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CHAIN FLOW ALGORITHM IN EVACUATION PLANNING: CASE OF SUIDO-CHO IN NAGAOKA CITY, JAPAN

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Abstract. *Many earthquakes and typhoons occur in Japan. In preparation for the large-scale disasters, the detailed evacuation plan, such as the location of shelters and evacuation route to shelters, is important. In this paper, we review chain flow algorithm and propose to use this to consider the evacuation plan. As the case study, the chain flow algorithm is applied to Suido-cho in Nagaoka City, Japan. As the result, we found that the evacuation times obtained in the chain flow were relatively realistic compared to those obtained in the time-expanded network that is well used to consider the evacuation plan.*
Keywords: Network model, Chain flow, Time-expanded network, Evacuation planning

1. **Introduction.** In recent years, the large-scale disasters such as earthquakes, tsunamis and typhoons occurred frequently. Particularly, the Great East Japan Earthquake in March 2011 caused many unexpected events, such as the failure of disaster prevention radios and the collapse of breakwaters, which resulted in extensive damage.

On the other hand, according to the Headquarters for Earthquake Research Promotion, as of June 2020, the probability of an earthquake of the magnitude 8 or greater occurring in the Nankai Trough is 70%-80% within the next 30 years [1].

In the advance of such a large-scale disaster, it is important to make the adequate evacuation plans. The evacuation plan should be based on the assumption of various scenarios, such as the time of occurrence, the population distribution and weather conditions to cope with unexpected situations. The network flow model/problem [2], which is easy to model for the reality, is often used for the evacuation planning problem.

Depending on the scale of the target disaster, the evacuation plan is approached differently. In the case of the fire of a specific building, e.g., the station premise and movie theaters [3], the approach is mainly based on the planning and simulation of evacuation routes and facilities. On the other hand, in the case of wide-area disasters, such as earthquakes, Tsunami and volcanic eruptions, the evacuation plans for the large-scale disasters are made. There are some approaches, e.g., an approach to calculating the equilibrium distribution of facility users [4], an approach to finding the lower limit of evacuation time by solving the network flow problem [5], an approach to verifying the crowd behavior by using simulations [6], and an approach of the simulations that evacuees use SNS to spread and collect the evacuation information [7].

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For the evacuation plans of the large-scale disasters, one of the effective approaches is the network flow model/problem [2]. The solution of the network flow problem as a mathematical programming problem was first proposed by Ford and Fulkerson [8, 9]. In these papers, a solution based on the time-expanded network was proposed. Moreover, Kamiyama et al. [2] made a formulation that takes account of the capacity of the shelter. However, a method using time-expanded network requires a computational cost [9]. On the other hand, the regional government offices need to make the evacuation plans for a large number of scenarios, which requires high-speed calculations (on a general-purpose PC).

Katoh and Takizawa [10] proposed a chain flow algorithm to obtain an approximate solution of the fastest evacuation without using the time-expanded network. By using the chain flow algorithm, we can expect to obtain the results in a faster computation time than that using time-expanded network. If the realistic results can be obtained in the faster computation time, the large scale regions can be more easily handled on a general-purpose PC. In this paper, we introduce our model of the evacuation planning problem using the chain flow algorithm based on Katoh and Takizawa [10]. Moreover, as a case study, we apply our model to Suido-cho in Nagaoka City, Japan.

The paper is organized as follows. In Section 2, we briefly explain the outline of the evacuation planning as the network flow model/problem. We also briefly review the time-expanded network and chain flow algorithm. In Section 3, we overview the data of Suido-cho in Nagaoka City, Japan, which we use in this paper. Moreover, we show the result of the simulation of the evacuation planning of Suido-cho by the chain flow algorithm and time-expanded network. Both results are compared and discussed. Section 4 is devoted to a summary.

2. **Evacuation Planning.** The evacuation planning is the problem of finding the completion time of evacuation by flowing from the beginning point to the end point of the network.

