International Journal of Geo-Information

MDPI

Article

A Two-Phase and Bi-Level Spatial Configuration Methodology of Shelters Based on a Circular Assignment Model and Evacuation Traffic Flow Allocation

Yujia Zhang [1], Wei Chen [2,*], Guangchun Zhong [1], Guofang Zhai [1] and Wei Zhai [3]

[1] School of Architecture and Urban Planning, Nanjing University, Nanjing 210093, China; yujiazhang@smail.nju.edu.cn (Y.Z.); gczhong@smail.nju.edu.cn (G.Z.); guofang_zhai@nju.edu.cn (G.Z.)
[2] School of Management, Nanjing University of Posts and Telecommunications, Nanjing 210003, China
[3] School of Architecture and Planning, University of Texas at San Antonio, San Antonio, TX 78249, USA; wei.zhai@utsa.edu
* Correspondence: chen_wei@njupt.edu.cn

Abstract: With the continued recognition of the devastating effects of natural hazards, the construction of shelters has become essential in urban disaster preparedness planning systems. After analyzing the deficiency of the conventional spatial allocation model of shelters and the hierarchy of evacuation assignments, this study proposes a bi-level and two-phase spatial configuration methodology of shelters. The first hierarchy aims to evacuate refugees from demand blocks to both emergency shelters and resident emergency congregate shelters. The second hierarchy aims to transfer refugees from selected shelters in the first hierarchy to resident emergency congregate shelters. Each hierarchy contains two phases of optimizing calculations. The optimization objects for the first phase and second phase are minimizing the number of new shelters and the evacuation time, respectively. A genetic algorithm and exhaustive approach are programmed to determine the solution of the model in the first and second phases, respectively. The evacuation assignment rule is proposed based on the gravity model, which distributes evacuees proportionally to nearby shelters. This study uses the deterministic user equilibrium problem to present the evacuation traffic flow allocation, which improves the scientificity of the location model of shelters. The refuge demands differentiate the population between daytime and nighttime through mobile signaling data and improve the accuracy from the plot scale to the building scale. Using mobile signaling data to differentiate refuge demands between day and night populations enhances the model's precision. Finally, to validate the proposed methodology, this study selected the main area of Changshu City, Jiangsu Province, China, which has a population of 1.6 million, as a case study area.

Keywords: shelters; spatial configuration; bi-level and two-phases; circular assignment model; deterministic user equilibrium problem

check for updates

Citation: Zhang, Y.; Chen, W.; Zhong, G.; Zhai, G.; Zhai, W. A Two-Phase and Bi-Level Spatial Configuration Methodology of Shelters Based on a Circular Assignment Model and Evacuation Traffic Flow Allocation. *ISPRS Int. J. Geo-Inf.* **2024**, *13*, 455. https://doi.org/10.3390/ijgi13120455

Academic Editors: Wolfgang Kainz and Godwin Yeboah

Received: 13 October 2024
Revised: 26 November 2024
Accepted: 5 December 2024
Published: 16 December 2024

Copyright: © 2024 by the authors. Published by MDPI on behalf of the International Society for Photogrammetry and Remote Sensing. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Urbanization has intensified the risks from hazards like earthquakes and floods, making efficient evacuation and shelter planning essential to minimize casualties and property loss. A reasonable configuration of earthquake shelters can greatly improve evacuation efficiency, guarantee the life safety of refugees, and enhance the urban capacity for disaster prevention and mitigation.

To determine the scientific spatial distribution of shelters and assign refugees to shelters, in the early phase of this type of research, scholars proposed a site selection model [1,2], P-center model [3], and P-median model [4]. Previous studies mainly improved the constraint conditions and objective functions. Early models, like the P-center and P-median models, focused on basic shelter placement, while later adaptations incorporated constraints like capacity and distance. The differences in the refugee service levels of shelters

and the influence of complex environmental elements were also considered. In terms of constraints conditions, Wang et al. [5] and Gama et al. [6] added distance constraints and capacity constraints to the conventional P-median model. Galvão and ReVelle proposed a capacitated P-median model, [2] which replaced the constraint conditions of the number of shelters, "P", with the maximum capacity. In terms of objective functions, some researchers established a multi-objective optimization model by consolidating multiple optimization objectives, such as evacuation distance [7], equity, the construction cost of shelters [8], egress time [9], the safety of the evacuation road [10], and evacuation risks [11–13]. For instance, Zhao et al. [14] took the maximized number of refugees and the minimized construction cost of shelters as objective functions to establish a two-phase optimization model. Xu et al. [15] took the minimized overall distance, the maximized coverage population, and the number of demand blocks as objective functions. Doerner et al. [11] took the minimized overall evacuation hurricane risk and overall construction cost as the objective functions of the shelter location optimization model. Alçada-Almeida et al. [13] established four objective functions of the shelter optimization model under fire by minimizing the overall evacuation distance, the overall risk where the evacuation route becomes impassable due to fire, the fire risk assessment of shelters, and the required time for refugees to transfer from the shelter to the hospital. Broadly speaking, three approaches have been proposed to solve the multi-objective shelter location optimization model: (1) convert multi-objectives to a single objective by the weighted method [16]; (2) convert the multi-objective problem to a two-phase single-objective problem [17]; and (3) determine the Pareto optimal solution by the heuristic algorithm [18]. The Pareto optimal solution achieves an optimal balance across multiple objectives without sacrificing one for another. Some researchers have incorporated the distribution of relief materials [19,20], simulations of hazard processes [6,21], residents' willingness to enter shelters [22], and behavioral rationality [23] into the shelter location optimization and evacuation assignment model.

In terms of refuge demands, Sugimoto et al. [24] simulated the population distribution and population density in the areas most affected by tsunamis, providing a reference for the capacity design of corresponding shelters. Chou et al. [25] used the TELES analysis approach to predict the number of homeless people in Taiwan after an earthquake and proposed quantitative guidance on the site selection strategy of shelters. Fan et al. [21] assessed the maximum number of refugees exposed to multi-hazards through a scenario simulation. In addition to spatial factors, scholars also consider the time factor when calculating refuge demands. Chen et al. [26] considered the differences in population density on different land use types of blocks and determined refuge demands in the daytime and nighttime through census data and land use data.

With the deepening of research, some scholars proposed hierarchical shelter location models based on single-objective or multi-objective models. Generally, two kinds of hierarchical models have been developed: (1) In two-hierarchy models, the upper hierarchy dominates the lower hierarchy. The upper hierarchical model determines the quantity or spatial distribution of shelters; the lower hierarchical model determines the evacuation route and evacuation assignment schemes. Kongsomsaksakul et al. [17] proposed an evacuation scheme for flood disasters, and the upper hierarchy is designated by the government management department to minimize the required time for evacuation; the lower hierarchy determines the selection of evacuation routes based on the user equilibrium principle. Li et al. [27] established a DTA-based stochastic bi-level generalized model. The upper hierarchy determines the location of shelters first, and the lower hierarchy determines the evacuation routes of refugees based on scenario simulations for hurricane disasters. (2) According to the differences in grade and service distance of shelters, scholars have proposed a multi-hierarchy model that considers the transfer of refugees between shelters with different levels. Hierarchical models have been widely developed in diverse scenarios (e.g., healthcare [28], education [29], emergency medical aid systems, waste management [30], and production–distribution systems [31]. However, few studies have concentrated on the hierarchy of shelter location selections [32]. Chen et al. [33] proposed a

three-hierarchy shelter location model that minimizes the overall evacuation distance and considers the transformation of refugees varying with time. Lee et al. [34] developed a hierarchical model for the location selection of shelters in response to instant, short-period, and long-period floods, which minimizes the overall travel distance and risk index. Zhao et al. [35,36] considered the minimization of the overall evaluation time and the overall shelter area as the objective functions and proposed the MPSO-GA combined algorithm to solve the location and evacuation assignment model. Table 1 provides a summary of the aforementioned models.

Table 1. Literature table on different location models of shelters.

Model	Objectives	Advantages	Disadvantages
P-median model	Determine the optimal location of the shelter to minimize the total evacuation distance from the demand point to the shelter	Achieves fairness and minimized distance costs	Does not consider distance restrictions and shelter capacity limitations
P-center model	Determine the optimal location of the shelter to minimize the longest distance from the demand point to the shelter	Considers fairness and efficiency; it ensures the maximization of the interests of the most disadvantaged refugees	Does not consider the cost of global evacuation distance
Covering site selection model	Meet all shelter needs with the minimum number of shelters and ensure that all shelters are covered	Considers fairness, achieving full coverage of asylum services	Does not consider the cost of evacuation distance
Maximum coverage model	The demand within the coverage area of the shelter is the highest, and the number of people who can be served within a certain distance is the highest	Considers the efficiency of evacuation services	Does not consider fairness and does not cover all required personnel
Multi-objective model	——	Considering different objectives	Large solution process
Multi-level model	——	Considering different types of shelters	Complex model establishment process

The research on the location optimization of shelters has experienced a process from single objective to multi-objective, from redundant accurate solution processes to heuristic approaches, and from single hierarchy to multi-hierarchy. However, the assumptions of the current studies are still far from the actual situation. The main shortcomings of the current hierarchical models are summarized as follows: (1) The current hierarchical models presume that refugees from one demand block should be assigned to one shelter in order to maintain an orderly evacuation and assignment, which is not aligned with the preferences and actual behavior of refugees and the actual evacuation process. (2) The calculation for refugee demand is not precise enough. The number of refugees is determined through statistical data and the permanent population in conventional hierarchical models [34,37]. However, the population varies with time and space, and the spatial difference between daytime and nighttime is particularly significant. For example, commercial districts experience a high

daytime population that decreases significantly at night. What is more, the number of refugees is not only determined by population, but also depends on the seismic damage state of buildings. The current hierarchical models do not consider the differences in population in the space–time dimension and do not couple population with the consequences of earthquakes. (3) Traditional models often overlook the critical role of traffic flow and route availability, which directly impact evacuation time. For a spatial configuration model of shelters that takes minimum evacuation time as the objective function, evacuation traffic flow is a vital factor.

