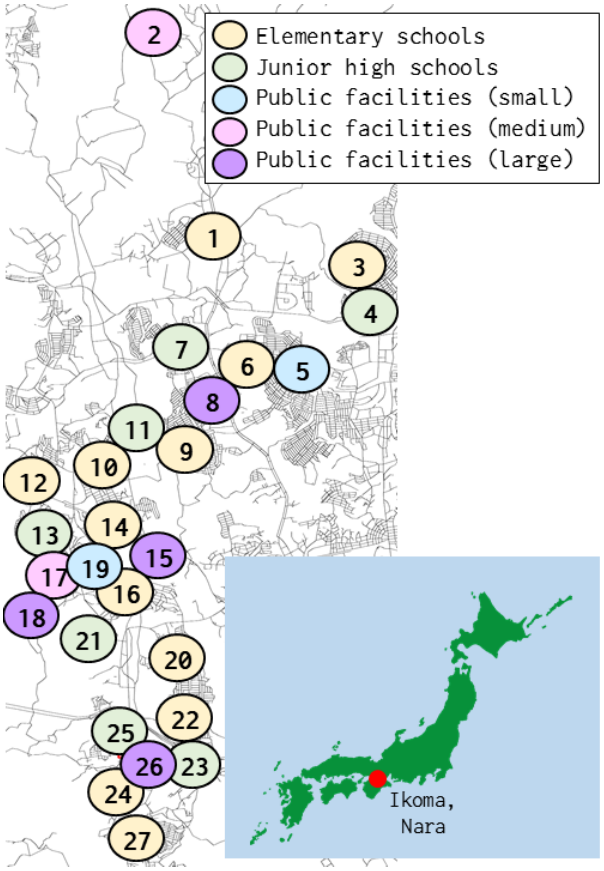


Figure 2: Ikoma City in Nara Prefecture, indicated by red circle in lower right: Shelters are categorized into five colors by type of facility.

where $\boldsymbol{p}_m$ is the coordinate of shelter m and $||\boldsymbol{p}_m - \boldsymbol{p}_{m'}||$ is the Euclidean distance between shelter m and m'. The return time of an evacuee is set independently for simplicity, although such times might not be independent because disaster situations are wildly different depending on the region. We used $\$100$ per person per km for λ.

Comparing Methods

We compared the proposed methods (ESCP, Greedy, and FastGreedy) with ESSP. We used Eqs. (1) - (11) to solve ESSP. To align the conditions, the initial location of the evacuees was set at a shelter. Since ESSP is computationally expensive, we only compared the computation time with ESSP for less than $10,000$ evacuees.

Experimental Environment

For the experiments, we used a computer with an Intel(R) Core(TM) i7-6850K, 3.60GHz CPU, and 64GB memory. Gurobi (Gurobi Optimization 2021) was used as an integer linear programming solver. The time limit of Gurobi was set to 9000 seconds for ESSP. For ESCP, to investigate how much the solution quality decreases with the time limit, the time limit was set to 900 and 9000 seconds. In the results section, the time limit is indicated to the right of ESSP or ESCP.

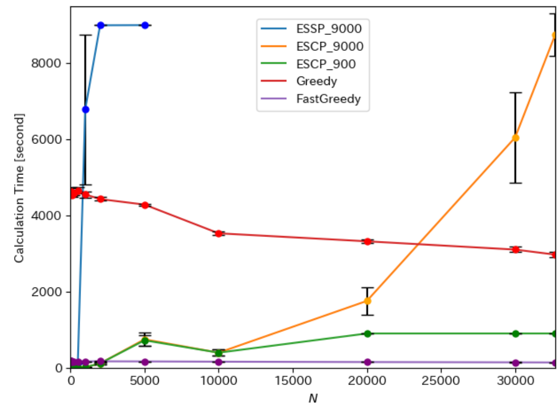


Figure 3: Calculation time for various N (the number of evacuees indicated on the horizontal axis). The line and error bars show the mean and standard deviation of ten trials.

Results

Calculation Time

Figure 3 shows the calculation time for each method. The horizontal axis is evacuees N, and the vertical axis is the computation time (seconds). For ESSP_9000, when $N > 5000$, the calculation could not be performed due to insufficient memory capacity. ESCP, on the other hand, was able to run the optimization even when $N = 32707$. For $N = 5000$, the computation time of ESCP is 12 times faster than that of ESSP. The actual computational time of ESCP increased at a rate more than proportional to the number of evacuees up to $N = 30000$ though its space complexity does not depend on the number of evacuees. This may be due to the fact that when N is small, the number of candidate combinations for the optimal solution is small because a small number of shelters can accommodate all the evacuees.

The calculation time of ESCP_9000 reaches the upper limit of 9000 seconds at $N = 32707$. On the other hand, the time for Greedy and FastGreedy decreases as N increases. This is because the larger N is, the fewer shelters can be closed. For $N \geq 3000$, Greedy takes less time than ESCP_9000. For $N \geq 5000$, FastGreedy takes less time than ESCP_900.