As shown in Figure 1, the starting point (source) has the evacuees (supply) and the end point (sink) has the capacity of the shelter (sink). We also define two special vertices: a super source ss that drains evacuees at each starting point and a super sink st that allows evacuees to flow in from each end point.

Then we define a directed graph $G = (V, A)$ with the vertices $v \in V$ (V: vertex set) for the intersections on the road and the edges $a \in A$ (A: edge set) for the road between the

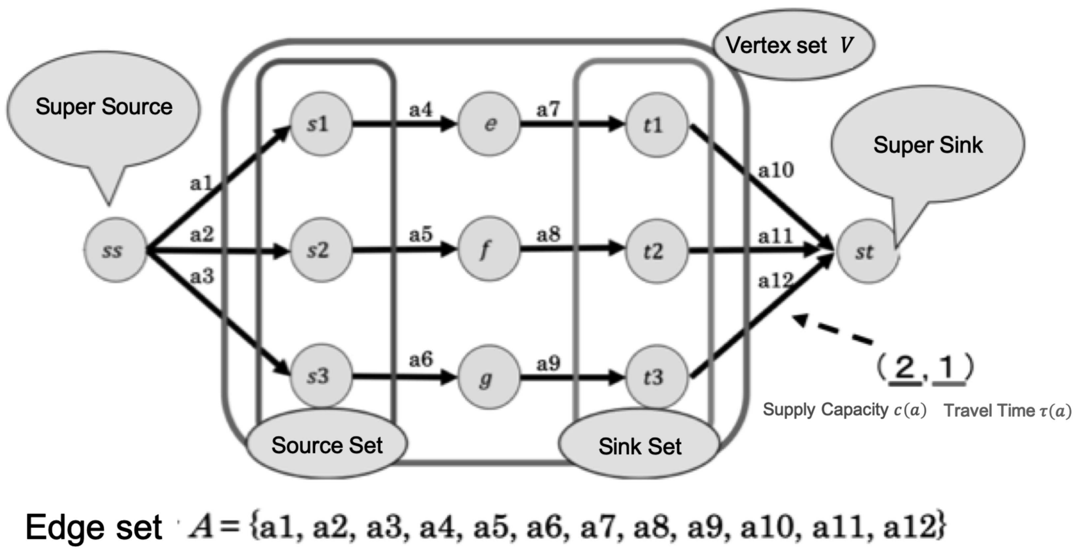


FIGURE 1. Example of the directed graph $G = (V, A)$

intersections. Each edge a has supply capacity that means an upper limit of the number of evacuees allowed to pass per unit of time: $c(a) > 0$ and a travel time $\tau(a)$.

The time of completion of the evacuation is determined by the summation of the time of movement/travel from the start time of the evacuation.

In the following subsections, we describe the features of the time-expanded network that well uses the method of evacuation planning and the chain flow algorithm that uses our proposed method.

2.1. **Time-expanded network.** First, we briefly explain a standard method of evacuation planning based on the time-expanded network. The schematic view of the time-expanded network is shown in Figure 2. The time-expanded network transforms the dynamic network into a static network and finds the maximum flow rate that can flow from the starting point to the end point in a set time [8, 9].