Based on the experience and deficiency of current research, this study takes minimizing the number of new shelters and the overall evacuation cost of residents as optimization objectives. Under the constraints of service radius and the maximum capacity of shelters, this study puts forward a two-hierarchy and two-phase model for the layout optimization of shelters and evacuation assignments. In this model, the first hierarchy determines the spatial configuration of emergency shelters (ESs), and the second hierarchy considers the transportation of refugees from emergency shelters to higher-level shelters and determines the distribution of resident emergency congregate shelters (RSs). Each hierarchy includes two phases for calculation. The first phase determines the minimum number of shelters through an improved set coverage model and is solved by a genetic algorithm. In the second phase, from the minimum number of shelters in the first phase, the spatial distribution scheme with the minimum evacuation cost is determined through an enumeration approach. This paper improves the over-idealized hypothesis of "refugees from the same demand block enter the same shelter" in the conventional model and proposes the circulation assignment model, which better simulates the evacuation flexibility in the authentic evacuation process and improves the utilization efficiency of the shelter. Meanwhile, this study increases the consideration of the population difference in the daytime and nighttime and couples the damage status of buildings with population to determine the number of refugees in building dimensions accurately. What is more, this study uses a deterministic user equilibrium problem to reflect the evacuation traffic flow allocation.

2. Research Methodology

2.1. Research Framework

The proposed methodology includes the following five steps. Figure 1 illustrates the framework of the methodology.

(1) Basic data preparation: through remote sensing images, field research, and planning documents provided by the government, the current shelters and the possible sites for constructing new shelters are determined.
(2) Suitability evaluation for candidate sites: the suitability assessment is carried out to determine the candidate sites that are suitable for constructing new shelters. The suitable sites will be regarded as candidate shelters and be entered into the spatial allocation model.
(3) This study proposes the distribution rules of crowd evacuation based on the gravity model, which calculates the overall egress time and the corresponding relationship between the number of refugees received by each shelter and egress time.
(4) The evacuation routes are important for the location of shelters, which strongly influences the evacuation time. In order to simulate authentic evacuation roads, to avoid problems such as longer time required for dynamic traffic allocation processes, multiple input parameters and high accuracy requirements, and difficulty in iteration convergence [38], this study uses a deterministic user equilibrium problem [39] to reflect the evacuation traffic flow allocation.
(5) This study proposes a two-hierarchy and two-phase optimization model for the location of shelters. In the first hierarchy, refugees from demand blocks can be transferred to both emergency shelters (ESs) and resident emergency congregate shelters (RSs). Each hierarchy contains two phases of optimizing calculations. The optimization objectives for the first phase and second phase are minimizing the number of new shelters and the

overall evacuation time, respectively. The second hierarchy aims to transfer refugees from selected shelters in the first hierarchy to resident emergency congregate shelters. The demand blocks are determined as emergency shelters in the second-hierarchy optimization. The destinations are determined as resident emergency congregate shelters in the second-hierarchy optimization. The objective functions and two-phase solution procedures are the same as the first-hierarchy optimization.

(6) The optimization algorithm is designed to determine the solutions of the two-hierarchy model. In each hierarchy, the first-phase optimization, which is aimed at minimizing the number of newly built shelters, is solved through a designed genetic algorithm, and the second-phase optimization, which aims at minimizing the overall evacuation time, is solved through an enumeration approach.

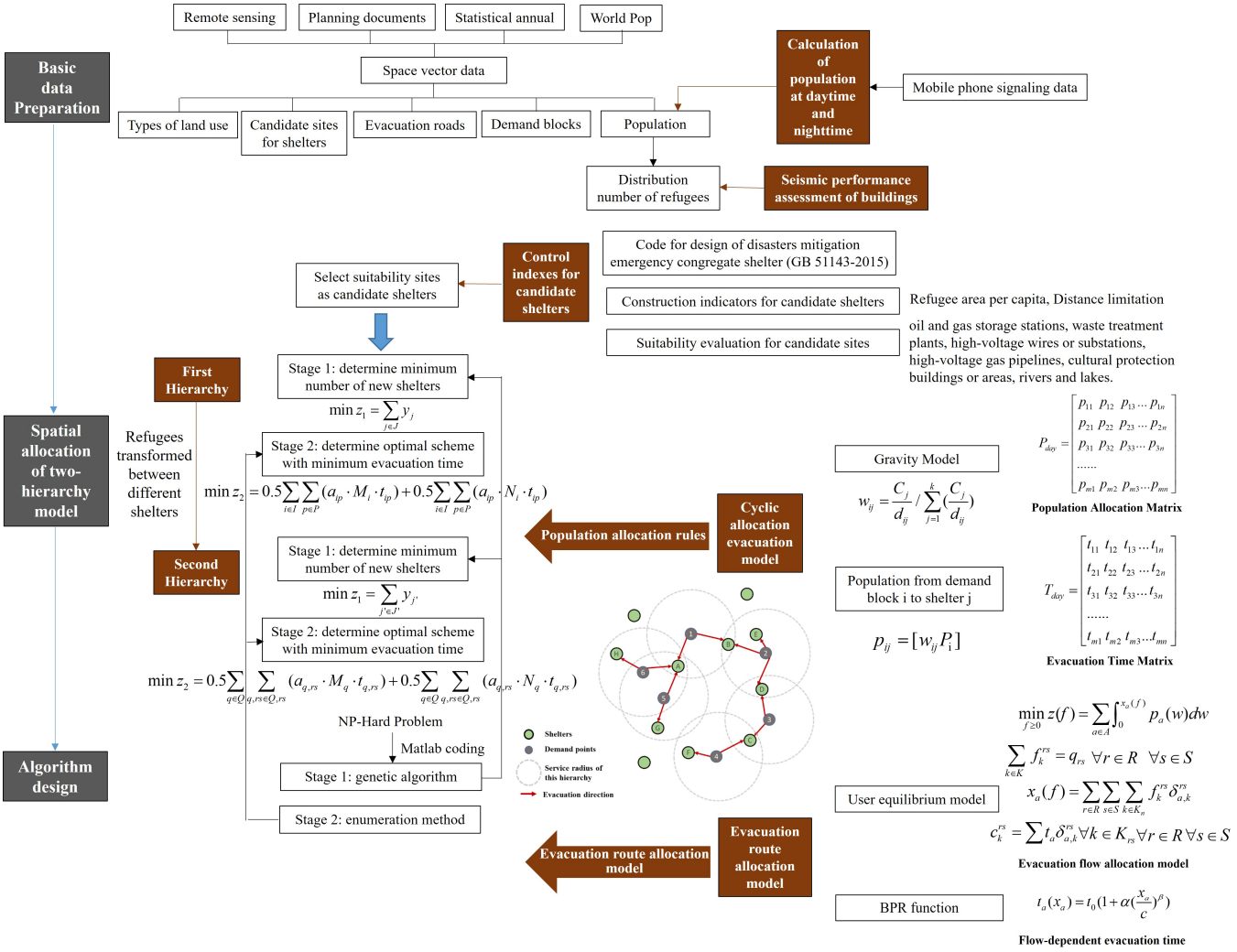


Figure 1. Framework of the methodology.

2.2. Control Indexes for Candidate Shelters

With the overall consideration of the refugee demands, maximum capacity, and construction conditions, the selection of candidate shelters is based on two indicators [40]: (1) construction requirements, including the effective refuge area, refuge area per capita, and maximum distance limitation for refuge service; (2) suitability evaluation indexes. When completing shelter planning, we should not only make full use of the refuge function of shelters but also guarantee the safety of the shelters themselves. The safety distance and defense capacity should be determined according to the distribution of hazard sources.

2.3. Construction Indicators for Candidate Shelters

According to the regulations for emergency shelters (ESs) and resident emergency congregate shelters (RSs) in the Code for Design of Disasters Mitigation Emergency Congregate Shelter [40], the construction indicators of two types of shelters in Changshu City are illustrated in Table 2, including the effective refuge area, refuge area per capita, service distance, and period.

Table 2. The construction indicators of various shelters.

