

## Article

# Multi-Objective Evacuation Planning Model Considering Post-Earthquake Fire Spread: A Tokyo Case Study

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**Abstract:** As an integral part of the 2030 Agenda for Sustainable Development, Disaster Risk Reduction (DRR) is essential for human safety and city sustainability. In recent years, natural disasters, which have had a tremendous negative impact on economic and social development, have frequently occurred in cities. As one of these devastating disasters, earthquakes can severely damage the achievements of urban development and impact the sustainable development of cities. To prepare for potential large earthquakes in the future, efficient evacuation plans need to be developed to enhance evacuation efficiency and minimize casualties. Most previous research focuses on minimization of distance or cost while ignoring risk factors. We propose a multi-objective optimization model with the goal of reducing the risk during the evacuation process, which is called the risk reduction model (RRM). Problem-specific indicators for screening optimal solutions are introduced. The research selects the Ogu area in Tokyo as a case study, where there is a relatively high density of wooden structures, increasing the risks of building collapse and fire spread after an earthquake, and is based on a two-phase evacuation flow that considers secondary evacuation for fire response. The results indicate that, in this case, RRM can, in most situations, reduce the risk level during the evacuation process and improve evacuation efficiency and success rate without significantly increasing the total evacuation distance. It proves to be superior to the traditional distance minimization model (DMM), which prioritizes minimizing the total distance as the objective function.

**Keywords:** location-allocation; multi-objective optimization; disaster risk reduction; Tokyo



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## 1. Introduction

The United Nations Office for Disaster Risk Reduction (UNDRR) indicates a substantial rise in the number of reported disasters annually over the past two decades [1]. Based on the data from the United States Geological Survey (USGS), as one of the most fatal natural disasters, the frequency of powerful earthquakes also demonstrates a significant growth trend. Earthquakes could result in structural damage, casualties, and environmental risks caused by debris [2]. In the 2011 Great East Japan Earthquake, a total of 22,318 people were reported to be dead or missing, 406,067 buildings were identified as damaged, and the economic loss was estimated at 16 to 25 trillion yen [3]. The aftermath of seismic events often includes economic setbacks, social upheaval, and environmental degradation, hindering the long-term progress and resilience of urban areas. Recovering from a big earthquake usually takes a long time, slowing down the sustainable development of cities. Moreover, earthquake-induced secondary disasters (i.e., landslides, liquefaction, tsunami, fire, avalanches, barrier lakes, and floods) could also result in additional losses [4]. According to the investigation by Marano et al., approximately 21.5% of deadly earthquakes result in fatalities attributed to secondary effects [5]. Fire is one of the most serious secondary effects of earthquakes, which can easily spread in dense urban areas, especially when there are large areas of wooden buildings. In 1995, a total of 285 fires broke out immediately following the Great Hanshin Awaji Earthquake [6], resulting in 504 deaths [7].

Since earthquakes can seriously disrupt the sustainable development of cities, prioritizing earthquake preparedness is essential to ensuring the sustainable development of the economy and society. Improving the seismic resilience of buildings [8] can directly decrease damage caused by earthquakes. Additionally, disaster mitigation planning, including risk assessment, disaster prevention, and humanitarian responses, leading to sustainability actions [9], is critical for protecting the gains of development [10]. Successful cases around the world have proven this. For example, in New York, multi-layered protection measures are adopted and resilient infrastructures are built to mitigate flood risks. As an important part of disaster planning, a well-designed evacuation plan can effectively reduce risks and minimize losses for cities in the aftermath of earthquake disasters, thereby further ensuring the resilience and sustainability of urban economic and social development. As a crucial procedure in the disaster response phase, it could significantly reduce loss by quickly transferring evacuees from nearby residential areas to safer places, simultaneously reducing the time people are exposed to risk [11]. Almost every city in Japan has an emergency plan that includes locations of shelters and allocations of residential areas to shelters [12]. In Tokyo, to prepare for the possibility of a major earthquake [10], a hierarchical structure of shelters is adopted. There are three levels of shelters: The lower-level shelter (LS), called Temporary Evacuation Area, is used for a short stay immediately after an earthquake; the intermediate-level shelter (MS), called Evacuation Area, is usually a large area of fire-resistant open space; and the higher-level shelter (HS), called Evacuation Center, is utilized as accommodations for those affected who are not suitable to continue living in their homes [13]. To address potential fire hazards in areas with a dense distribution of wooden structures after an earthquake, a two-phase evacuation flow is proposed to allocate evacuees between these hierarchical shelters. Compared to a direct evacuation plan, the two-phase evacuation flow is expected to significantly reduce casualties by evacuating the population to MSs, which protect people from fire spreading when a fire occurs near LSs [14]. Although fire is dangerous in many cities, most current research does not discuss this two-phase evacuation and may fail to generate a safety evacuation plan. Our proposed model is based on a two-phase evacuation and aims to minimize disaster risk to ensure the safety of evacuees.

This research aims to investigate a multi-objective approach to determine the optimal locations of LSs and the allocations among residential areas and shelters. The remainder of this paper is structured as follows: Section 2 reviews the literature related to shelter location-allocation models and risk assessment. Section 3 proposes the model formulation and introduces the procedure to solve it. Section 4 applies the method to a real-world case in Tokyo. Finally, Section 5 summarizes this study and provides prospects for future research directions.

## 2. Literature Review

The shelter location and allocation/routing model have been extensively investigated in a large body of literature. The model formulation, including the selection of decision variables and objectives, varies based on the real-world problem it addresses. Typically, a location model is used to determine the location of facilities, while an allocation model is employed to assign evacuees or resources. Some literature also considers routing decisions alongside location and allocation decisions [15]. Several disasters garnering the most attention include hurricanes [16], floods [17,18], and earthquakes [11,19,20]. Multi-hazard scenarios containing all these disasters can also be found in some literature [21]. In this study, we focus on the literature in two main areas: (1) Multi-objective shelter location/allocation/routing model; and (2) assessment of risk during evacuation. We will examine previous studies in these two fields and identify the research gaps that current research is addressing.

### 2.1. Objective of Shelter Location-Allocation Model

The objectives or criteria for selecting locations of facilities for disaster management and deciding allocation plans differ according to the disaster management phase and the type of disaster. In the pre-disaster phase, the priority is to strengthen vulnerable facilities to prepare for possible upcoming disasters. Therefore, the cost of constructing shelters or other infrastructures is most considered [11,15,19,22–27]. Some studies also include the cost of pre-positioning resources at this stage [25,26]. Usually, the (weighted) number of shelters, which can also be regarded as the cost of establishing new shelters, is used as a constraint [16] or a minimization objective due to budget limitations [14,23,24]. In the post-disaster phase, the main objective is to quickly relocate as many people as possible to safe places, which can be further decomposed into two sub-goals: (1) Transferring people to shelters or other facilities as soon as possible, and (2) minimizing the number of people remaining in hazardous areas when shelter capacities are limited and cannot fulfill all demands [16]. Therefore, evacuation time [17,28,29] and total evacuation distance [11,19,22,30–32] are the primary objectives that need to be included in the optimization model first, while unmet demand [16] or covered demand [24,30] are other objectives that also need to be taken into consideration. For car evacuation or relief distribution problems, transportation costs for relief are also an important indicator that needs to be included in the objectives [25,26]. These works, as shown in Table 1, mainly focus on cost or demand, while there is a lack of literature examining other disaster-related factors, such as risk [33,34], which could highly influence the safety of evacuees in real disasters. The way to solve such multi-objective problems includes using the weighted sum of different objectives after standardization [16,24] or heuristic algorithms [15,19,30,31].

**Table 1.** Literature of multi-objective shelter location/allocation/routing model.

| Author                         | Preparedness Stage Objective                                                                                                                                             | Response Stage Objective                                              | Method                                           |
|--------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|--------------------------------------------------|
| Li et al. [30]                 | -                                                                                                                                                                        | Total evacuation distance,<br>Covered demand                          | Genetic algorithm, Simulated annealing algorithm |
| Aghaie and Karimi [15]         | Shelter cost construction                                                                                                                                                | Relief transportation time                                            | NSGA-II                                          |
| Hammad [23]                    | Shelter cost construction                                                                                                                                                | Total evacuation time, Individual evacuation time                     | Lexicographic optimization                       |
| Hallak et al. [24]             | Shelter construction cost,<br>Cash-for-work amount,<br>Number of facilities that have portable WASH facilities,<br>Number of facilities with future scale-up flexibility | Covered demand,<br>Covered demand with vulnerability                  | Weighted-goal programming (WGP)                  |
| Xu et al. [31]                 | Total shelter area                                                                                                                                                       | Total evacuation distance                                             | Particle swarm optimization (PSO)                |
| Hu et al. [19]                 | Shelter construction cost                                                                                                                                                | Total evacuation distance                                             | NSGA-II                                          |
| Li et al. [16]                 | -                                                                                                                                                                        | Unmet demand,<br>Total evacuation time                                | Weighted-goal programming (WGP)                  |
| Coutinho-Rodrigues et al. [33] | Risk of shelters, Num of shelters                                                                                                                                        | Total evacuation distance,<br>Total evacuation time,<br>Risk of paths | Hierarchical method                              |

### 2.2. Risk Assessment during Evacuation

The estimation of fire risk has been widely investigated by researchers and government departments. Current research primarily focuses on the fire risks of buildings and natural environments, with only minimal research dedicated to urban fire risks [35]. Nishino et al. [36] define the fire risk of a certain district as the probability that the number of burned-down buildings exceeds a threshold within a period. Zhang [37] presents a definition of urban fire risk, which is an indicator system including three first-level indicators (risk of urban fire, urban vulnerability, and urban anti-fire capability) and 13 s level indicators. Evacuation risk can be considered the risk of a certain area that evacuees move through, which is associated with several components within urban transportation networks: Nodes (demand points/facilities) and paths (primary paths/backup paths) [33]).

As noted by Esposito Amideo et al. [38], there are only several studies considering risk in shelter location/allocation/routing models. Existing research mainly focuses on fires or floods because these two kinds of risks directly threaten people's lives. In most evacuation studies, a ready-made hazard risk assessment method is directly applied to estimate. Chowdhury et al. [39] assess the flood risk as the product of the vulnerability index and hazard index, in which the hazard index is measured by the product of the occurrence probability and flood depth, and the vulnerability index is measured by the density of unmet demand. Coutinho-Rodrigues et al. [33] minimize fire risk related to both shelters and paths using the Fire Risk Index Method proposed by Magnusson and Rantatalo [40]. Lämmel et al. [41] use an integrated equation containing damage, coping capability, and the probability of the wave reaching the coast. There is also an indirect way to use the pass ratio to indicate risk. For example, Opasanon et al. [42] maximize the minimum probability of arriving at an exit to reduce the risk evacuees may face.