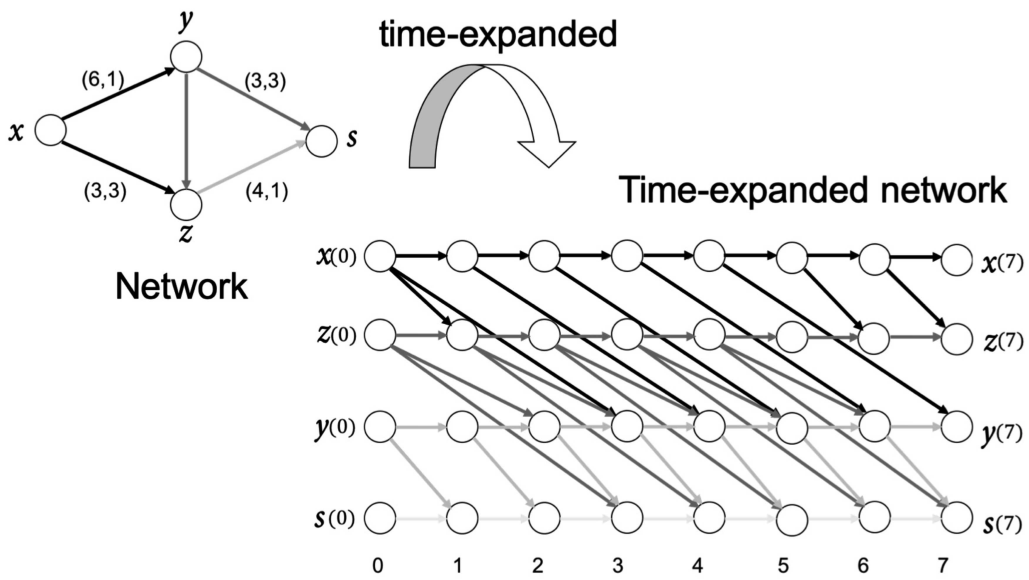


FIGURE 2. Example of the time-expanded network

The brief flowchart of the time-expanded network algorithm is shown in Figure 3. The algorithm using the time-expanded network consists of four steps.

Step 1: Let us set the time $T = 0$

Step 2: Find the minimum-cost-maximum flow with the travel time from ss to st as the cost

Step 3: Add 1 to the time T

Step 4: Repeat Step 2-Step 3 until the total flow rate reaches the number of evacuees

The transformation from a dynamic network to a static network is done by replicating the network for a period of time T (shown in Figure 2). Since the computational cost of the time-expanded network is (the target network) $\times$ (period T), in the case of the large networks, the computation time tends to become long.

2.2. **Chain flow algorithm.** Next, we explain the chain flow algorithm that uses our proposed method. The schematic view of the chain flow is shown in Figure 4.

The chain flow is defined as the flow along each directed route when the minimum-cost-maximum-flow from the super source ss to the super sink st is decomposed into an aligned directional and the supply flows [10]. Here, the minimum-cost-maximum-flow means the path that the cost is minimized among the flows that give the maximum flow.

In the chain flow algorithm, there are two events that trigger the start and the end of the chain flow, respectively, i.e., the starting point event and arrival point event. In the