	Effective Refuge Area/hm^2	Refuge Area Per Capita/m^2	Service Distance/km	Service Period/d
Emergency shelter (ES)	—	≥1.5	≤0.5	≤3
Resident emergency congregate shelter (RS)	≥5.0	≥2.5	≤2.5	15~100

2.4. Suitability Evaluation Index for Candidate Sites

At present, the safety of shelters is the most important index to evaluate their suitability. For the safety of candidate sites, this study adopts the minimum value dominance approach [41], which uses the minimal value of different indexes as the final value. The minimum value dominance approach scores all types of factors affecting the safety of shelters. The evaluation factor with the lowest score becomes the restrictive factor of the overall safety conditions.

Based on the standard for urban planning on earthquake resistance and hazardous prevention [42], the influencing factors leading to potential safety hazards to shelters in Changshu City include oil and gas storage stations, waste treatment plants, high-pressure wires or substations, high-voltage gas pipelines, cultural protection buildings or areas, and rivers and lakes. The influencing factors are calculated through the evaluation criteria in Table 3: "−1" denotes an unsafe area, "0" denotes a candidate site on which emergency shelters can be constructed, and "1" denotes a candidate site on which both ESs and RSs can be constructed.

Table 3. Reference of safety scoring.

Influence Factor	Standard for Scoring	Score
High-voltage power lines	Distance less than 50 m	−1
	50–100 m	0
	Distance larger than 100 m	1
Gas pipeline for high-pressure	Distance less than 25 m	−1
	25–50 m	0
	Distance greater than 50 m	1
Garbage disposal sites	Distance less than 100 m	0
	Distance greater than 100 m	1
Gas station	Distance less than 50 m	−1
	50–100 m	0
	Distance greater than 100 m	1
Oil and gas storage station	Distance less than 100 m	−1
	100–300 m	0
	Distance greater than 300 m	1
Lake and river	Water body	−1
	Distance less than 30 m	0
	Distance greater than 30 m	1
Historic preservation region	Inside the preservation region	−1
	Distance less than 30 m	0
	Distance greater than 30 m	1
Earthquake fault zone influence	Distance to earthquake fault zone less than 15 m	−1
	Distance to earthquake fault zone greater than 15 m	1

Two-hierarchy and two-phase spatial allocation model of shelters.

2.4.1. Basic Assumptions

This study improves the maximum coverage model on the aspects of the corresponding approaches of demand blocks and shelters. The conventional maximum coverage model makes an assumption that one demand block only corresponds to one shelter, which is not consistent with the actual evacuation situation. The assumption that refugees from one demand block are assigned to the same shelter will result in congestion or the waste of refugee resources due to the mismatch between the number of refugees and the capacity of the shelters. Therefore, this study makes the hypothesis that the multiple demand blocks correspond to multiple shelters, which means the refugees from one demand block have the authority to choose to enter different shelters rather than being strictly assigned to one shelter. The quantity of refugees from demand block i is assigned to adjacent shelters according to the gravity model under the restrictive conditions on maximum capacity and refuge service distance.

2.4.2. Other Basic Assumptions

Other Basic Assumptions Are Illustrated as Follows

(1) Refugees from demand block i enter shelter j through the same route. The congestion of evacuation roads is not considered. The average speed of the refugees is determined as v_{ij} from demand block i to shelter j.
(2) During evacuation, the horizontal distance and vertical dimension between each person are set to 0.75 m and 1.34 m, respectively [43]. The road width matches the road grade. The widths of the bypass evacuation road, secondary evacuation road, and main evacuation road are determined as 18 m, 20 m, and 30 m, respectively [44].
(3) All refugees enter the shelter on foot during both the first and second hierarchies.

2.5. Simulation for Evacuation Scenario

Gravity Model

With restrictive conditions on the service radius and maximum capacity of shelters, refugees from the same demand block can enter multiple adjacent shelters through the gravity model. The number of refugees originating from block i assigned to shelter j is negatively correlated with the distance from block i to shelter j and positively correlated with the maximum capacity of shelter j. The larger the capacity and the shorter the evacuation distance is, the more refugees the shelter will receive. If there are k shelters around demand block i within the service radius limit, then the number of refugees from block i to shelter j is calculated through Equation (1).

$$p_{ij} = [w_{ij} P_i] \tag{1}$$

where [] denotes the downward integral function and w_{ij} denotes the proportion of evacuees from plot i to shelter j, which is calculated through Equation (2). P_i denotes the total number of refugees.

$$w_{ij} = \frac{C_j}{d_{ij}} / \sum_{j=1}^{k} \left(\frac{C_j}{d_{ij}}\right) \tag{2}$$

where d_{ij} denotes the minimum distance from demand block i to shelters j, which originates from the OD matrix determined through the Dijkstra algorithm [45]. C_{ij} denotes the maximum capacity of a shelter.

2.6. Cyclic Assignment Evacuation Model

The target of the evacuation assignment model is evacuating all refugees and making full use of all shelters. The conventional model makes a hypothesis that refugees from one block can only go to one shelter, which may lead to the waste of refugee resources. The shelters are not full but can no longer receive refugees from other demand blocks.

Therefore, the cyclic assignment evacuation model allows refugees from the same demand block to enter different shelters within the service radius (Figures 2–4). Assuming that there is a difference in time sequence when the crowd flows to shelters, if the number of refugees reaches the upper limit of the capacity of shelter *j*, shelter *j* will be closed at this time. The refugees on the evacuation routes are immediately assigned to the other surrounding shelters, which means entering the next round of the assignment process. The idea and process of the cyclic assignment evacuation are illustrated in Figures 2 and 3.

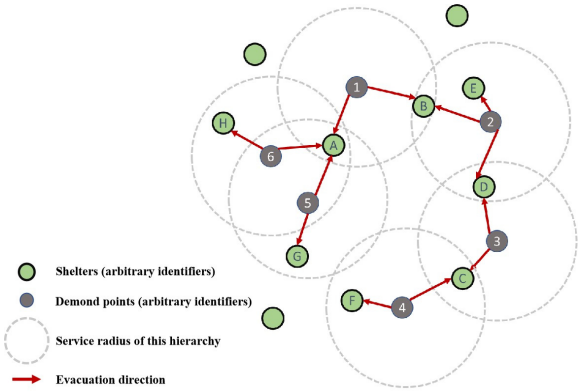


Figure 2. Schematic plot of cyclic assignment model.

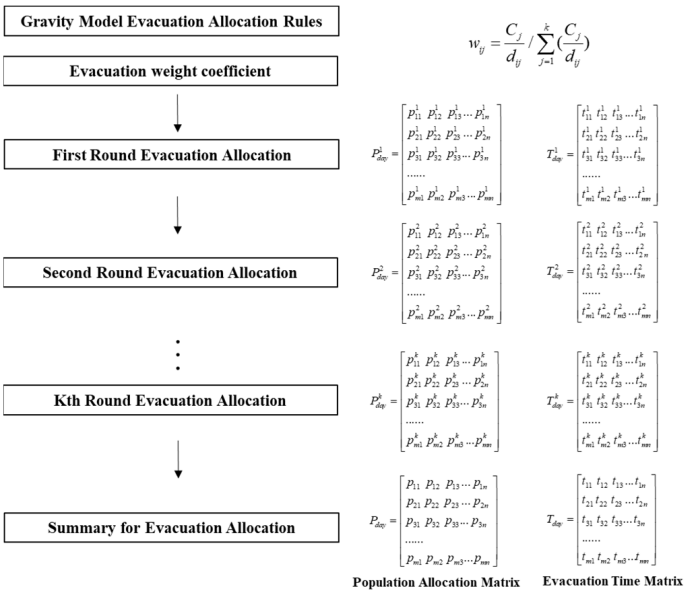


Figure 3. Process of cyclic evacuation assignment model.

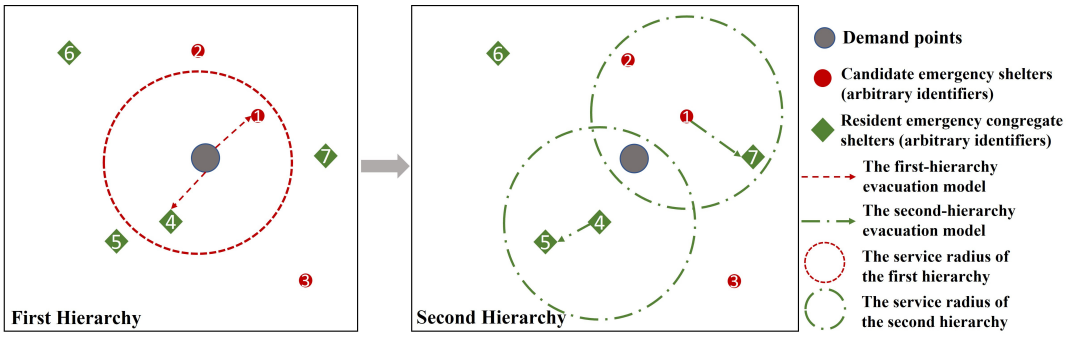


Figure 4. Coverage area of the two-hierarchy shelters.