Based on the previous studies, there are several points that need to be further explored. As mentioned in the literature review, most location models do not directly incorporate risk into their objective functions, although reducing risks should be the primary goal for evacuation planning. A common alternative approach is to maximize efficiency as the objective function. In theory, to improve effectiveness, minimizing the total travel distance or total travel time can also reduce the risk exposure evacuees face during evacuation simultaneously [43], and minimizing the amount of unmet demand can decrease the number of people exposed to risk [44]. However, for disasters like earthquakes, fire spreading along street-facing buildings may increase the risk of a selected allocation. In such cases, another allocation with a longer distance but a safer path is preferable. Correspondingly, if only reducing fire risk is considered in the model, it may result in very long evacuation paths. It is necessary to strike a balance between risk and distance. The solving method proposed by Coutinho-Rodrigues et al. [33] is to delete all paths longer than walking range. Some authors include both distance and risk in objective functions [33,34]. However, these studies do not specify how to choose the most appropriate solution from a set of Pareto solutions.

The contributions of this research are: (1) proposing a multi-objective risk reduction model that considers risks from multiple sources, including not only fire risk but also the risk of blockage caused by building collapse; and (2) proposing a two-step indicator system to filter the most appropriate solution from the set of Pareto solutions.

### 3. Methodology

#### 3.1. Estimation of Fire Risk

In this research, both the risks related to links (streets) and nodes (shelters) will be quantified. Table 2 regulates the meaning of all suffixes in this article, Table 3 shows the details of all variables, parameters and sets. We use the sum of the catching fire probability of street-facing buildings, the collapse probability of street-facing buildings, and the blockage probability of streets to denote the risk of passing through a street. Additionally, we use the sum of the catching fire probability of buildings within a 50 m radius, which is a reasonable safety distance for fire, to denote the risk of a shelter. The following equation can be used to measure the static risk concentration in link  $l$  (every path consists of at least one link) if we disregard the time factor [44].  $l_a, l_b$  are the start and end points of a link, respectively, and  $r(x)$  is the function of risk at a certain location  $x$ . The risk of a link, denoted as  $r_l$ , is the integral of the risk along the path.

$$r_l = \int_{l_b}^{l_a} r(x) dx, \quad (1)$$

Therefore, the total risk of a path  $p$  can be defined as the combination of the expected value of the number of burned-down street-facing buildings, the expected value of the number of collapsed buildings, and the expected value of blocked streets. Equation (2) shows how to calculate the risk for a path. Firstly, the collapse risk and fire risk for every

building along the street are calculated. In Equation (2), we denote the fire risk and collapse risk for building  $b$  as  $u_b$  and  $v_b$ , respectively. We add them together and obtain the risk for all buildings in the set  $B_l$ , which includes all street-facing buildings along link  $l$ . Secondly, the risk for the street, denoted as  $z_l$ , is added. By these two steps, we can obtain the total risk for a link. Finally, sum up the risk for all links within a path.

$$r_p = \sum_{l \in L_p} (\sum_{b \in B_l} (u_b + v_b) + z_l), \quad (2)$$

**Table 2.** Suffixes.

| Type   | Symbol | Description                     |
|--------|--------|---------------------------------|
| Suffix | $d$    | DP (demand point)               |
|        | $t$    | LS (lower-level shelter)        |
|        | $e$    | MS (intermediate-level shelter) |
|        | $b$    | Building                        |
|        | $l$    | Link                            |
|        | $p$    | Path                            |
|        | $dt$   | From DP to LS                   |
|        | $de$   | From DP to MS                   |
|        | $te$   | From LS to MS                   |

**Table 3.** Decision variable, parameter, and set.

| Type              | Symbol   | Description                                                                                                     |
|-------------------|----------|-----------------------------------------------------------------------------------------------------------------|
| Decision variable | $x_t$    | 1 if LS $t$ is available, 0 otherwise                                                                           |
|                   | $v_{dt}$ | 1 if people in DP $d$ is allocated to LS $t$ , 0 otherwise                                                      |
|                   | $v_{de}$ | 1 if people in DP $d$ is allocated to MS $e$ , 0 otherwise                                                      |
|                   | $v_{te}$ | 1 if people in LS $t$ is allocated to MS $e$ , 0 otherwise. People will evacuate to MS $e$ if LS $t$ is on fire |
| Parameter         | $p_l$    | Pass ratio for link $l$                                                                                         |
|                   | $n_d$    | Demand in DP $d$                                                                                                |
|                   | $r_l$    | Risk of link $l$                                                                                                |
|                   | $r_p$    | Risk of path $p$                                                                                                |
|                   | $r_{dt}$ | Average risk of tolerant paths from DP $d$ to LS $t$                                                            |
|                   | $r_{te}$ | Average risk of tolerant paths from LS $t$ to MS $e$                                                            |
|                   | $r_{de}$ | Average risk of tolerant paths from DP $d$ to MS $e$                                                            |
|                   | $l_{dt}$ | Average length of tolerant paths from DP $d$ to LS $t$                                                          |
|                   | $l_{te}$ | Average length of tolerant paths from LS $t$ to MS $e$                                                          |
|                   | $l_{de}$ | Average length of tolerant paths from DP $d$ to MS $e$                                                          |
|                   | $r_t$    | Risk of LS $t$                                                                                                  |
|                   | $u_b$    | Fire probability of building $b$                                                                                |
|                   | $v_b$    | Collapse probability of building $b$                                                                            |
|                   | $z_l$    | Blockage probability of link $l$                                                                                |
|                   | $c_t$    | Capacity of LS $t$                                                                                              |
|                   | $u$      | The maximum distance between a node and the node to which it is allocated                                       |
|                   | $M$      | A big number                                                                                                    |
|                   | $N_{dt}$ | Number of tolerant paths between DP $d$ and LS $t$                                                              |
|                   | $P_{dt}$ | Set of all tolerant paths between DP $d$ and LS $t$                                                             |
| Set               | $D$      | Set of DPs                                                                                                      |
|                   | $T$      | Set of LSs                                                                                                      |
|                   | $E$      | Set of MSs                                                                                                      |
|                   | $L_p$    | Set of links in path $p$                                                                                        |
|                   | $L_{dt}$ | Set of links in shortest path from DP $d$ to LS $t$                                                             |
|                   | $L_{de}$ | Set of links in shortest path from DP $d$ to MS $e$                                                             |
|                   | $L_{te}$ | Set of links in shortest path from LS $t$ to MS $e$                                                             |
|                   | $B_l$    | Set of street-facing buildings along link $l$                                                                   |
|                   | $B_t$    | Set of buildings within 50 m range of LS $t$                                                                    |

In addition to the shortest path, the risk of evacuation from one node to another should also consider other “tolerant paths,” which refer to those paths exceeding the minimum

distance but within a tolerable range. The definition of “tolerant paths” can be seen in Section 3.2. Since the probability of choosing each tolerant path is assumed to be equal, the risk between two nodes (take risk between DP  $d$  and LS  $t$  as an example) is represented as the average value of the risk of all tolerant paths between DP  $d$  and LS  $t$ . As shown in Equation (3),  $P_{dt}$  represents all “tolerant paths” from DP  $d$  to LS  $t$ . We added the risk value of all these paths together and then divided it by  $N_{dt}$ , which represents the number of ‘tolerant paths’.

$$r_{dt} = \frac{1}{N_{dt}} \sum_{p \in P_{dt}} r_p, \quad (3)$$

The risk of node  $t$  is measured by the sum of the probabilities of nearby buildings catching fire (within a range of 50 m), as shown in Equation (4).  $U_b$  represents the fire probability for building  $b$ , and  $B_t$  is the set of all neighboring buildings of LS  $t$ .

$$r_t = \sum_{b \in B_t} U_b, \quad (4)$$

### 3.2. Multi-Objective Location-Allocation Model for Hierarchical Shelters

A hierarchical facility location problem (HFLP) determines the locations of facilities in a multi-level system where higher-level facilities provide services for lower-level facilities [45]. While the majority of literature related to hierarchical facilities is mostly present in fields such as healthcare, education, or waste management, there is also a necessity for multi-level shelter location models in the field of disaster management. This is because a disaster is not a static process; in each time period, the demand for shelter and the condition of the network, availabilities, or capacities of facilities may vary. One example is flooding [17]; the evolution of water speed and depth leads to changes in road conditions and demand for shelters over time.

In this research, a multi-objective model is proposed to determine the locations of open shelters and the allocation between demand points (DP), lower-level shelters (LS), and intermediate-level shelters (MS). To ensure evacuation safety and avoid chaotic situations, a two-phase evacuation flow is implemented by the Tokyo Metropolitan Government. The flow of this two-phase evacuation is illustrated in Figure 1. In the first phase, evacuees will be allocated to nearby LSs or directly to MSs. In the second phase, for those evacuees staying at LSs, if a fire occurs near the LS, evacuees will continue to move to MSs. This is because LSs are usually small parks or green areas, which could become dangerous in case of a fire, while MSs, typically larger parks or open spaces, can protect evacuees from fire spread due to their larger open area. If no fire occurs, evacuees will continue to stay at LSs until the danger is resolved. The following assumptions are made in order to make the problem more manageable:

- A major earthquake is assumed, requiring all residents to initially relocate to LSs or MSs.
- For the sake of convenience in management, residents within one DP will be assigned to the same LS or MS. Additionally, evacuees in one LS can only be assigned to the same MS.
- People will choose evacuation routes that do not exceed 20% of the shortest path length with equal probability. This ratio of 20% is also referred to as the tolerance factor or level of tolerance by Jahn et al. [46] and Bayram et al. [29]. This level typically falls within the range of 0 to 100%. To avoid excessive computational workload, we assume it as 20%. In the remaining part of the paper, we refer to these paths as “tolerant paths”.

A risk reduction model (RRM) with the objectives of minimizing the risk associated with shelters and paths, and maximizing the probabilities of reaching shelters, is proposed. In the RRM, we consider three objectives: Equation (6) minimizes the risks related to shelters, Equation (7) minimizes the risks of paths, and Equation (8) maximizes the sum of pass ratios for all paths. Equation (9) ensures that each DP is allocated to either one LS or one MS, while Equation (10) indicates that if the LS is not available, there will be no allocation from any DP to this node. Equation (11) ensures that evacuees in the same

LS will only be allocated to one MS if there is a fire nearby, and also ensures that if this LS is not available, there will be no allocation from this node. Equation (12) guarantees that the number of evacuees in each LS will not exceed the capacity limit of the LS, and Equations (13)–(15) indicate that the allocated shelter should not be too far away from the DP or the former shelter. Constraint (16) defines the binary variables. Another distance minimization model (DMM) with only one objective (5), which is the minimization of the total evacuation distance, is proposed as a control model.