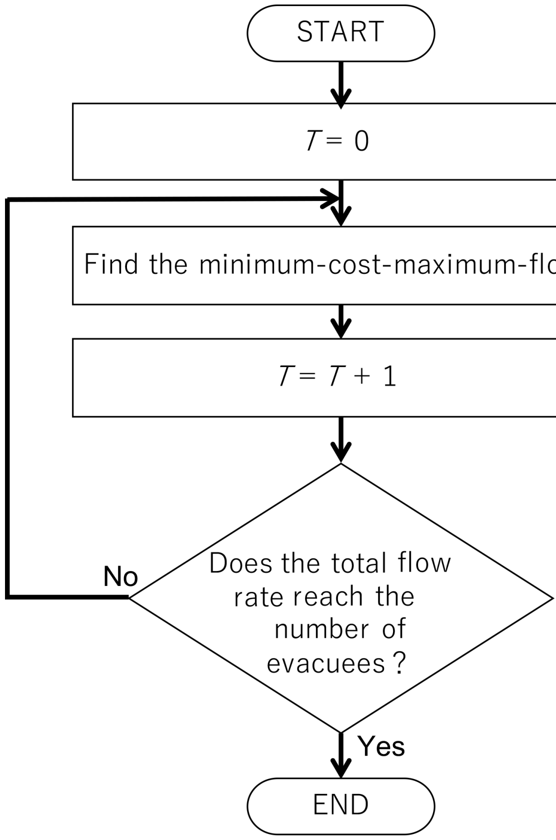


FIGURE 3. Brief flowchart of algorithm using the time-expanded network

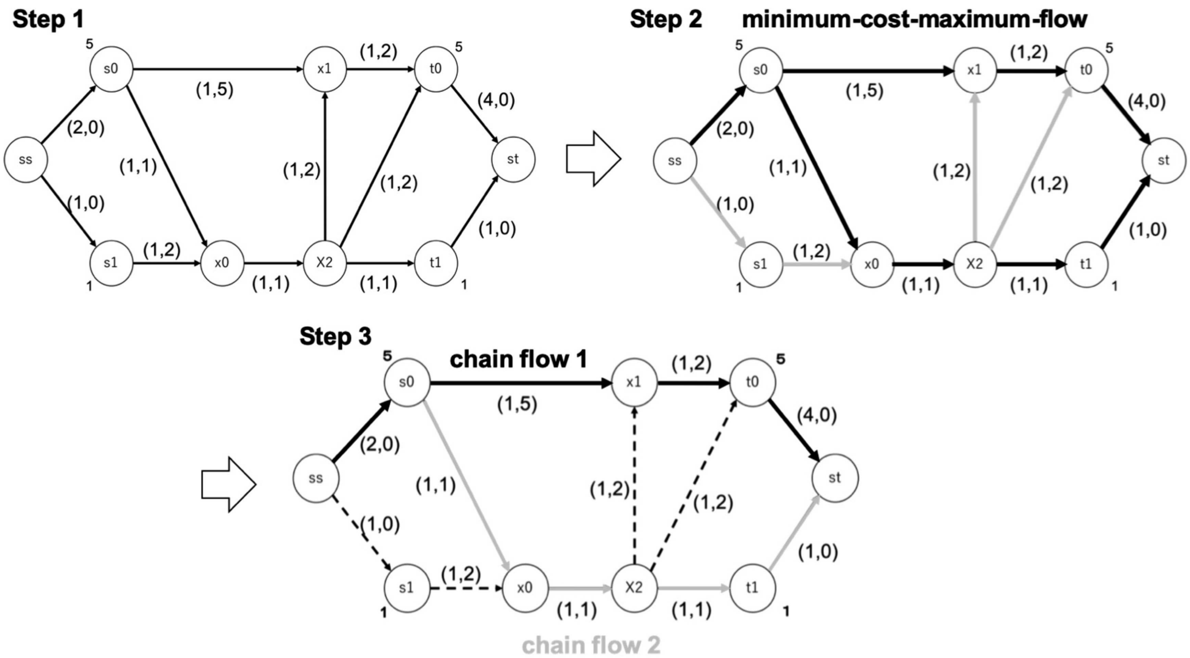


FIGURE 4. Example of the chain flow

starting point event (except for time 0), all the supplies of a source on the chain flow are drained and will become zero. In the arrival point event (except for end time T), the supplies build up to the sink capacity limit of the sink.