(1) Calculation for refuge demands

When the number of refugees entering shelter j arrives at maximum capacity C_j at moment t_j^1, the shelter is closed and cannot receive more refugees. At that moment, the quantity of refugees who have not been received by shelters enters the next cycle. Taking evacuation in the daytime as an example, the first-round population assignment matrix through the gravity model is as follows:

$$P_{\text{day}}^1 = \begin{bmatrix} p_{11}^1 & p_{12}^1 & p_{13}^1 \cdots p_{1n}^1 \\ p_{21}^1 & p_{22}^1 & p_{23}^1 \cdots p_{2n}^1 \\ p_{31}^1 & p_{32}^1 & p_{33}^1 \cdots p_{3n}^1 \\ \cdots & & \\ p_{m1}^1 & p_{m2}^1 & p_{m3}^1 \cdots p_{mn}^1 \end{bmatrix} \tag{3}$$

where p_{ij}^1 denotes the number of refugees originating from demand plot i entering candidate shelter j in the first round and n and m denote the overall number of candidate shelters and demand plots, respectively. P_{day}^1 denotes the first-round population assignment matrix in the daytime. The column j of the matrix is the number of refugees from demand blocks 1, 2, … m to shelter j. The row i of the matrix denotes the number of refugees originating from demand block i to shelter 1, 2, … n. The total number of refugees entering each shelter in the first round is determined by adding the value of each column ($\sum_{i=1}^{m} p_{ij}^1$). The number of refugees completing evacuation at each demand block are determined by adding the value of each row $p_i^1(p_i^1)$ The number of refugees entering the next round of evacuation assignment is determined through subtracting p_i^1 from the total number of refugees at the demand block.

(2) Calculation for egress time

In Assumption (2), the horizontal and longitudinal spacing between pedestrians is determined as 0.75 m and 1.34 m. Based on different grades of the evacuation roads, the valid width is determined as h meters. The number of refugees contained on the transverse space of the evacuation road is $[h/0.75]$. Therefore, the required time for refugees to transfer from block i to shelter j is calculated through Equation (4).

$$t_{ij} = \left(p_{ij}/[h/0.75] \times 1.34 + d_{ij}\right)/v \tag{4}$$

Therefore, the first round of the matrix for egress time is determined by Equation (5).

$$T_{\text{day}}^1 = \begin{bmatrix} t_{11}^1 & t_{12}^1 & t_{13}^1 \cdots t_{1n}^1 \\ t_{21}^1 & t_{22}^1 & t_{23}^1 \cdots t_{2n}^1 \\ t_{31}^1 & t_{32}^1 & t_{33}^1 \cdots t_{3n}^1 \\ \cdots\cdots & & \\ t_{m1}^1 & t_{m2}^1 & t_{m3}^1 \cdots t_{mn}^1 \end{bmatrix} \tag{5}$$

In the first round of evacuation, the shelter that has reached its maximum capacity at moment t_j^1 is closed. The subsequent evacuation process will not consider the situation in which the refugees are assigned to this shelter.

(3) Summary of multiple rounds of the circular evacuation

The total matrix for refugee demands is determined by adding the assignment matrix of all rounds, as illustrated in Equation (6).

$$P = P_{\text{day}}^1 + P_{\text{day}}^2 + P_{\text{day}}^3 + \ldots = \begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots & p_{1n} \\ p_{21} & p_{22} & p_{23} & \cdots & p_{2n} \\ p_{31} & p_{32} & p_{33} & \cdots & p_{3n} \\ \cdots\cdots & & & & \\ p_{m1} & p_{m2} & p_{m3} & \cdots & p_{mn} \end{bmatrix} \tag{6}$$

Meanwhile, the total egress time is summarized (daytime situation as an example) in Equation (7).

$$T = T_{\text{day}}^1 + T_{\text{day}}^2 + T_{\text{day}}^3 + \ldots = \begin{bmatrix} t_{11} & t_{12} & t_{13} & \ldots & t_{1n} \\ t_{21} & t_{22} & t_{23} & \ldots & t_{2n} \\ t_{31} & t_{32} & t_{33} & \ldots & t_{3n} \\ \ldots\ldots & & & & \\ t_{m1} & t_{m2} & t_{m3} & \cdots & t_{mn} \end{bmatrix} \tag{7}$$

In addition, for demand block i, the overall time required for all pedestrians completing evacuation is determined as $\max(t_{ij})(i = 1, 2, \ldots n)$. The total number of refugees finally accepted by shelter j is determined as $\sum_{i=1}^{m} p_{ij}$ The overall time for shelter j to receive all refugees is determined as $\max(t_{ij})(j = 1, 2, \ldots m)$.

2.7. Evacuation Flow Allocation Model

After allocation schemes from each demand plots to shelters are determined, evacuees from demand plot i to shelter j have several evacuation routes. The evacuation routes are important to the location of shelters, which strongly influences the evacuation time. In order to simulate authentic evacuation roads, to avoid problems such as longer times required for the dynamic traffic allocation process, multiple input parameters and high accuracy requirements, and difficulty in iteration convergence [38], this study uses a deterministic user equilibrium problem [39].

The user equilibrium model assumes that no evacuees can shorten their evacuation time by changing their evacuation route [39]. Wardrop rules provide an equivalent definition of the user equilibrium model [46], which is the first criterion of Wardrop: for a random O-D pair, the evacuation time of all selected routes is equal to or shorter than the evacuation time of the unselected routes. The mathematical model proposed by Beckmann [47] satisfies the Wardrop first criterion. Equations (8)–(11) are the simple form of the deterministic user equilibrium model [39], in which evacuees find their shortest routes to the shelters they are assigned to.

$$\min_{f \geq 0} z(f) = \sum_{a \in A} \int_0^{x_a(f)} p_a(w) dw \tag{8}$$

$$\sum_{k \in K} f_k^{rs} = q_{rs} \ \forall r \in R \ \forall s \in S \tag{9}$$

$$x_a(f) = \sum_{r \in R} \sum_{s \in S} \sum_{k \in K_n} f_k^{rs} \delta_{a,k}^{rs} \tag{10}$$

$$c_k^{rs} = \sum t_a \delta_{a,k}^{rs} \ \forall k \in K_{rs} \ \forall r \in R \ \forall s \in S \tag{11}$$

where a represents a section of the entire road network; A is the aggregation of road segments in the road network; and R is the aggregation of starting points. We denote a transportation network by G = (R, A), where the set R is the set of nodes and A is the set of links of the network. S is the aggregation of the end point; r-s is an O-D pair in the road network; f_{krs} represents the k-th routes between O-D pairs; and $\delta_{a,k}^{rs}$ represents that section a belongs to the k-th path. If this path belongs to the set of paths between the O-D pair from r to s, the value of $\delta_{a,k}^{rs}$ is 1; otherwise, it is 0. c_k^{rs} represents the evacuation time on the k-th route between the O-D pair from r to s; $t_a(x_a)$ represents the relationship between evacuation time and evacuation flow on section a, which is expressed by the BPR function. The Bureau of Public Roads (BPR) function [48] is a common choice in transportation to evaluate the flow-dependent evacuation time on congested roads (Equation (12)).

$$t_a(x_a) = t_0(1 + \alpha(\frac{x_a}{c})^{\beta}) \tag{12}$$

where x_a represents the evacuation flow on section a; t_0 represents the evacuation time on section a under free-flow conditions; α and β represent the model parameter, which are determined as 0.15 and 4, respectively; and C represents the capacity of the evacuation roads.

2.8. Spatial Allocation Model of Two-Hierarchy Shelters

Following the principles of fairness (satisfying the refuge demands of all people) and economy (minimizing the construction cost and the evacuation cost), this study sets the overall evacuation time and the number of shelters as optimization objectives to establish a two-hierarchy and two-phase spatial allocation model for earthquake shelters. The spatial allocation model designed in this study is divided into two hierarchies, in which each hierarchy contains two phases. Figure 4 demonstrates the site selection model of the two-hierarchy shelters, the coverage radius at different hierarchies, and the evacuation assignment process for refugees at different hierarchies. In the first hierarchy, candidate shelters can be ESs and RSs. All refugees are assigned and transferred from demand blocks to ESs and RSs. In the second hierarchy, refugees are transformed from ESs to RSs. The purpose of constructing a two-phase model is to simplify the complexity and the difficulty of solving the multi-objective location model. In the first phase of model solving, with the restrictive conditions on maximum capacity and service distance, the spatial configuration schemes with the minimum construction cost are determined (assuming that the number of new shelters is positively correlated with the construction cost). The objective of the second phase of model solving is minimizing the overall evacuation cost, which means the overall evacuation time. Each hierarchy optimization has the same first phase and second phase.

The two-hierarchy model considers the situation where refugees transfer between different hierarchical shelters to obtain more refugee areas, better refuge facilities, and higher service levels. The transfer process of the two-hierarchy model is demonstrated in Figure 5. With the continuation of time, refugees will require a higher level of refuge services. If the existing shelters cannot provide the required services, the refugees will be transferred to a shelter with a higher level. In the second hierarchy, when ESs can no longer meet the refugees' demands for relief resources and facilities, refugees will be relocated (from ESs to RSs). If refugees are initially assigned to the shelter that can satisfy higher refuge demands, there is no necessity for resettlement, which indicates that higher-grade shelters can afford the same refuge services as lower-grade shelters. RSs can be regarded as ESs, but ESs cannot be regarded as RSs.