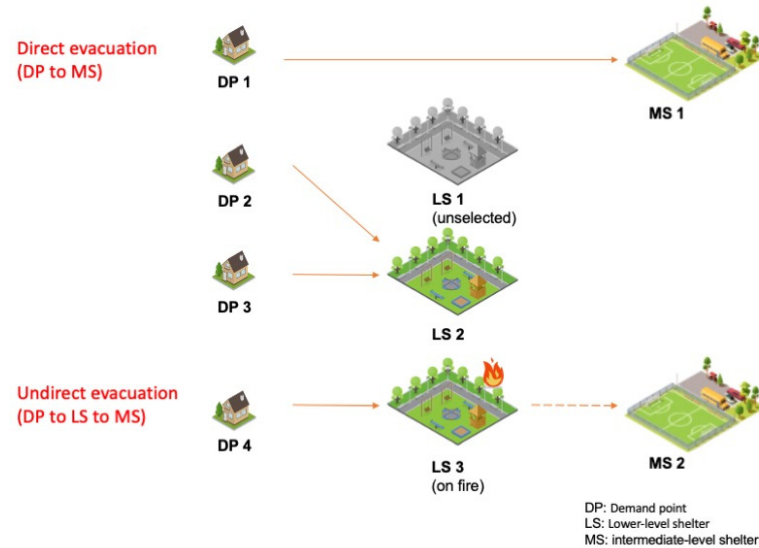


Figure 1. Two-phase evacuation flow.

- Objective 0: minimize the total evacuation distance.

$$\min f_0 = \sum_{d \in D} \sum_{t \in T} v_{dt} n_d l_{dt} + \sum_{d \in D} \sum_{e \in E} v_{de} n_d l_{de} + \sum_{t \in T} \sum_{e \in E} v_{te} n_t l_{te}, \quad (5)$$

- Objective 1: minimize the risk in LSs.

$$\min f_1 = \sum_{t \in T} x_t r_t, \quad (6)$$

- Objective 2: minimize the risk along paths.

$$\min f_2 = \sum_{d \in D} \sum_{t \in T} v_{dt} n_d r_{dt} + \sum_{d \in D} \sum_{e \in E} v_{de} n_d r_{de} + \sum_{t \in T} \sum_{e \in E} v_{te} r_{te} (\sum_{d \in D} v_{dt} n_d), \quad (7)$$

- Objective 3: maximize the pass ratio.

$$\max f_3 = \sum_{d \in D, t \in T} v_{dt} \prod_{l \in L_{dt}} p_l + \sum_{d \in D, e \in E} v_{de} \prod_{l \in L_{de}} p_l + \sum_{t \in T, e \in E} v_{te} \prod_{l \in L_{te}} p_l, \quad (8)$$

- Constraints.

$$\sum_{t \in T} v_{dt} + \sum_{e \in E} v_{de} = 1 \quad \forall d \in D, \quad (9)$$

$$x_t \leq \sum_{t \in T} v_{dt} \leq M x_t \quad \forall t \in T, \quad (10)$$

$$\sum_{e \in E} v_{te} = x_t \quad \forall t \in T, \quad (11)$$

$$\sum_{d \in D} n_d v_{dt} \leq c_t \quad \forall t \in T, \quad (12)$$

$$v_{dt} l_{dt} \leq u, \quad (13)$$

$$v_{de} l_{de} \leq u, \quad (14)$$

$$v_{te}l_{te} \leq u, \quad (15)$$

$$v_{dt}, v_{de}, x_t \in \{0, 1\}, \quad (16)$$

### 3.3. Solution Procedure

The modified epsilon-constraint method called AUGMECON by Mavrotas, G [47] is used to solve the RRM. This method is widely acknowledged for solving multi-objective problems [48,49]. The detailed steps are as follows:

- Step1: construct payoff table

Risks during the evacuation process, including fire, collapse, and blockage, pose significant threats to evacuees after an earthquake. Therefore, we prioritize minimizing  $f_2$  as our main optimization goal. Using the payoff table shown in Table 4, we can determine the lower bound and range for  $f_1$  and  $f_3$ . For example, the lower bound for  $f_1$  is the minimum value among all optimization results for  $f_1$  (i.e., R11, R12, R13), the upper bound is the maximum value among R11, R12, R13, and the range is the gap between the upper bound and the lower bound. These optimization models are solved using the commercial solver Gurobi (download from <https://www.gurobi.com/downloads/> (accessed on 1 December 2023)).

**Table 4.** Payoff table for three-objective problem.

|                                                              |                                                                              |                                                                              |
|--------------------------------------------------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| R11: Independently optimization result<br>for $f_1$          | R21: Optimization result for $f_2$ by setting<br>$f_1 = R11$                 | R31: Optimization result for $f_3$ by setting<br>$f_1 = R11$ and $f_2 = R21$ |
| R12: Optimization result for $f_1$ by setting<br>$f_2 = R22$ | R22: Independently optimization result<br>for $f_2$                          | R32: Optimization result for $f_3$ by setting<br>$f_2 = R22$ and $f_1 = R12$ |
| R13: Optimization result for $f_1$ by setting<br>$f_3 = R33$ | R23: Optimization result for $f_2$ by setting<br>$f_3 = R33$ and $f_1 = R13$ | R33: Independently optimization result<br>for $f_3$                          |

- Step2: solve epsilon-constraint problem to obtain Pareto solutions.

The objective function and constraints of the epsilon-constraint problem are shown by Equations (17)–(21). Firstly, minimization objective 1 and objective 2 are transformed into standard form as  $\max(-f_1)$  and  $\max(-f_2)$  in the epsilon-constraint problem, where  $lb_1$  is the lower bound for  $f_1$ ,  $lb_2$  is the lower bound for  $f_3$ ,  $r_1$ ,  $r_2$  are the ranges for  $f_1$ ,  $f_3$ , respectively,  $g_1$ ,  $g_2$  are the number of grid points (they indicate the number of solutions can be acquired).  $i_1$  and  $i_2$  are integers, by changing  $i_1$  from 1 to  $g_1$ ,  $i_2$  from 1 to  $g_2$ , we can obtain one solution for each pair of  $i_1$  and  $i_2$ . For each solution acquired, no other solution is considered superior without compromising at least one objective.

$$\max(-f_2), \quad (17)$$

$$(-f_1) \geq e_1, \quad (18)$$

$$f_3 \geq e_3, \quad (19)$$

$$e_1 = lb_1 + \frac{i_1 r_1}{g_1}, \quad (20)$$

$$e_3 = lb_3 + \frac{i_3 r_3}{g_3}. \quad (21)$$

- Step3: Pareto pruning.

After obtaining a set of solutions, the subsequent step involves identifying the most suitable solutions from a large set of options. Various pruning methods exist for this purpose, categorized into preference-based methods (where the standard for choosing the

best solution is based on the decision-maker's preference), diversity-based methods (which aim to identify a well-distributed set of solutions), efficiency-based methods (which aim to select solutions with a high marginal rate of return), and problem-specific methods (which develop pruning methods based on the specific problem) [50].

In this study, we develop a problem-specific, two-step method to filter out the optimal solution. The pruning steps and indicators are shown in Table 5. The first step is to attempt to exclude solutions that have a higher number of high-risk paths and low-pass ratio paths; we call these paths “dangerous paths”. The solutions with many high-risk LSs also need to be excluded; we call these LSs “dangerous LSs”. The indicators employed in this step are  $numDp(k)$ , which means the number of dangerous paths of solution  $k$ , and  $numDs(k)$ , which means the number of dangerous LSs. The second step is to select the solution with the shortest total travel distance. For the purpose of comparison with DMM, the indicator  $rtDis(k)$  in the second step is the ratio of the total distance obtained by RRM to the one obtained by DMM. The process to identify the most promising solution includes two steps: First,  $numDp(k)$  and  $numDs(k)$  are counted for each path and each LS, respectively; those solutions with  $numDp(k)$  or  $numDs(k)$  bigger than a certain value will be pruned. In the second step, the solution with the minimum  $rtDis(k)$  from the remaining solutions will be chosen as the most promising one.

**Table 5.** Indicator used in Pareto pruning.

| Pruning Step | Indicator  | Description                                                               |
|--------------|------------|---------------------------------------------------------------------------|
| 1            | $numDp(k)$ | Number of generated dangerous paths for solution $k$                      |
| 1            | $numDs(k)$ | Number of selected dangerous LSs for solution $k$                         |
| 2            | $rtDis(k)$ | Ratio of total travel distance obtained by RRM to the one obtained by DMM |

## 4. Case Study

### 4.1. Data Generation

The Ogu Area, situated in the northeast of Tokyo Metropolitan, as shown in Figure 2, spans a total area of 2.7 km<sup>2</sup> with a population of 54,650 (as of November 2023). This area is characterized by a large number of wooden structure buildings, as shown in Figure 3, rendering it vulnerable to both earthquakes and fires. According to the Ninth Community Earthquake Risk Assessment Study, approximately half of the communities in the Ogu Area receive the highest risk ratings for both building collapse and fire hazards [51]. Within this area, there are 34 DPs (communities), 13 LSs (temporary evacuation areas), and 2 MSs (evacuation areas) as shown in Figure 4. Each DP represents an administrative unit called Chōnaikai, comprising one or several communities. The Chōnaikai is responsible for establishing and managing shelters, as well as stockpiling disaster relief supplies. Utilizing the methods proposed by Hirokawa and Osaragi [52], we obtained disaster simulation data, including the probabilities of building collapse, street blockage, and fire outbreak. It is important to note that the parameters used for estimating building collapse probabilities are derived from the research conducted after the 2016 Kumamoto Earthquake and the 1995 Great Hanshin Earthquake [53], which are considered to be more accurate than previous studies. By employing these methods, we obtained probabilities of building collapse, road blockage, and fire spread as depicted in Figures 5–7. The capacities of these shelters were estimated by dividing the effective sheltering area by the per capita sheltering area, set at 2 m<sup>2</sup>, exceeding the minimum standard of 1 m<sup>2</sup> per person established by the Tokyo Metropolitan Government [13] in order to provide a better environment for evacuees to stay.

As discussed in Section 3.2, tolerant paths are those whose lengths do not exceed 1.2 times the length of the shortest path. Additionally, to ensure all nodes are covered within a reasonable distance, we set 1.5 km as the maximum distance for allocation. Yen's K-shortest algorithm [54] was utilized to select paths meeting these criteria. By averaging the risks along multiple paths, a relatively reasonable risk value between two nodes

can be derived. Figure 8 illustrates an example of all-tolerant paths between two nodes, demonstrating significant differences in risk values and pass ratios among different paths. Based on the acquired tolerant paths and the methods proposed in Section 3.1, we estimated the risks associated with shelters and paths. The results of risk estimation are presented in Figures 9–11.



Figure 2. Location of study area.