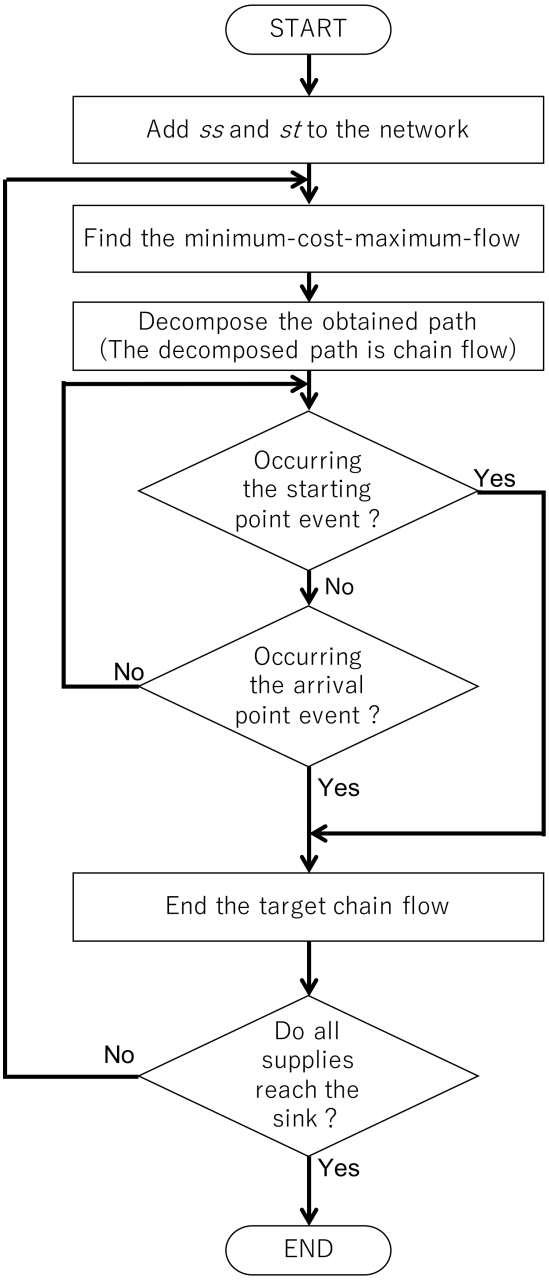


Figure 5. Brief flowchart of the chain flow algorithm

The brief flowchart of the chain flow algorithm is shown in Figure 5. The chain flow algorithm consists of the following six steps.

Step 1: Add ss and st to the network
Step 2: Find the minimum-cost-maximum-flow with the travel time from ss to st as the cost
Step 3: Decompose the path obtained in Step 1 to determine the chain flow
Step 4: Run the supply in each chain flow
Step 5: Terminate the use of chain flow when one of the events occurs
Step 6: Repeat Step 2-Step 5 until all supplies reach the sink

We illustrate the chain flow algorithm by using Figure 4. In Step 2, the minimum-cost-maximum-flow is obtained based on the travel time of the graph. In Step 3, to obtain the chain flows, we decompose the minimum-cost-maximum-flow obtained in Step 2. As the results, we can obtain the chain flow 1 (dark solid line) and the chain flow 2 (light solid line) shown in Figure 4.

One of the features of the chain flow algorithm is that the inter-chain flows are greatly separated from each other. This is due to the fact that we have to wait for the end of the current chain flow in order to acquire a set of chain flows, which increases the time interval between chain flows. In order to reduce the time interval, the algorithm is rearranged to flow without gaps while maintaining the viability of the chain flows [10].

3. **Simulation.** We overview the the data of Suido-cho in Nagaoka City, Niigata Prefecture, Japan, which is used in our simulation. In Figure 6, we show the geographic information of Suido-cho. The data of the road network of Suido-cho is based on the basic map information provided by GSI [11]. The information on the location and capacity of the shelter (t1-t5) is taken from the open data provided by Nagaoka City [12]. From these data and information, we construct the network of Suido-cho shown in Figure 7. In addition, the travel speed of each side was adopted as a single rate of 4 km/h, which is considered to be the average walking speed during disaster evacuation [13].