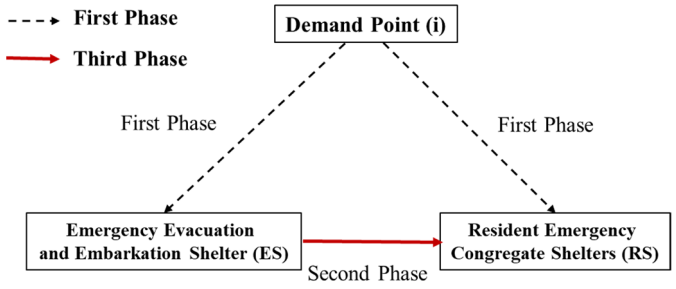


Figure 5. Two-hierarchy transfer process of crowd evacuation.

2.9. The First-Hierarchy Shelter Location Model

In the first hierarchy, all candidate shelters (ESs or RSs) are regarded as emergency shelters, which means each shelter can provide a refuge area of 1.5 m^2 per capita, and the evacuation distance from to one demand block to one shelter does not exceed 500 m (Table 2).

(1) The first phase of optimization in the first hierarchy

Variable declaration:

The variables a_{ij} and b_j are decision variables. If candidate shelter j is selected, the numerical value of b_j is 1. On the contrary, its value is determined as 0. If refugees from block i enter shelter j, the numerical value of a_{ij} is 1. On the contrary, it is 0.

J denotes the set of all types of shelters, and I denotes the set of all demand blocks.

M_i and N_i denote the refugee demands of demand block i in the daytime and nighttime.

C_j denotes the maximum capacity of shelter j.

The variable g_{ij} denotes the distance limitation matrix. If the road network distance from demand block i to shelter j is within the service radius of an ES (500 m), the numerical value of g_{ij} is 1; on the contrary, the value is determined as 0.

In the first phase, the objective is minimizing the number of new shelters. The objective function value is determined through Equation (13).

$$\min z_1 = \sum_{j \in J} y_j \tag{13}$$

Meanwhile, it is necessary to ensure that refugees from all demand blocks can be evacuated within the capacity and service radius limitations of each shelter. The constraint conditions are as follows:

$$\sum_{j \in J} a_{ij} \geq 1 \; \forall i \in I \tag{14}$$

$$a_{ij} \leq g_{ij} \; \forall i \in I \; \forall j \in J \tag{15}$$

$$\sum_{i \in I} (a_{ij'} \cdot M_i) \leq b_j \cdot c_j \; \forall j \in J \tag{16}$$

$$\sum_{i \in I} (a_{ij} \cdot N_i) \leq b_j \cdot c_j \; \forall j \in J \tag{17}$$

$$b_{1,2,\ldots,B} = 1 \tag{18}$$

$$\sum_{j=1}^{n} p_{i,j}^{day} = M_i \; \forall i \in I \tag{19}$$

$$\sum_{j=1}^{n} p_{i,j}^{night} = N_i \; \forall i \in I \tag{20}$$

$$a_{ij} = 0 \; or \; 1 \tag{21}$$

$$b_j = 0 \; or \; 1 \tag{22}$$

Equation (14) ensures that the crowd at each demand block can be evacuated to at least one shelter. Equation (15) ensures that the evacuation distance is less than the service radius of the ESs. Equations (16) and (17) ensure that the number of refugees received by each shelter in the daytime and nighttime does not exceed its maximum capacity. Equation (18) indicates that the number of selected ESs is B. Equations (19) and (20) ensure that refugees from different rounds of the circular assignment model can complete evacuation in the daytime and nighttime. Equations (21) and (22) are the constraints for decision variables a_{ij} and b_j.

(2) The second phase of optimization in the first hierarchy

In the second phase of optimization, based on the minimum number of new shelters calculated in the previous phase, the optimal decision with the minimum overall evacuation time is determined from C_A^B feasible schemes using the enumeration approach. A denotes the number of all candidate shelters. B denotes the number of selected shelters in solving the first-phase model.

Variable declaration:

Q denotes the set of all selected shelters (ESs and RSs): $Q = \{q \mid q = 1, 2, 3 \ldots, B\}$, $k \leq n$, $\forall q \in Q$.

The variable a_{ip} is the decision variable. When its value is 1, the crowd from demand block i chooses to take refuge at the selected shelter q.

C_q denotes the maximum capacity of the selected shelter q.

The variable t_{ip} denotes the evacuation time from demand block i to the selected shelter q.

For evacuees from demand block i to the selected shelter q, t_{ip} is determined by Equation (23), which represents the objective of minimizing the total evacuation time in the evacuation flow allocation:

$$t_{ip} = \min \sum_{\alpha} x_a t_a(x_a) \tag{23}$$

The objective function value of the second-phase optimization is determined by Equation (24).

$$\min z_2 = 0.5 \sum_{i \in I} \sum_{p \in P} (a_{ip} \cdot M_i \cdot t_{ip}) + 0.5 \sum_{i \in I} \sum_{p \in P} (a_{ip} \cdot N_i \cdot t_{ip}) \tag{24}$$

The constraint conditions are consistent with the first-phase model solution.

2.10. The Second-Hierarchy Shelter Location Model

In the second hierarchy, all candidate shelters are RSs. Refugees are transferred from selected shelters in the first hierarchy to RSs. Each RS can provide a refuge area of 2.5 m^2 per capita, and the evacuation distance from one ES to one RS does not exceed 2500 m (Table 2).

Because the refuge area per capita increases from 1.5 m^2 to 2.5 m^2, the selected RSs may not accommodate refugees determined in the first hierarchy. It is pointed out that in the second hierarchy, refugees may evacuate from RSs selected in the first hierarchy to other RSs.

(1) The first phase of optimization in the second hierarchy

Variable declaration:

Q denotes the set of all selected shelters (ESs and RSs) in the first hierarchy; $Q = \{q \mid q = 1, 2, 3 \ldots, B\}, \forall q \in Q$.

$Q_{es,1}$ denotes the set of selected ESs in the first hierarchy, $\forall q_{es,1} \in Q_{es,1}$.

$Q_{rs,1}$ denotes the set of selected RSs in the first hierarchy, $\forall q_{rs,1} \in Q_{rs,1}$.

J' denotes the set of all RSs, the selected RSs in the first hierarchy, and the RSs that are not selected in the first hierarchy; $\forall j' \in J'$; $Q_{rs,1} \subseteq J'$.

M_q and N_q denote the quantity of refugees in shelters in the first hierarchy in the daytime and nighttime, respectively.

$C_{j'}$ denotes the maximum capacity of RSs.

The variable $g_{qj'}$ is the distance limitation matrix. If the distance of the road network from shelter q to shelter j' is within the service radius of RS (2500 m), $g_{qj'}$ is taken as 1; on the contrary, $g_{qj'}$ is taken as 0.

The variables $a_{qj'}$ and $b_{j'}$ are decision-making variables. If resident emergency aggregate shelter j' is selected, $b_{j'}$ is taken as 1; on the contrary, it is 0. If refugees from shelter q enter shelter j', the value of $a_{qj'}$ is 1. On the contrary, it is 0.

As with the first hierarchical model, the first phase of the second hierarchical model is devoted to minimizing the quantity of new shelters.

The objective function value is determined through Equation (25).

$$\min z_1 = \sum_{j' \in J'} y_{j'} \tag{25}$$

Meanwhile, the constraint conditions ensure that all refugees can receive services at higher-grade shelters with restrictive conditions on maximum capacity and service radius. The constraints are illustrated in Formulas (26) to (32).

$$\sum_{j' \in J'} a_{qj'} \geq 1 \ldots \forall q \in Q \tag{26}$$

$$a_{qj'} \leq g_{qj'} \ldots \forall j' \in J' \; \forall i \in I \tag{27}$$

$$\sum_{q \in Q} (a_{qj'} \cdot N_{j'}) \leq b_{j'} \cdot c_{j'} \forall j' \in J' \tag{28}$$

$$\sum_{q \in Q} (a_{qj'} \cdot M_{j'}) \leq b_{j'} \cdot c_{j'} \forall j' \in J' \tag{29}$$

$$b_{1,2,\ldots,Brs} = 1 \tag{30}$$

$$a_{qj'} = 0 \; or \; 1 \tag{31}$$

$$b_{qj'} = 0 \; or \; 1 \tag{32}$$

Equation (26) ensures that the crowd at each shelter q can be evacuated to at least one shelter j'. Equation (27) ensures that the evacuation distance is less than the service radius of RSs. Equations (28) and (29) ensure that the number of refugees received by each RS in the daytime and nighttime does not exceed its maximum capacity. Equation (30) denotes that the selected RS in the first hierarchy must also be selected in the second hierarchy. Equations (31) and (32) are the constraints for decision variables $a_{qj'}$ and $b_{j'}$.