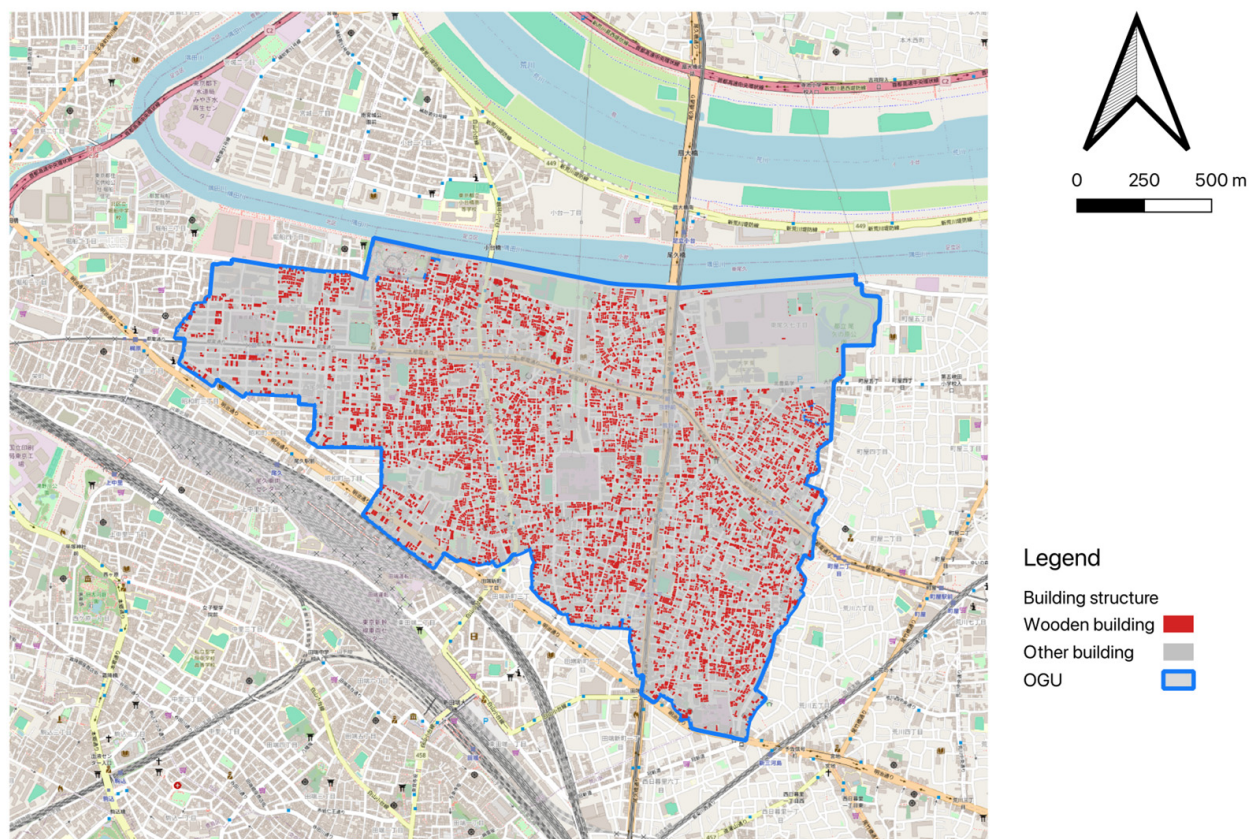


Figure 3. Distribution of wooden buildings.

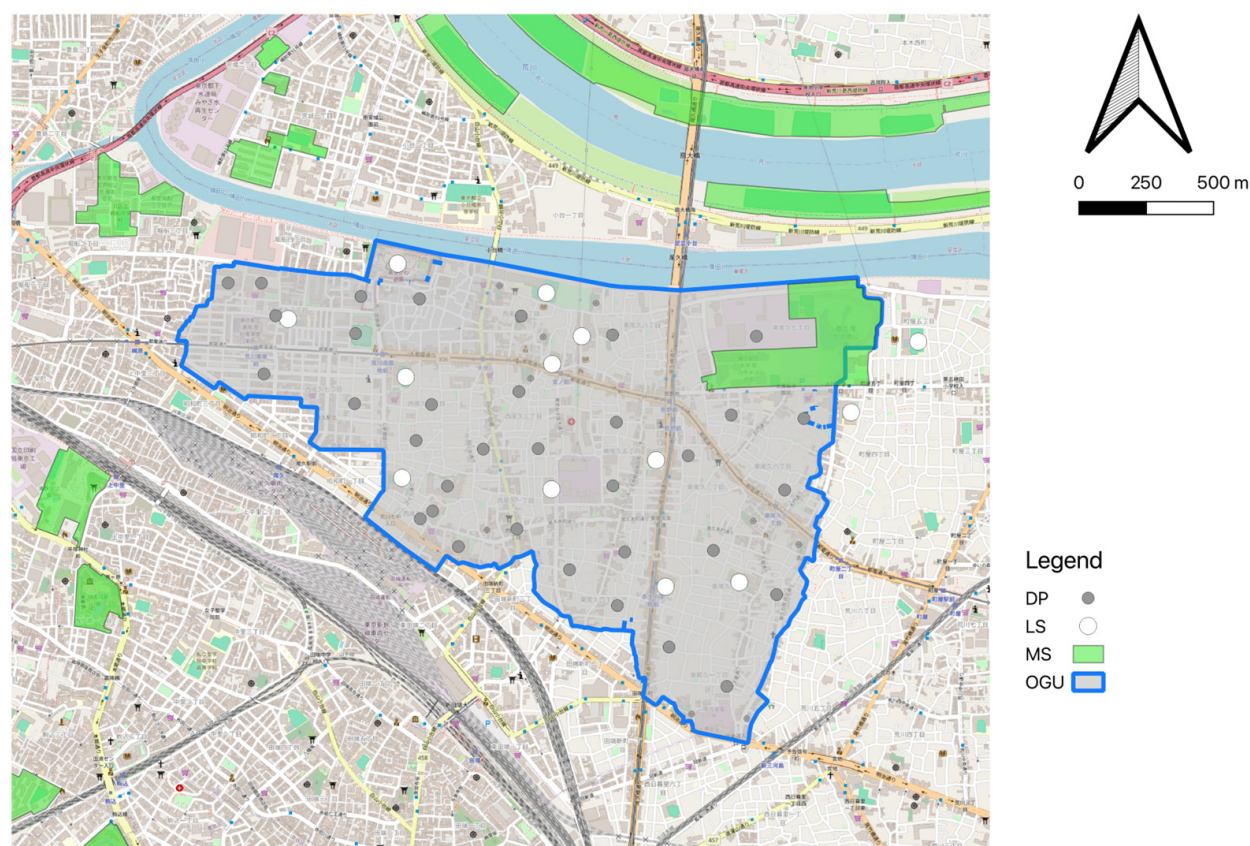


Figure 4. Distribution of DPs, LSs, and MSs.

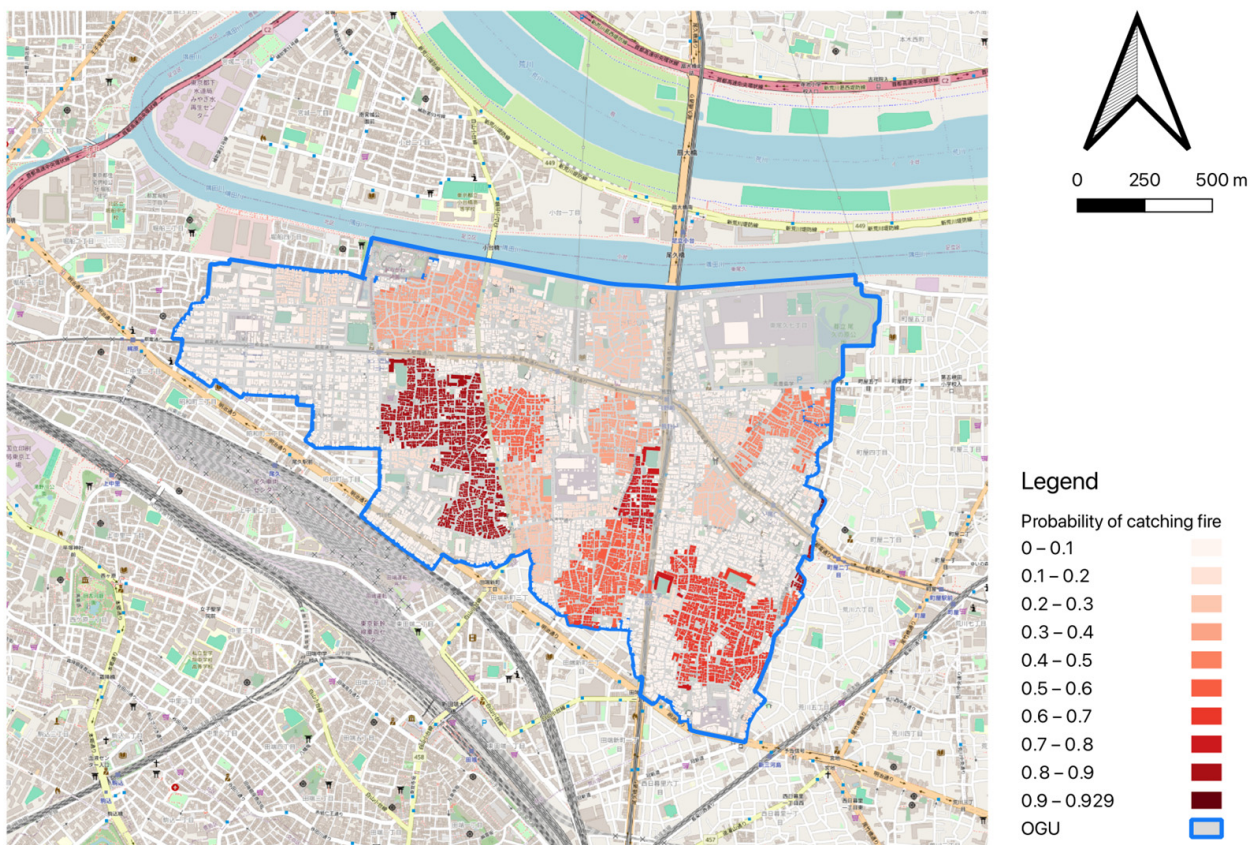


Figure 5. Distribution of probability of catching fire.