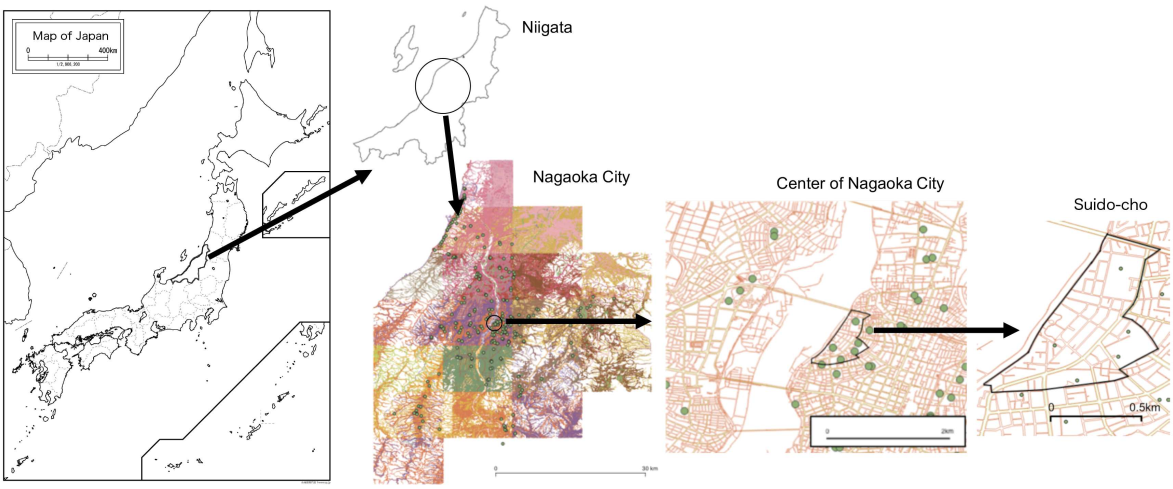
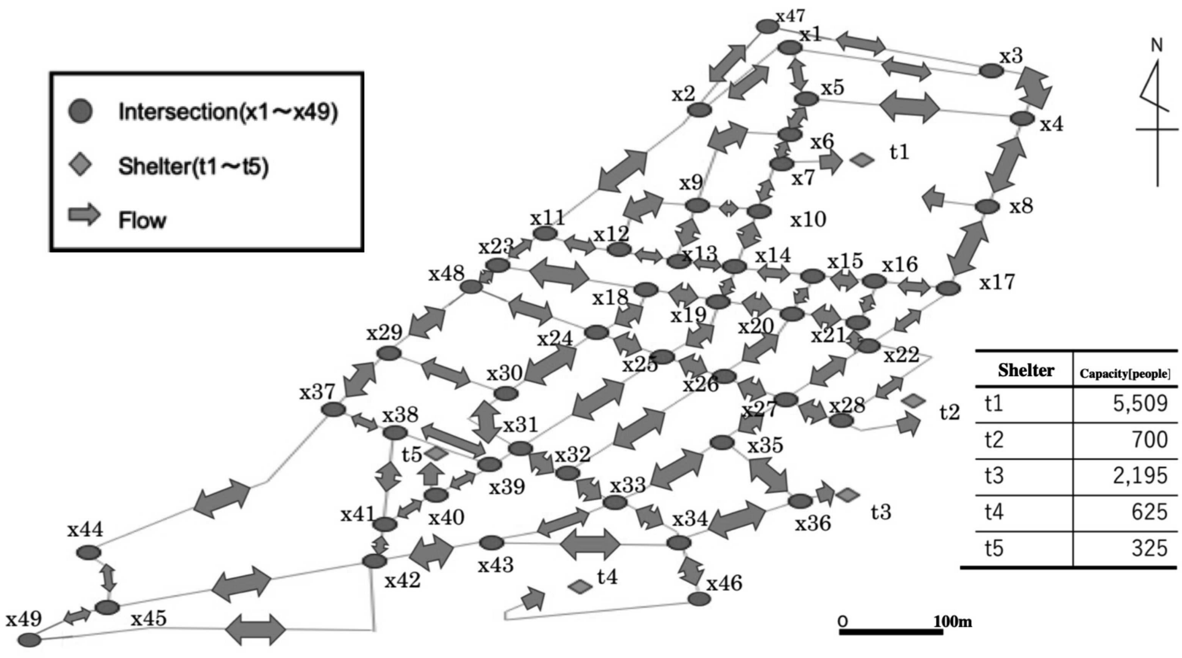


FIGURE 6. Map of Suido-cho in Nagaoka City, Niigata, Japan



Shelter	Capacity[people]
t1	5,509
t2	700
t3	2,195
t4	625
t5	325

FIGURE 7. Network in Suido-cho

The chain flow algorithm and time-expanded network were computed under the same conditions. We set the starting points for evacuation from 1-40 points, and we randomly placed them on 49 intersections (vertices). We then distributed the number of evacuees to the vertices equally and run the supply through the flow to the network. We perform 100 times simulations and calculate the average evacuation time for each of the 49 intersections.

Our simulation of both the chain flow algorithm and time-expanded network is conducted by a MacBook Air (CPU Intel Core i7 1.7 GHz, 8 GB memory).