(2) The second phase of optimization in the second hierarchy

In the second phase of optimization, based on the minimum number of new shelters calculated in the previous phase, the optimal decision with the minimum overall evacuation time is determined from feasible schemes using the enumeration approach.

Variable declaration:

$Q_{rs,2}$ denotes the set of selected RSs in the second hierarchy, $\forall q_{rs,2} \in Q_{rs,2}$.

Q_{rs} denotes the union set of $Q_{rs,1}$ and $Q_{rs,2}$; $\forall q_{rs} \in Q_{rs}$.

The variable $a_{q,rs}$ is the decision variable. When its value is 1, the crowd from shelter q can choose to take refuge at the selected RS q_{rs}.

C_{rs} denotes the maximum capacity of the selected resident emergency aggregate shelter q_{rs}.

The variable $t_{q,rs}$ denotes the evacuation time from shelter q to the selected resident emergency aggregate shelter q_{rs}.

For evacuees from demand block q to the selected resident emergency aggregate shelter q_{rs}, $t_{q,rs}$ is determined by Equation (33), which represents the objective of minimizing the total evacuation time on evacuation flow allocation:

$$t_{q,rs} = \min \sum_{\alpha} x_a t_a(x_a) \tag{33}$$

The objective function value of the second phase is determined by Equation (34).

$$\min z_2 = 0.5 \sum_{q \in Q} \sum_{q,rs \in Q,rs} (a_{q,rs} \cdot M_q \cdot t_{q,rs}) + 0.5 \sum_{q \in Q} \sum_{q,rs \in Q,rs} (a_{q,rs} \cdot N_q \cdot t_{q,rs}) \tag{34}$$

The constraint conditions are consistent with the first-phase model solution in the second hierarchy.

The two-hierarchy and two-phase spatial allocation model of shelters considers the crowd transformation between different RSs within the second hierarchy because the refuge area per capita increases from 1.5 m^2 to 2.5 m^2, which means the number of refugees received by RSs in the first hierarchy may exceed the capacity in the second hierarchy. The relationship between different hierarchies of shelters is demonstrated in Figure 6.

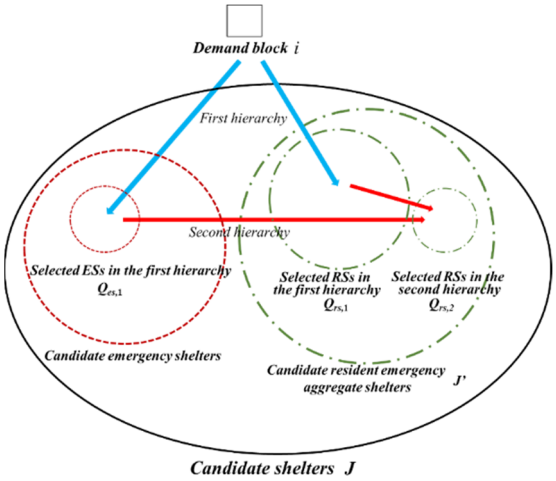


Figure 6. The relationship between different hierarchies of shelters.

2.11. Solutions Based on Genetic Algorithm

Two approaches are used to determine the solution of planning and the location model of shelters. One approach is to use linear programming software to solve the problem for small-scale areas. For calculations with large amounts of data, particle swarm optimization, genetic algorithms, ant colony algorithms, simulated annealing, and other heuristic or intelligent algorithms are used and then visualized through the ArcGIS platform [16,49]. The proposed two-hierarchy model is an NP-hard problem. The first phase of each hierarchy is solved by a designed genetic algorithm, which includes the following process:

(1) Establish mapping relationship and encoding.

Firstly, a set of location schemes is mapped into a chromosome using binary genetic encoding. Each chromosome has two types of genes, 1 or 0, corresponding to selecting the candidate shelters or not.

(2) Generate a population group with size N.

For all genes on a chromosome, we assume that the probability of being 0 or 1 is the same, and then one chromosome is randomly generated. After N random repetitions, the initial population $P(0)$ with a size of N is generated.

(3) Calculate the value of fitness function value.

The value of the fitness function for a location scheme is the sum of the number of genes whose value is determined as 1 (i.e., the number of shelters selected in the scheme). When the site selection scheme cannot meet the restrictive conditions, the penalty function is introduced, meaning the number of shelters is increased by 200 in its fitness function. After T iterations, the T^{th} generation population is expressed as $p(T)$. Figure 7 illustrates a population case and its corresponding fitness function value f_i.

01000100 (f_i=2)	01001100 (f_i=3)	00101010 (f_i=3)	01010101 (f_i=4)	00010101 (f_i=3)
11010110 (f_i=5)	10110110 (f_i=5)	10111000 (f_i=4)	11010111 (f_i=6)	10011111 (f_i=6)

Figure 7. Chromosomes and their corresponding fitness function values.

(4) Generation of new chromosomes by selection, crossover, and mutation operations.

Genetic manipulation includes selection, crossover, and mutation operations. Firstly, the selection operation is completed through roulette wheel operation. In the selection process, the selection probability of each chromosome is positively proportional to the value of the fitness function. The probability is determined through the individual fitness function values divided by the sum of all the chromosomes' fitness function values in one population.

However, the roulette rules may ignore and fail to select the chromosomes with the optimal fitness function values to enter the crossover and mutation phase. The fitness function value of progeny chromosomes may be better than that of parent chromosomes. Combined with the elite retention strategy, this algorithm directly copies the chromosome corresponding to the optimum value of the fitness function into progeny population, thus guaranteeing that the optimum value of the fitness function in the progeny is superior to the value of the previous generation.

The crossover process adopts the multiple-point crossover operation in the early phase and the single-point crossover operation in the later phase. The crossover operation is completed with a stationary probability p_c. In the multiple-point crossover, the number of random crossover points is set to 10, and the gene blocks are exchanged. The intersection point of the single-point crossover is determined through the random number approach. Figure 8 illustrates the process of the crossover operation.

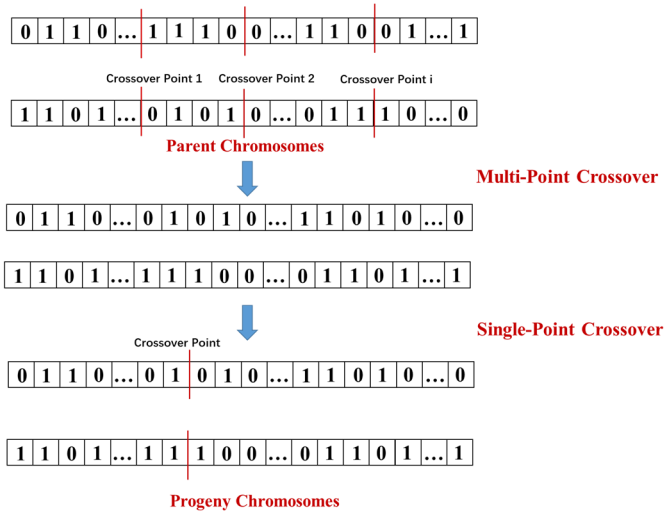


Figure 8. Generation of progeny chromosomes through crossover operation.

In the later phase of the algorithm, the chromosomes complete mutation operations randomly to guarantee the variety of the new population. Each gene on the chromosome generated by the crossover operation mutates with a fixed probability $\boldsymbol{p_m}$. Then, the new chromosomes are produced. Population $P(T)$ produces the next generation of population $P(T+1)$ through crossover operation, selection operation, and mutation operation.

(5) Termination judgment for algorithm.

In view of the solution accuracy and efficiency, the conditions for iteration termination are set as two rules, the genetic evolution algorithm reaches the maximum limit, and the value of the fitness function of the optimal individual and population will not increase. When the termination conditions are satisfied, the chromosome with the optimum value of the fitness function is selected as the solution of the first phase. The whole process of the designed genetic algorithm in the first phase of model solving is illustrated in Figure 9.

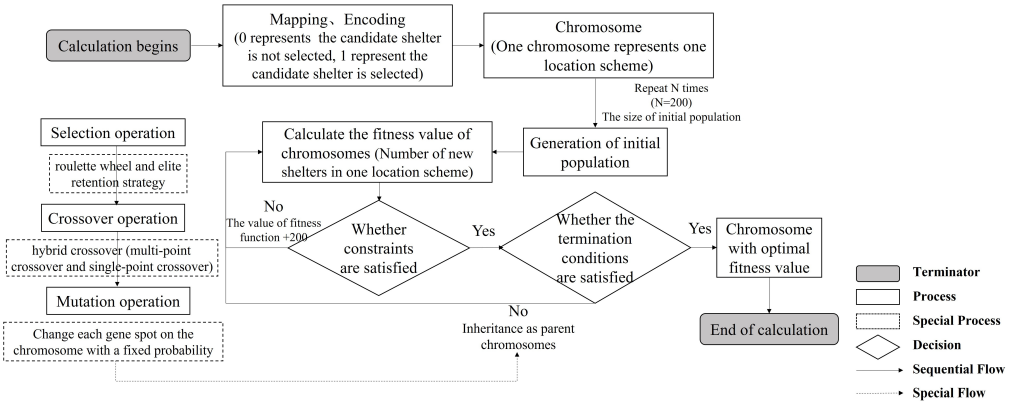


Figure 9. Process diagram of the designed genetic algorithm in this study.