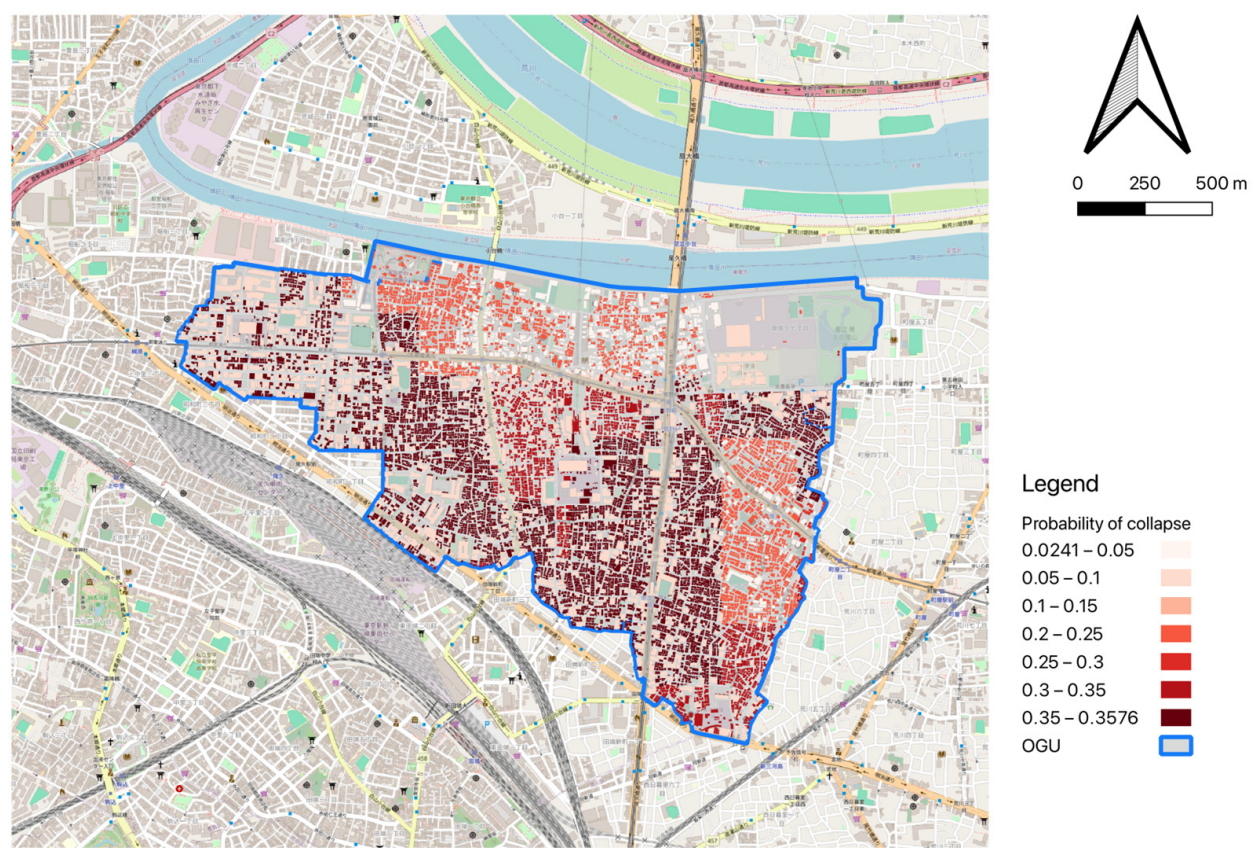


Figure 6. Distribution of probability of building collapse.

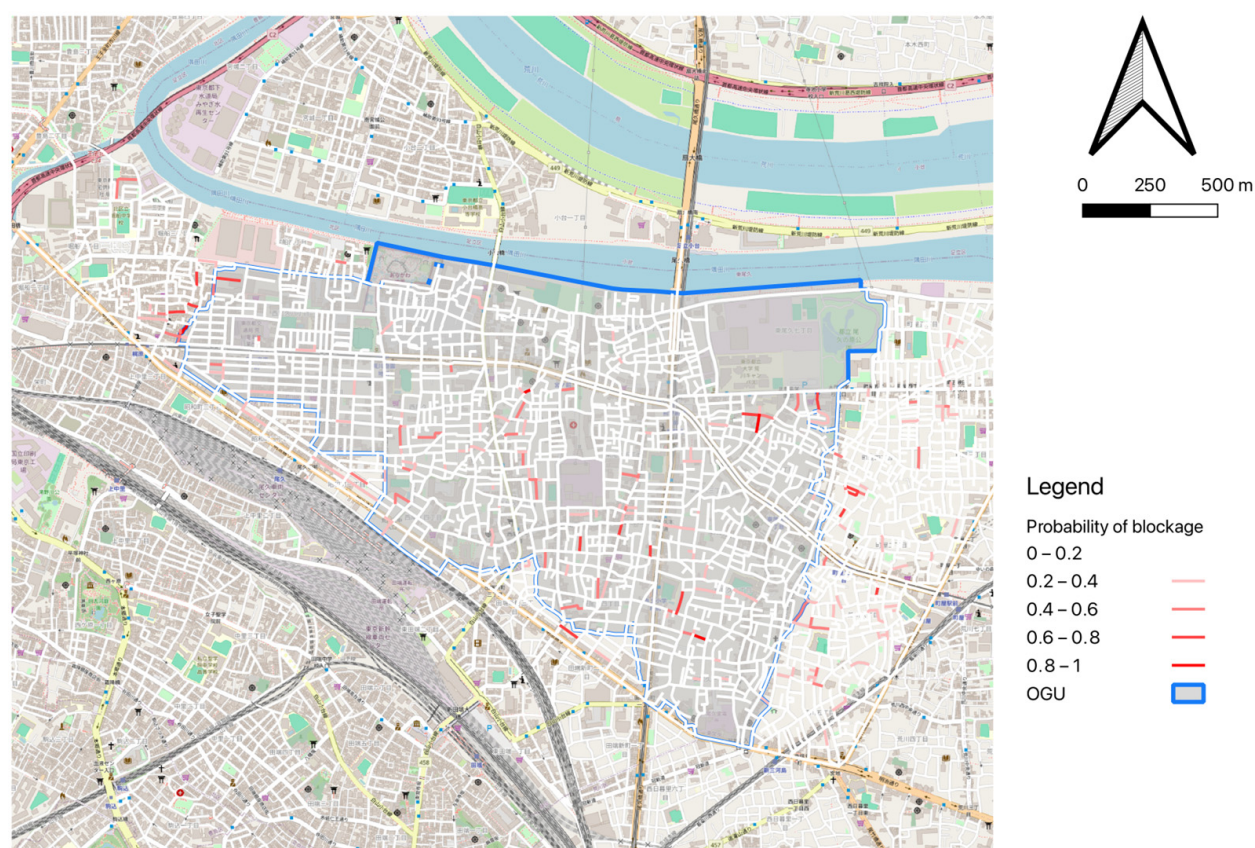
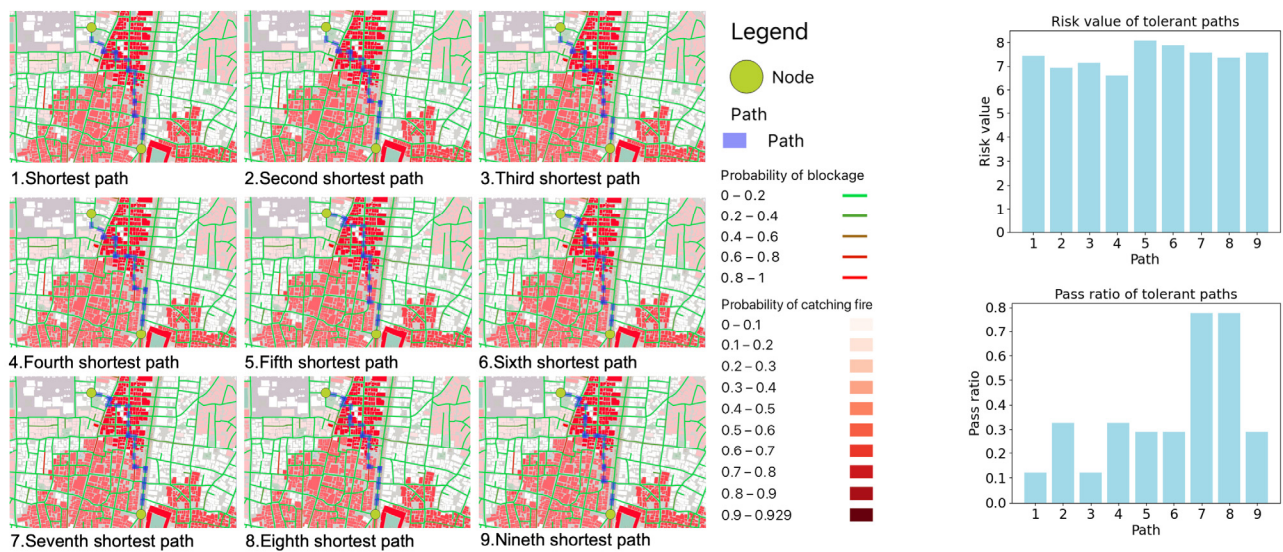
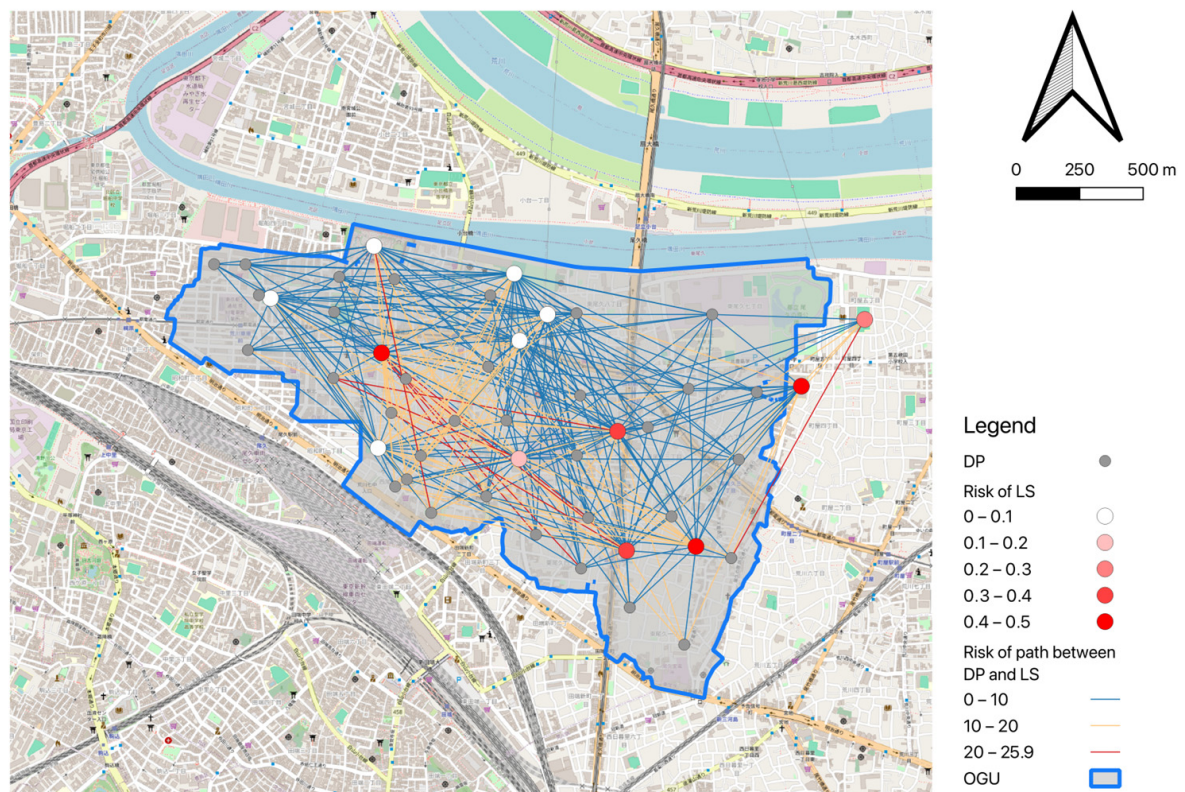