3.1. **Result of simulation.** Both results of the chain flow algorithm and time-expanded network are extracted for the cases that the evacuation starting points are set at 10, 20, 30, and 40 points. Table 1 and Table 2 show the mean evacuation time and standard deviation in each case for the chain flow algorithm and for the time-expanded network, respectively.

Table 1. Average evacuation time [sec] for the chain flow algorithm

Evacuation starting points	Average evacuation time	Standard deviation
10 points	880	131
20 points	907	139
30 points	910	124
40 points	956	133

Table 2. Average evacuation time [sec] for time-expanded network

Evacuation starting points	Average evacuation time	Standard deviation
10 points	714	82
20 points	715	63
30 points	717	36
40 points	710	35

From Table 1, the average evacuation time is proportional to the increase in the number of evacuation starting points. On the other hand, from Table 2, the average evacuation time is almost the same value. Since the chain flows created by the increase in the number of evacuation points, the travel time increases.

Figure 8 shows the time change of the remanning capacity of each shelter in the case of the maximum evacuation time (10 evacuation starting points) for the chain flow algorithm. From Figure 8, we found the behavior of the chain flow algorithm as follows: after the chain flow is created, the evacuees waiting at the evacuation starting point are flowed to the network in turn. The capacity of the shelter does not decrease until the first evacuee to flow out arrives at the shelter. The evacuees arrive at the shelter and then the capacity of the shelter starts the change. During the period when the remaining capacity has not decreased shown in Figure 8, we can understand that the first evacuee is heading to the shelter or the shelter is not selected for the chain flow. On the other hand, during the period of decreasing shelter capacity, we can understand that the evacuees are coming into the shelters. From this point of view, it can be seen that the behavior of the chain flow algorithm is as expected.

Figure 9 shows the same figure of Figure 8 but for the time-expanded network. From Figure 9, we found that once the evacuation begins and the first evacuees arrive at the shelter, the capacity of the shelter continues to decrease without stopping along the way compared to chain flow.

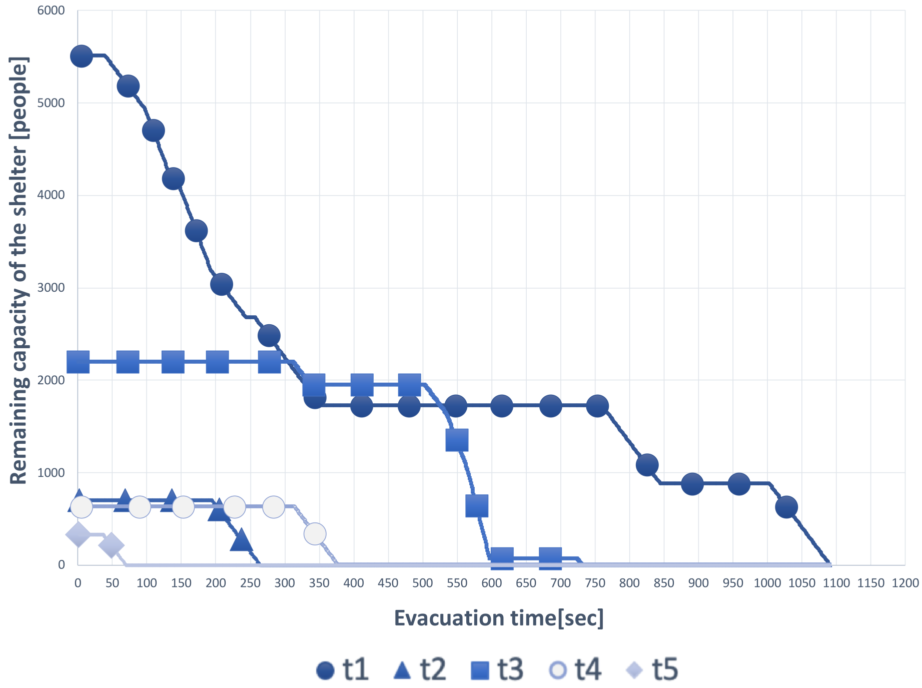


FIGURE 8. Time change of the remaining capacity of each shelter in the case of the maximum evacuation time (10 evacuation starting points) for the chain flow algorithm