2.12. Case Study

Location of Case Area and Basic Data Preparation

This study selected Changshu City, Jiangsu Province, China, as the case area (Figure 10). Changshu City is not only a national historical and cultural city but also a progressive manufacturing base and trade center in the Yangtze delta region. The population of Changshu is 1.683 million. Multiple seismic fault zones pass through Changshu City. A total of 47 earthquakes with a magnitude of 4 or higher have occurred in Changshu City since AD 701. The most serious earthquake, with a magnitude of 5.1, occurred on 10 February 1990. Therefore, earthquakes threaten the life security of residents. The study area is the main urban zone of Changshu City (Figure 1). Based on the code for the seismic design of buildings [50], the seismic fortification intensity of the study area is VII degrees.

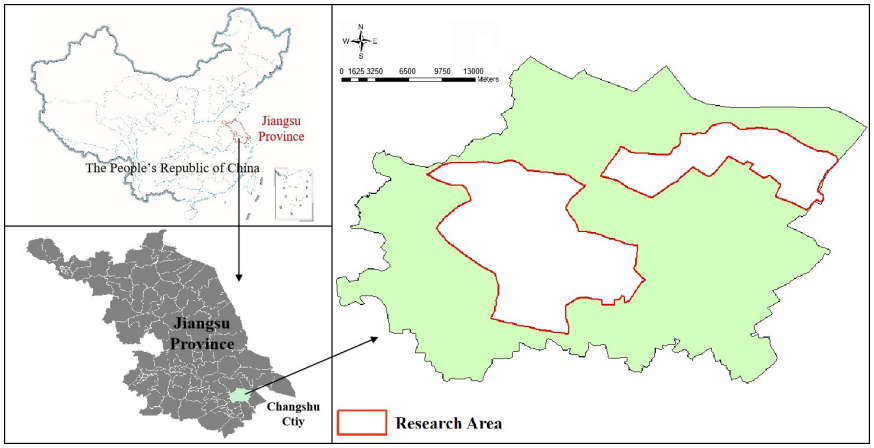


Figure 10. Location and range of the study area.

The basic data for the spatial configuration of shelters include spatial data and population data. The road network and division of demand blocks are derived from comprehensive planning of Changshu City and remote sensing images. Based on the Regulation on Standard of Urban Planning on Earthquake Resistance and Disaster Prevention [42], a total of 300 candidate shelters were selected from parks, green spaces, stadiums, and schools. Restrictive indexes such as effective area, maximum capacity, and the service level of all candidate shelters were determined (Figure 11).

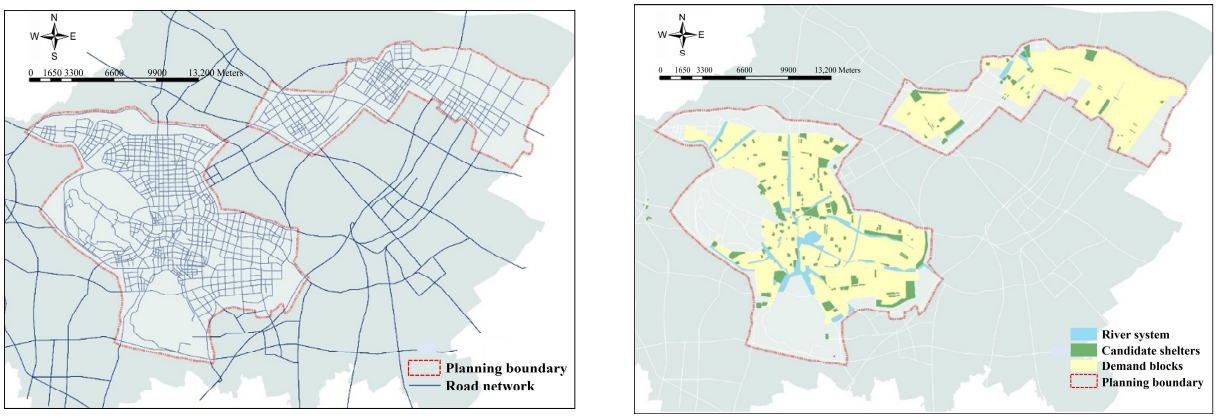


Figure 11. Basic spatial data of study area: (**a**) road network; (**b**) refuge demand areas and candidate shelters.

The evacuation route was generated according to the road network, entrances, and exits of the demand blocks and shelters (Figure 12). The evacuation demand of each demand block unit was concentrated at the demand block on ArcGIS. Then, a nearest neighbor analysis and "OD matrix from the layer as a line" were used to establish an OD matrix from demand blocks to shelters. The shortest road network distance from each demand block to the shelters was calculated based on the Dijkstra algorithm [51]. Tables 4 and 5 demonstrate the results of the OD matrix.

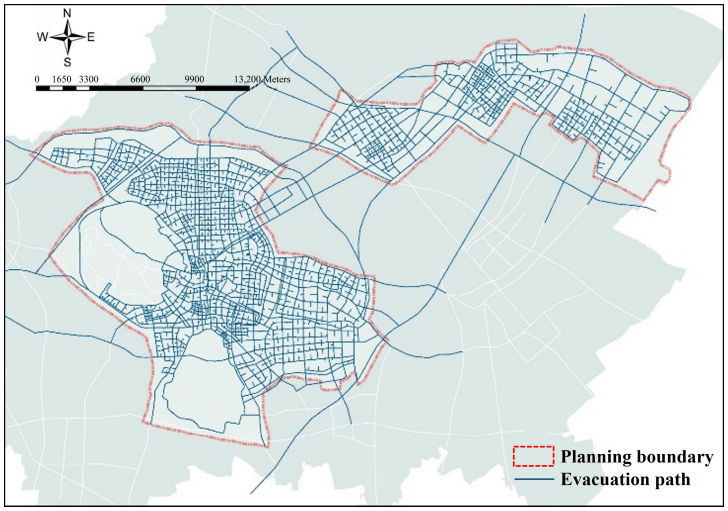


Figure 12. Evacuation paths from demand blocks to shelters.

Table 4. OD matrix from demand blocks to current shelters that have been built.

Demand Block	Current Shelter						
	1	**2**	**3**	.....	**73**	**74**	**75**
1	15,910	15,541	15,084	.....	11,258	25,295	5706
2	15,924	15,584	15,066	.....	10,936	24,694	5785
.....	.....	.....	.....	.....	.....	.....	.....
647	30,627	31,162	29,546	.....	22,690	3587	28,826
648	27,758	28,320	26,699	.....	20,091	3832	26,567

Note: nos. 1–63 are current ESs, nos. 64–75 are current RSs.

Table 5. OD matrix from demand blocks to candidate shelters.

Demand Block	Candidate Shelter						
	1	**2**	**3**	.....	**160**	**161**	**162**
1	2796	4397	13,435	.....	13,703	6394	4012
2	2675	4253	13,122	.....	13,640	6708	3938
.....	.....	.....	.....	.....	.....	.....	.....
647	2758	2702	2226	.....	28,154	31,476	27,580
648	25,569	24,897	19,506	.....	25,360	29,224	25,467

Note: nos. 1–116 are candidate ESs, nos. 117–162 are candidate RSs.

2.13. Determination of Refuge Demands

Population Distribution in the Daytime and Nighttime

The daily work, study, life, and commuting of urban residents make the distribution of population different in the daytime and nighttime. The common population density is usually calculated on the city and street scale, which is difficult to use for directly determining the population of each demand plot. More precise population density data derive from the Baidu Heat Map [52], mobile signaling data [53], Baidu Map Insight [54], and social network check-in data [55]. This study determines the day and night population distribution through the *Changshu Statistical Yearbook* [56] and Chinese mobile phone signaling data from 10 April 2022 to 23 April 2022, following the calculation approach in a previous study [57]. Figures 13 and 14 determine the population distribution in the daytime and nighttime.

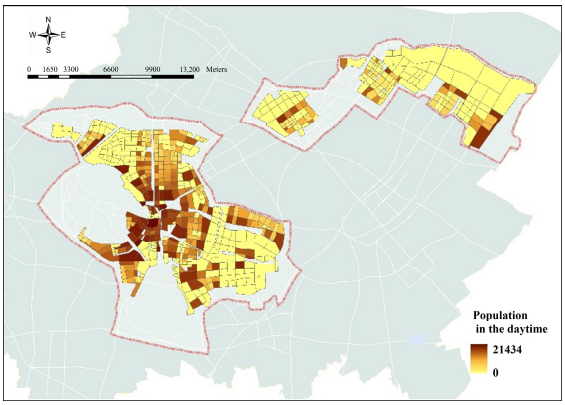


Figure 13. Population distribution in the daytime.