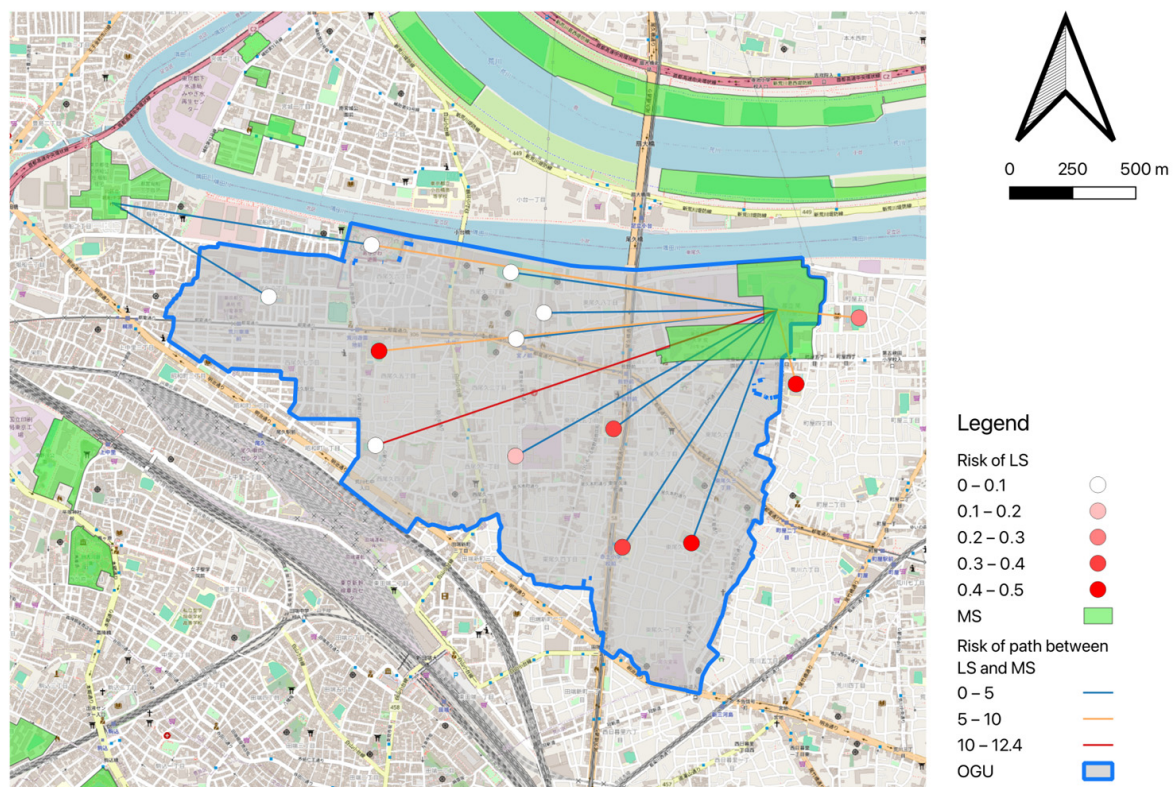
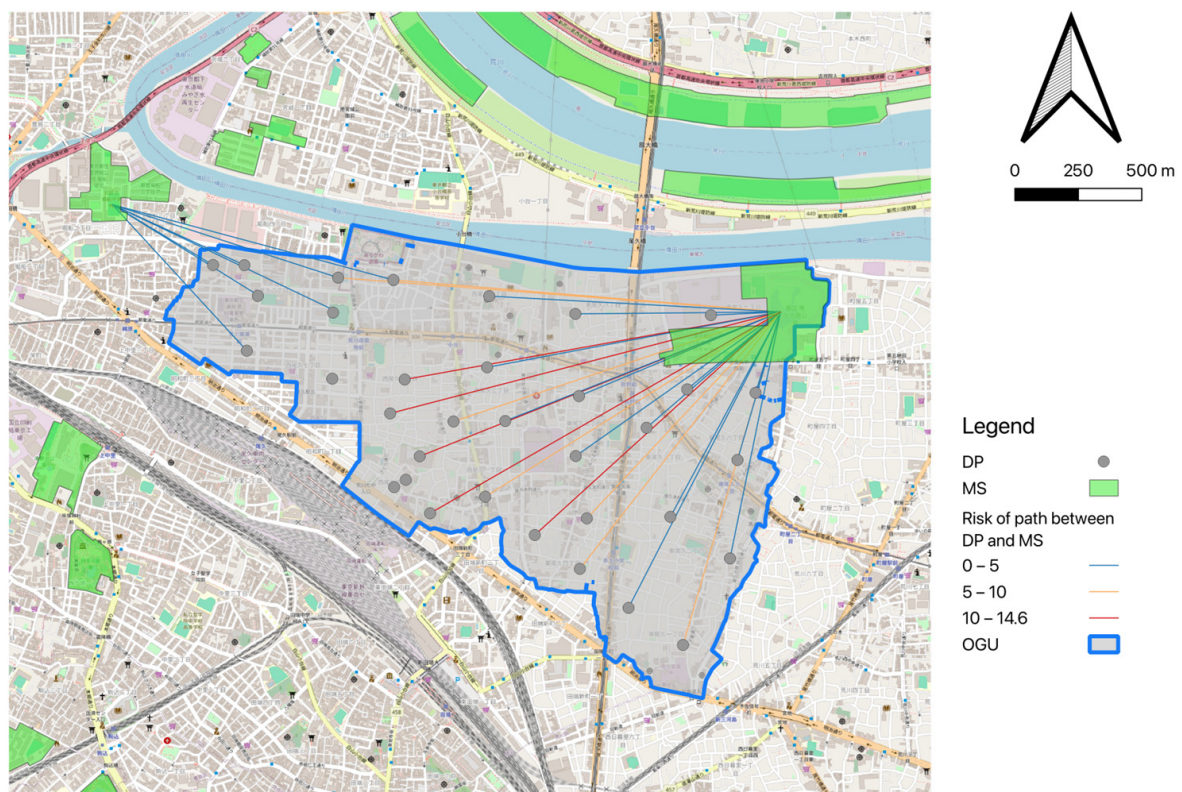
Figure 7. Distribution of probability of road blockage.



**Figure 8.** An example of tolerant paths and their risk values/pass ratios.



**Figure 9.** Node risk values of LSs and path risk values between DPs and LSs (use line to represent the risk along path; only show pairs with average path distances shorter than 1.5 km).



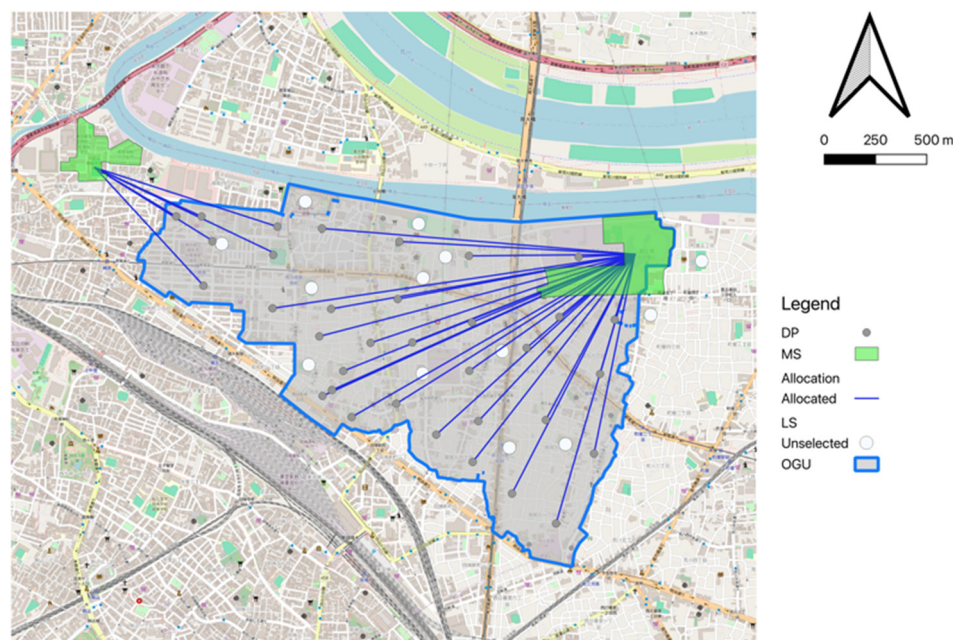
## 4.2. Result Discussion

### 4.2.1. Result of Distance Minimization Model (DMM)

The DMM minimizes the total distance without consideration of other factors. We run the model by setting the minimization of total travel distance as an objective and constraints as the same with RRM. According to the location and allocation results, we can calculate the value of  $f_1$ ,  $f_2$ , and  $f_3$  in RRM. The results (value of each objective, number of available LSs, number of direct allocations, and number of indirect allocations) are presented in Table 6. As shown in Table 6, when the maximum distance from two nodes is set as 1.5 km, the total travel distance is  $5.49 \times 10^7$  m, the sum of the pass ratio for each path is 18.107, and there is no LS being selected; in other words, all DPs are directly allocated to MS. Therefore, the risk for LSs is also equal to 0. The details of allocations from DPs to MSs are shown in Figure 12. Although MSs are large open spaces, we still think they can accept an infinite number of evacuees. Therefore, some DPs cannot be allocated to the nearest MS; instead, they will be assigned to the MS that is farther away due to the limit on the capacities of MSs. This result reflects some traditional location models.