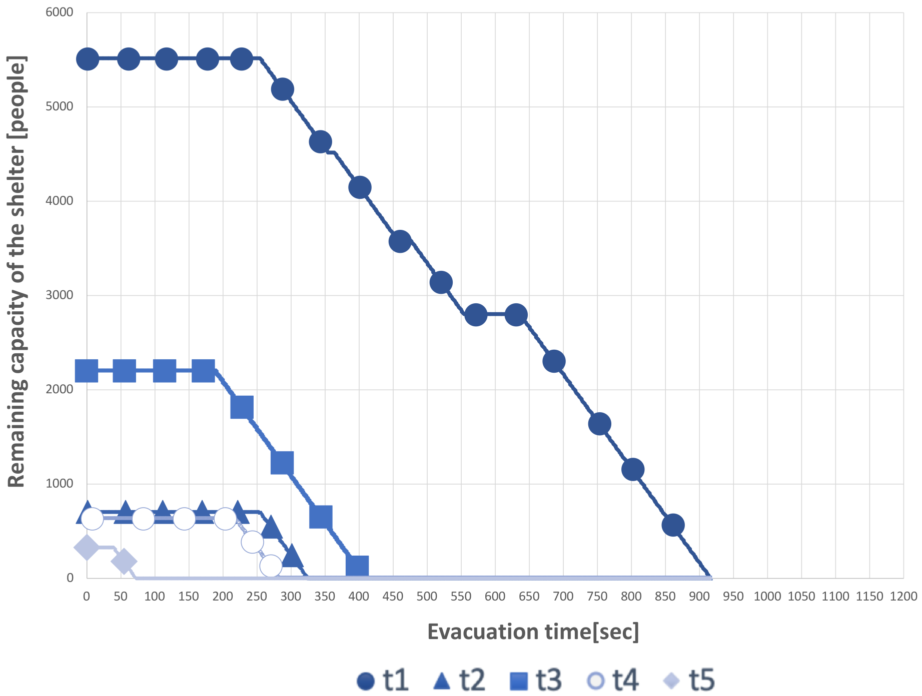


FIGURE 9. The same figure of Figure 8 but for the time-expanded network

3.2. **Comparison of chain flow algorithms and time-expanded network.** The chain flow algorithm and time-expanded network were computed under the same conditions. We randomly placed 10 starting points of the evacuation on the intersections (nodes) and simulated 100 times for the evacuation time. Then, we compared the result of the time-expanded network with the result of the chain flow algorithm. Table 3 shows

Table 3. Average evacuation time [sec] and computation time [sec]

	Average evacuation time	Computation time
Chain flow algorithm	880	3
Time-expanded network	731	2,432

the average evacuation time and computation time for the chain flow algorithm and the time-expanded network.

Since Suido-cho is an area of about 340,000 m^2, the evacuation time can roughly estimate 1,000 seconds or less. From Table 3, we found that the evacuation times obtained by the chain flow algorithm and the time-expanded network are both realistic values. On the other hand, the computation time of the time-expanded network is much longer than that of the chain flow algorithm. It is likely to be difficult to compute on a general-purpose PC when we consider the evacuation planning of the larger area.

4. **Conclusion.** In this paper, we modeled the evacuation plans using the chain flow algorithm, which is one of the network models, and compared the results with those obtained from the time-expanded network, which are often used as models for evacuation plans.

The results showed that the chain flow algorithm was able to obtain sufficiently reasonable evacuation time considering the topographic scale of the Suido-cho in Nagaoka City, Niigata, Japan. In comparison with the time-expanded network, both algorithms were able to obtain reasonable evacuation times, but the chain flow algorithm was found to be superior in terms of the computation time.

We emphasize that our result is only one case study. However, there is a possibility that we can use the chain flow algorithm to study the evacuation plan in the future. So we will have to confirm the different cases.

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