From the above results, in order to solve ESCP faster, we can shorten the time limit and calculate with a solver, while Greedy and FastGreedy may be effective when N is large. Comparing FastGreedy and ESCP_900 with $N = 32707$, the computation time can be reduced by 85%, although the objective function of FastGreedy is increased by 16%.

Performance Evaluation

Figure 4 shows the value of the objective function obtained by each method. ESSP_9000 computed up to a time limit of 9000 seconds with $N \geq 2000$, and obtained poor quality results due to insufficient time to improve the solution.

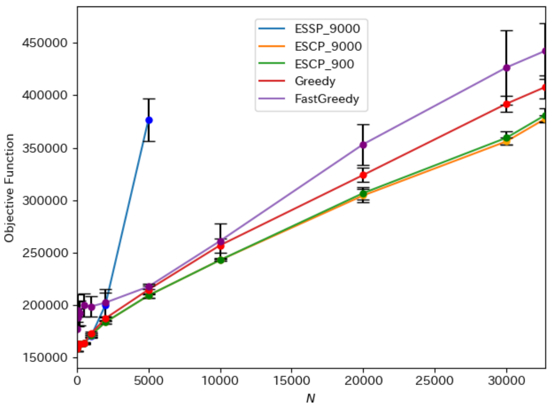


Figure 4: Objective function for various N (the number of evacuees indicated on the horizontal axis). The line and error bars show the mean and standard deviation of ten trials.

The reason of this poor result is that the time limit was reached before the optimization was completed. Compared with ESCP_9000, Greedy obtained an objective function that was about 10% larger in the large N, although the difference was small in instances with small N. Compared with ESCP_9000, FastGreedy showed a larger difference in small N instances and a 20% larger objective function in large N regions. The objective functions of ESCP_9000 and ESCP_900 differed by only about 1%.

Finally, an example of an shelter operation plan generated by ESCP is shown in Table 3. Shelter No.3, No.16, No.25, which have a large capacity for its cost, continues to operate until the end, while the other shelters are closed early. These characteristics seem to be reasonable results for a cost-minimizing solution.

Conclusion & Future Work

We formulated an ESCP (Evacuation Shelter Closing Problem) as a special case of ESSP (Evacuation Shelter Scheduling Problem) and proposed a fast method for ESCP. Our simulation experiments on IKOMA showed that ESCP was 12 times faster than ESSP at $N = 5000$, and that ESCP could solve the instance of more than 30,000 evacuees, which ESSP could not solve. We also proposed two fast heuristic methods for solving ESCP, and experiments show that the computation time can be reduced by 85%, although the value of the objective function increases by 16%.

ESCP can determine the number of evacuees who should be relocated among shelters, but the specific individuals who are actually relocated must be determined in another way. Since the relocation cost of an individual depends on whether he or she is actually relocated, evacuees must be fairly allocated among the group. However, this issue is beyond the scope of this study.

Our future work will address two issues. The first is to increase the speed further. Even though the amount of space complexity is no longer dependent on the number of evacuees, it still takes several hours to obtain the exact solution

Table 3: Number of evacuees assigned to each shelter by ESCP: Gray cells indicate that shelter is operating.

m	$t=0$	1	2	3	4	5	6	7
1	1682	1116	409	0	0	0	0	0
2	397	0	0	0	0	0	0	0
3	1292	1550	1440	1272	1008	784	617	331
4	1292	0	0	0	0	0	0	0
5	161	0	0	0	0	0	0	0
6	764	825	0	0	0	0	0	0
7	622	0	0	0	0	0	0	0
8	895	0	0	0	0	0	0	0
9	1103	0	0	0	0	0	0	0
10	2247	1171	0	0	0	0	0	0
11	1522	1530	1530	912	518	0	0	0
12	1204	0	0	0	0	0	0	0
13	2026	2040	1275	837	0	0	0	0
14	1619	1053	0	0	0	0	0	0
15	719	0	0	0	0	0	0	0
16	2481	2240	2240	2197	2240	2061	1606	822
17	908	0	0	0	0	0	0	0
18	691	0	0	0	0	0	0	0
19	644	310	310	310	310	0	0	0
20	1853	0	0	0	0	0	0	0
21	2284	1416	777	0	0	0	0	0
22	1474	1580	659	0	0	0	0	0
23	1026	0	0	0	0	0	0	0
24	1002	829	0	0	0	0	0	0
25	1007	1520	1520	1365	1020	725	576	322
26	1233	0	0	0	0	0	0	0
27	559	0	0	0	0	0	0	0

for tens of thousands of people, and there is still room for improvement. While computation times may be hardly a problem when creating a monthly plan, faster computation is desirable, especially when creating a plan with shorter time steps. The second issue is determining when evacuees return to their homes, for example, by predicting when transportation services will be restored and when temporary housing will be built. Although such return times for evacuees are assumed to be given, this issue is critical for the application of our proposed method.

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