**Table 6.** Solutions obtained by DMM.

|                    |                                     | DMM<br>Solution Value |
|--------------------|-------------------------------------|-----------------------|
| Objective values   | $f_0$ value                         | $5.49 \times 10^7$    |
|                    | $f_1$ value                         | 0                     |
|                    | $f_2$ value                         | $2.98 \times 10^5$    |
|                    | $f_3$ value                         | 18.107                |
| Location results   | Available LS                        | 0/13                  |
| Allocation results | Direct allocation (from DP to MS)   | 34                    |
|                    | Indirect allocation (from DP to LS) | 0                     |

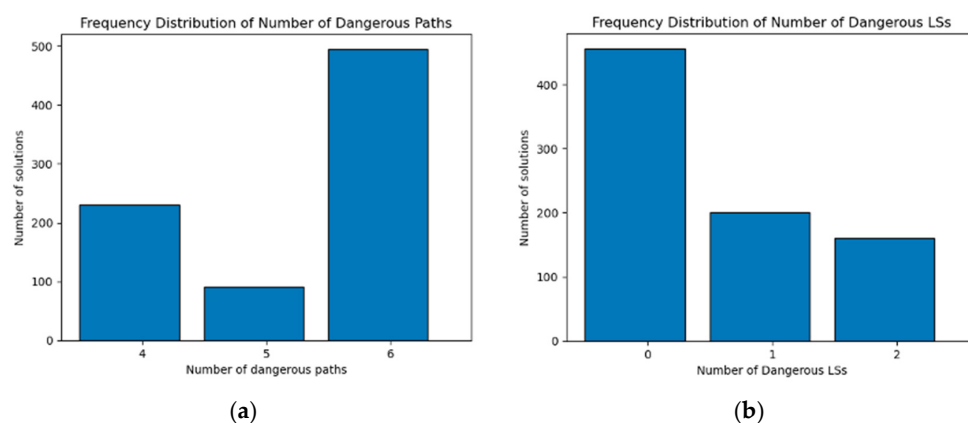


**Figure 12.** DMM results of allocations from DP to MS.

### 4.2.2. Result of Risk Reduction Model (RRM)

The RRM model is solved as a multi-objective model.  $g_1$  and  $g_3$  are set as 100, respectively. In theory, we can obtain 10,000 Pareto solutions, but finally only 816 unique solutions are obtained after deleting duplicate values. These generated Pareto solutions may include solutions which select a large number of dangerous paths or dangerous shelters, since the optimization model only focused on optimizing the total quantity while

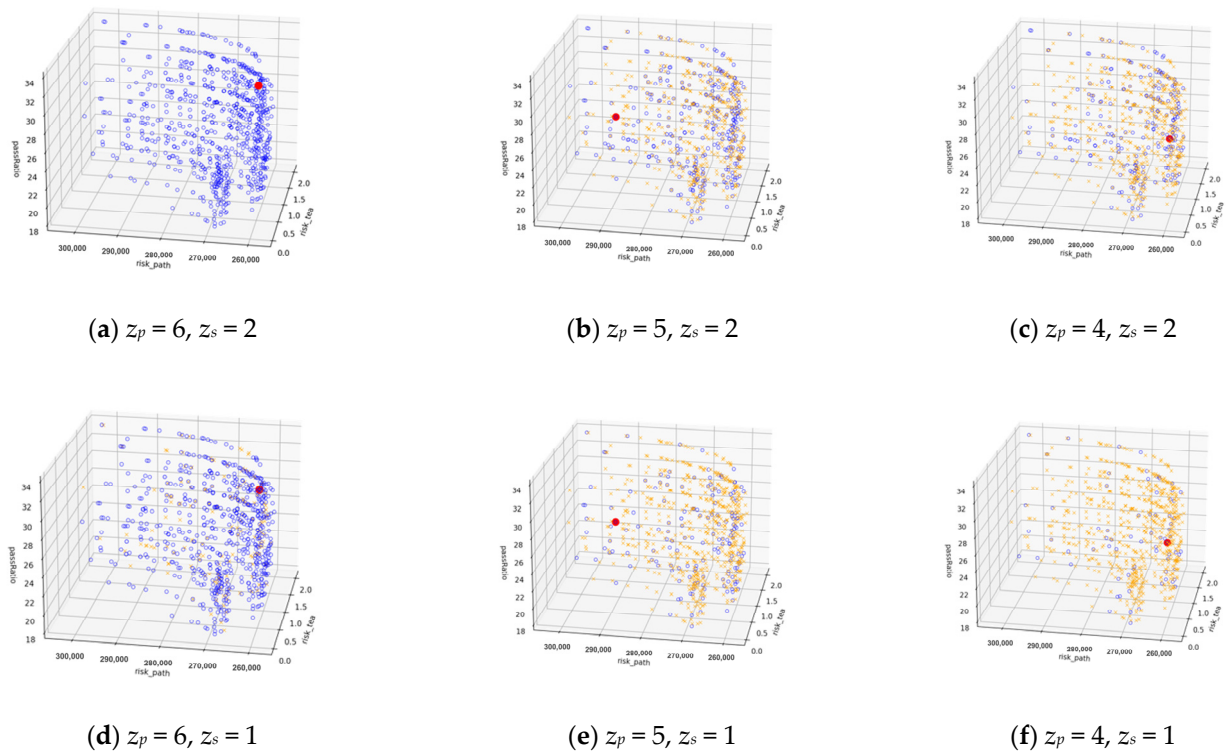
ignoring the extreme value. We use the indicators mentioned in Section 3.3 to find out these solutions. We define dangerous LSs and dangerous paths as LSs with a risk value higher than 0.5 (accounting for 23.1% of all LSs) and paths with a risk level higher than 10 (accounting for 34.5% of all paths). The distribution of the number of high-risk paths and LSs in Pareto solutions is represented in Figure 13. It is clear that over half of the solutions contain 6 dangerous paths, and near half of these solutions contain at least one dangerous LS. The thresholds for  $numDp(k)$  (number of dangerous paths in solution  $k$ ) and  $numDs(k)$  (number of dangerous LSs in solution  $k$ ) are denoted as  $z_p$  and  $z_s$ , which means that the solutions with  $numDp(k) > z_p$  or  $numDs(k) > z_s$  will be deleted. Use different  $z_p$  (in the range from 4 to 6 as shown in Figure 13) and  $z_s$  (in the range from 0 to 2 as shown in Figure 13) to implement the filtering; the results are depicted in Figure 14. The blue ring indicates the remaining solutions after filtering, while the orange cross denotes the solutions being deleted. The final optimal results obtained by different  $z_p$  and  $z_s$  can be different. This is because when  $z_p$  and  $z_s$  are set at higher values, the best solution acquired by the model with lower  $z_p$  and  $z_s$  may be cut off. When  $z_p = 6$  and  $z_s = 2$ , no solution will be deleted in step 1, and the final solution we acquire is the one with the minimum total travel distance within all Pareto solutions. When we decrease  $z_p$  to 5, it is lucky that this solution remains. However, when changing  $z_p$  to 5, the previous optimal solution will be cut off, and the new optimal solution is the same one when  $z_p = 5$  and  $z_s = 1$  or 2. Continually decreasing  $z_p$  to 4, we will obtain another new optimal solution. In summary, we could obtain 3 different solutions by setting different parameters, especially different  $z_p$ . The parameter  $z_s$  seems to have little to no impact on the results. The details of these 3 results are presented in Table 7, and the three allocation results are shown in Figure 15. It can be seen that when the threshold of the number of tolerant dangerous paths ( $z_p$ ) increases, as the previous optimal solution is cut off, total travel distance will also increase, and more DPs are forced to select indirection allocations. Since the distance gets longer, the sum of pass ratios will also decrease. The location and allocation results are shown in Figure 15. It can be seen that as the parameters  $z_p$  and  $z_s$  change, the result also differs.



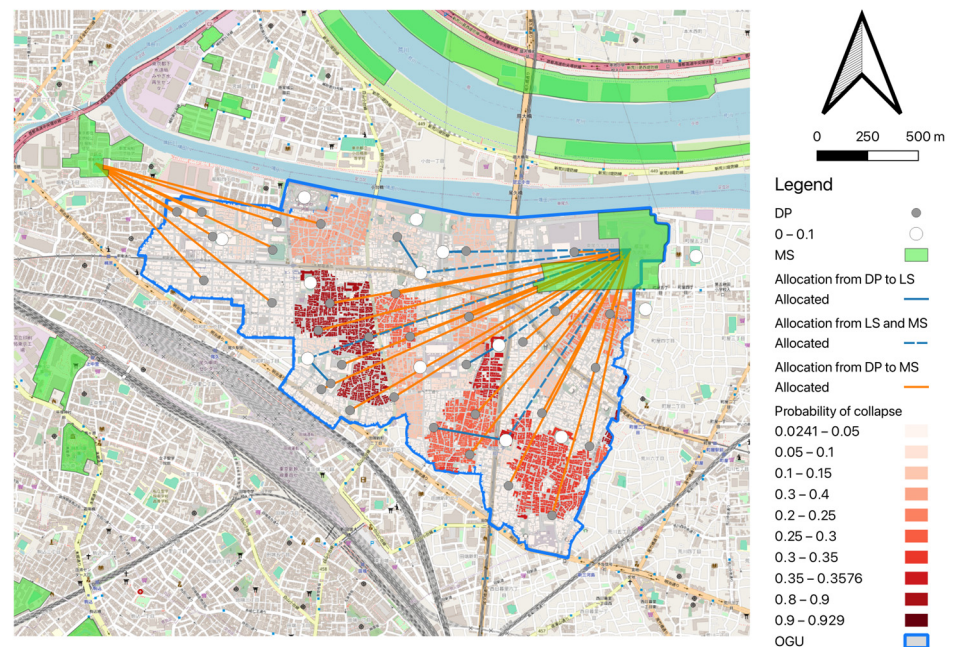
**Figure 13.** (a) Frequency distribution of number of dangerous paths within Pareto solutions; (b) frequency distribution of number of dangerous LSs within Pareto solutions.

**Table 7.** Solutions obtained by RRM.

|                    |                                     | RRM Solution 1 Value<br>$z_p = 6, z_s = 1 \text{ or } 2$ | RRM Solution 2 Value<br>$z_p = 5, z_s = 1 \text{ or } 2$ | RRM Solution 3 Value<br>$z_p = 4, z_s = 1 \text{ or } 2$ |
|--------------------|-------------------------------------|----------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|
| Objective values   | $f_0$ value                         | $5.67 \times 10^7$                                       | $5.72 \times 10^7$                                       | $5.80 \times 10^7$                                       |
|                    | $f_1$ value                         | 1.401                                                    | 0.516                                                    | 0.594                                                    |
|                    | $f_2$ value                         | $2.62 \times 10^5$                                       | $2.89 \times 10^5$                                       | $2.61 \times 10^5$                                       |
|                    | $f_3$ value                         | 29.309                                                   | 28.165                                                   | 26.099                                                   |
| Location results   | Available LS                        | 5/13                                                     | 6/13                                                     | 9/13                                                     |
| Allocation results | Direct allocation (from DP to MS)   | 29                                                       | 27                                                       | 22                                                       |
|                    | Indirect allocation (from DP to LS) | 5                                                        | 7                                                        | 12                                                       |
| Indicator          | $rtDis$                             | 1.032                                                    | 1.042                                                    | 1.056                                                    |

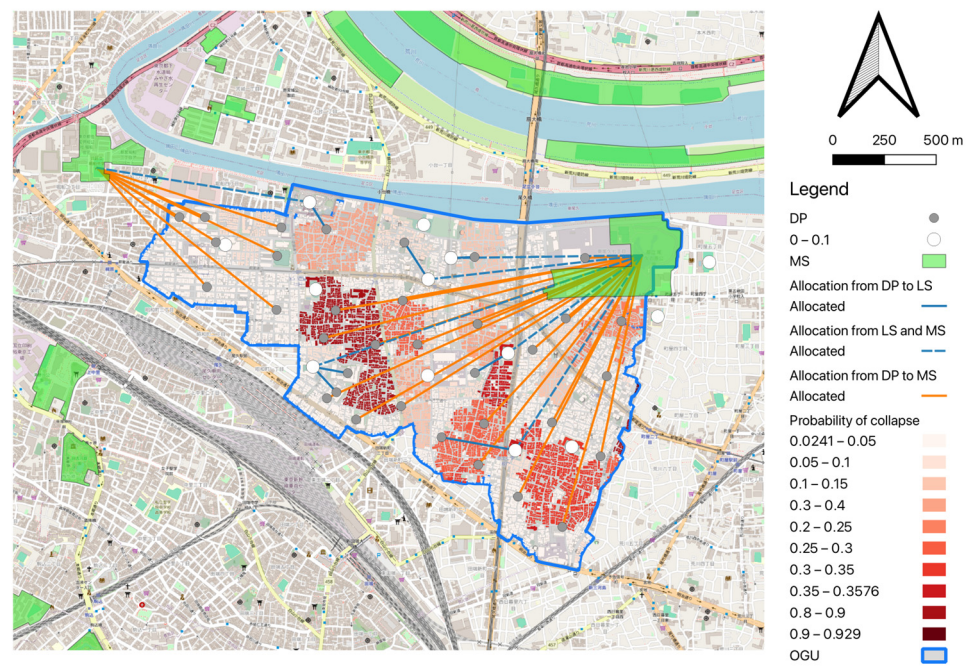
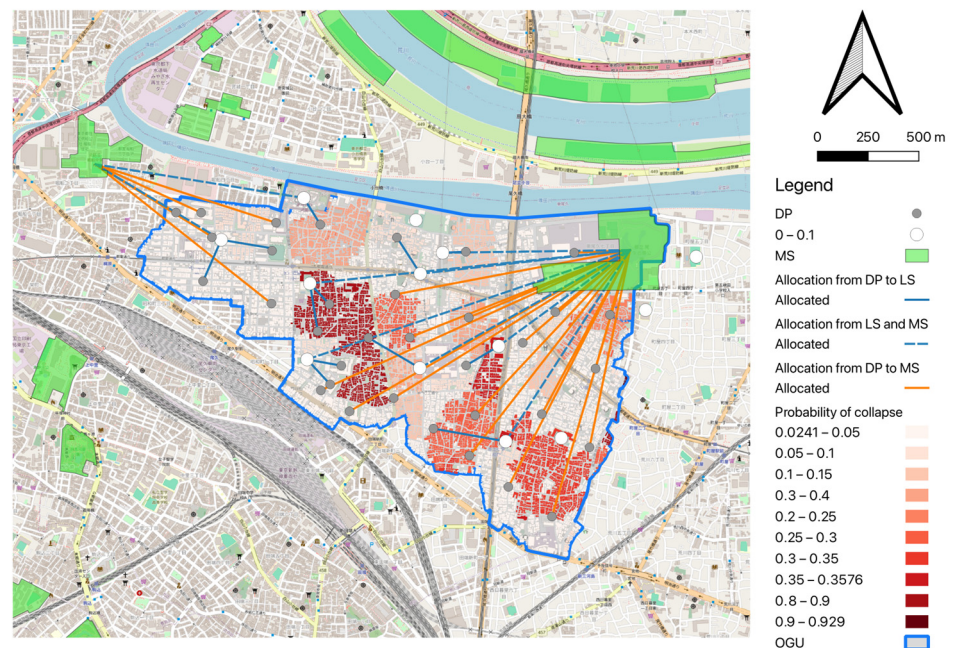


**Figure 14.** Optimal solution after screening from Pareto solutions (red circle: final optimal solution; orange cross: deleted solutions by step 1; blue ring: remaining solutions after step 1;  $z$  axis: sum of pass ratio;  $x$  axis: sum of path risk;  $y$  axis: sum of LS risk).



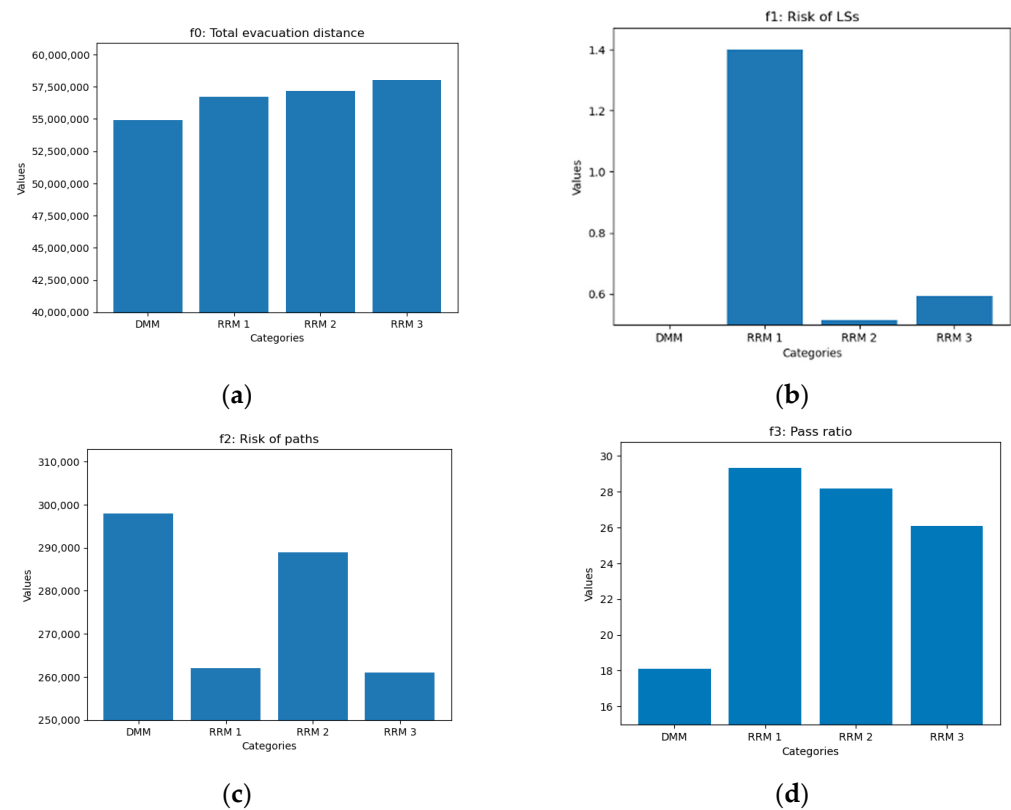
(a)  $z_p = 6, z_s = 1$  or 2

**Figure 15.** Cont.

(b)  $z_p = 5, z_s = 1$  or 2(c)  $z_p = 4, z_s = 1$  or 2**Figure 15.** RRM results of allocations from DP to LS to MS and allocations from DP to MS.

In order to directly compare the results obtained by DMM and RRM, we compared four objective values, respectively, as shown in Figure 16. It can be seen that RMM solution 3 can largely reduce the risk along the path and increase the pass ratio compared to DMM while only increasing slightly (in our case, the distance of RRM solution 3 is just 5.65% higher than that of DMM) in total distance. RMM solutions 1 and 2 also complete the work of increasing the pass ratio; however, RMM solution 1 generates a solution, which shows a relatively high level of risk of LSs, and the effect of reducing path risk for RMM solution 2 is not significant. Since risk along evacuation is regarded as the main threat to evacuees, we think RMM solution 3, which sets the highest level of filtering parameters ( $z_p$  and  $z_s$ ), is

the best solution. Overall, all RRM solutions can reduce risk and increase the pass ratio without significantly increasing (within 10%) total distance.



**Figure 16.** (a)  $f_0$  results obtained by DMM and RRM; (b)  $f_1$  results obtained by DMM and RRM; (c)  $f_2$  results obtained by DMM and RRM; (d)  $f_3$  results obtained by DMM and RRM.

## 5. Summary and Conclusions

For natural disasters such as earthquakes, which often entail secondary disasters, it is crucial to consider potential risks during evacuation in addition to factors such as evacuation time and distance. This approach aligns with the goal of creating safer living and working environments and building sustainable societies. Hence, there is a necessity to develop optimization models that go beyond minimizing evacuation distance and time.

This study proposes a model with the optimization objective of minimizing overall risk levels during evacuation. These risks encompass both the threat posed by road blockages, leading to insufficient accessibility, and the hazards posed by fires spreading to evacuees. Simultaneously, to ensure that the evacuation distance remains within a reasonable range, the  $rtDis$  indicator is utilized to select Pareto solutions with the shortest evacuation distance. Before this, two other indicators are employed to eliminate Pareto solutions that may result in significantly high-risk paths or shelters. Through empirical analysis of the Ogu region, it is observed that solutions with lower calculated risks may not necessarily yield very large total evacuation distances. Conversely, solutions obtained by minimizing distance may lead to relatively higher risk values. This method can also be applied to researching other disasters, such as floods [30], wildfires [55], and disease outbreaks [56], since these disasters also pose high risks. A model aimed at reducing risk to ensure safe evacuation is equally applicable for such scenarios.

While this paper introduces a new perspective for optimizing evacuation plans, there are areas that require further improvement. Firstly, apart from fires, other types of secondary disasters, especially in the case of large earthquakes accompanied by tsunamis, need to be comprehensively considered in future research. Secondly, the risk level not only varies spatially but also changes over time. Thus, during the evacuation process, evacuees

departing at different times may encounter varying risks at the same location. This aspect warrants further in-depth investigation in future research. Thirdly, the model's assumptions may not hold in real-world scenarios, as events like fires and building collapses are highly unpredictable. Therefore, additional factors should be considered in improving disaster simulation models, and further validation using real-world data should be conducted to test the proposed model. Finally, more effective methods are anticipated to be developed to strike a balance between distance and risk in future research endeavors.

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