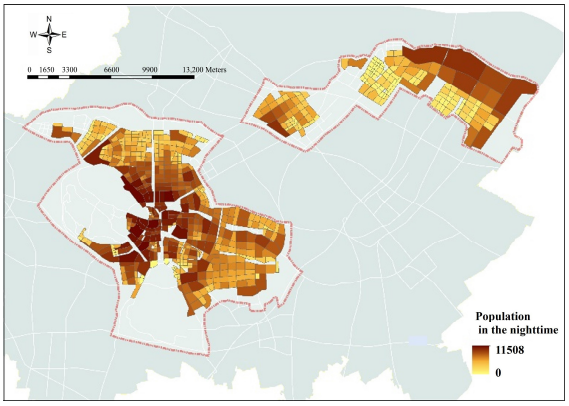


Figure 14. Population distribution in the nighttime.

2.14. Seismic Damage Assessment of Buildings in the Study Area

This study sets the disaster scenario in which an earthquake with an intensity of 8 occurs in Changshu City. The damage status of buildings is determined through Equation (35). [58]

$$D = \coprod_{m=1}^{M} \prod_{n=1}^{N} d_{mn} \tag{35}$$

where D denotes the indicator of the damage to buildings in Table 6. N denotes the number of factors for earthquake damage. M denotes the number of classifications of factors for earthquake damage. The value of d_{mn} and the six main influence factors for building damage can be determined in Table 7.

Table 6. Classification of level for structural damage with intensity 8 and damage index (D) [58].

Damage Level	Damage Index of Buildings (D)	Building Area (m^2)
Basic intact	<2	0
Slight damage	2–3	14,734,824
Moderate damage	3–5	18,537,360
Severe damage	5–8	13,784,191
Damage completely	>8	475,318

Table 7. Classification of damage level of buildings under earthquake [58].

Factor for Earthquake Damage	Classification	Value for Classification (d_{mn})
Seismic fortification criterion	None	2
	VI (α = 0.05 g)	1.5
Types of ground antiseismic type	Type IV	1.8
	Type III	1.5
	Type II	1.2
	Type I	1
Structural type	Reinforced concrete structure	1
	Brick structure	1.8
	Others	2.4
Number of floors	1–2	1.8
	3–6	1.5
	6–12	1.2
	>12	1
Construction period	Before 1980	1.4
	1980–1989	1.2
	From 1990 to today	1
Current situation	Basic intact	1
	Slight deformation of main load-bearing structure	1.3
	Severe damage	1.7

After the earthquake occurs, the number of people who need to be resettled is related to the damage to the building structure, which can be determined through Equation (36) [59,60]:

$$PR = \frac{1}{ra}\left(\frac{2}{3}A_1 + A_2 + \frac{7}{10}A_3\right) \tag{36}$$

where PR denotes the number of refugees after the earthquake and r_a denotes the building area per capita (m^2). A_1 denotes the building area with complete damage (m^2). A_2 denotes the building area with severe damage (m^2). A_3 denotes the building area under moderate damage. The values of A_1, A_2, and A_3 are demonstrated in Table 6 and Figure 15.

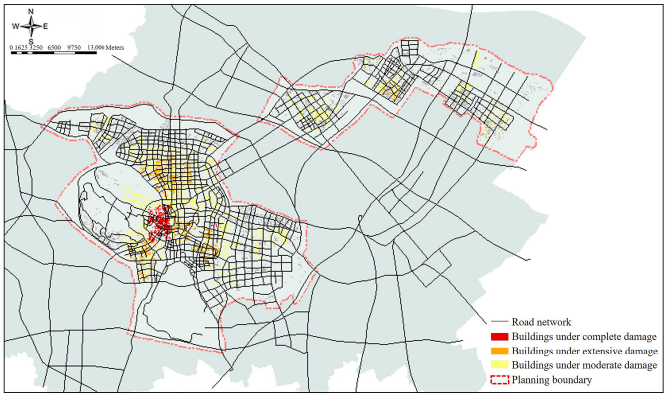


Figure 15. Structural damage assessment under earthquake with an intensity of 8 (building data from housing construction bureau of Changshu City).

We coupled the population data in Figures 13 and 14 with the damage state of buildings in Figure 15 to determine the number of refugees in each block through Equation (29). Firstly, the total population difference between daytime ($P_{\text{i,daytime}}$) and nighttime ($P_{\text{i,nighttime}}$) in demand block i is determined through mobile phone signaling data [57]. Secondly, the damage status of buildings is determined in Figure 4. Thirdly, the area of buildings with complete damage, severe damage, and moderate damage in each demand block is counted and determined. Fourthly, the number of refugees in each demand block in the daytime and nighttime is determined through Equations (37) and (38) after the earthquake (Table 6).

$$PR_{\text{i,daytime}} = \frac{P_{\text{i,daytime}}}{\sum_{b=1}^{n} A_b} \times \sum_{b=1}^{n} [D_b \times k_b \times A_b] \tag{37}$$

$$PR_{\text{i,nighttime}} = \frac{P_{\text{i,nighttime}}}{\sum_{b=1}^{n} A_b} \times \sum_{b=1}^{n} [D_b \times k_b \times A_b] \tag{38}$$

where the number of buildings in demand area i is n (b = 1, 2, …, n). $PR_{\text{i,daytime}}$ and $PR_{\text{i,nighttime}}$ denote the number of refugees at daytime and nighttime in demand block i. A_b denotes the total area of building b; k_b denotes the conversion coefficient of the number of refugees in building b with different functions. The values of k_b for residential buildings, commercial buildings, official buildings, and schools are determined as 0.04, 0.7, 0.2, and 0.09, respectively, in this study [54]. D_b denotes the damage coefficient of building b, which is determined as 2/3, 1, and 7/10 under complete damage, severe damage, and moderate damage, respectively, based on Equation (29). The evacuation demand calculation realizes the spatio-temporal coupling between the damage state of buildings and population distribution and improves the accuracy of evacuation demand from the plot scale to building scale. In the first hierarchy, the refuge demand is determined

as the total population in Figures 13 and 14. In the second hierarchy, the refuge demand is determined through Equations (37) and (38) (Table 8).

Table 8. Refuge demands of each demand block in the daytime and nighttime.

Serial Number of Demand Blocks	Refugee Demands in the Daytime	Evacuation Demands in the Nighttime
1	2745	673
2	129	296
...	...	...
645	906	220
646	905	2027
647	610	2056

2.15. Suitability Evaluation of Candidate Shelters

According to the suitability evaluation approach in Section 2, the evaluation results are shown in Figure 16. A total of 63 unsuitable locations are excluded from 300 candidate sites, and 237 suitable locations are reserved as candidate sites for the subsequent optimization of shelter location, including 12 current RSs, 63 current ESs, 46 candidate RSs, and 116 candidate ESs (Figures 17 and 18).

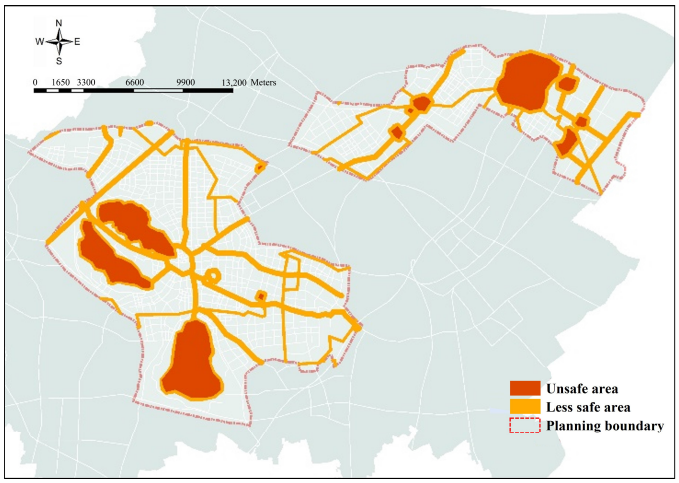


Figure 16. Results of safety assessment in study area.

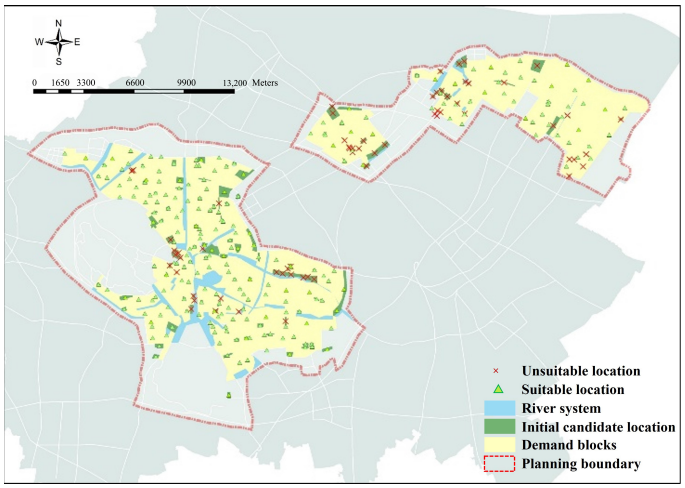


Figure 17. Suitable and unsuitable locations in the study area.

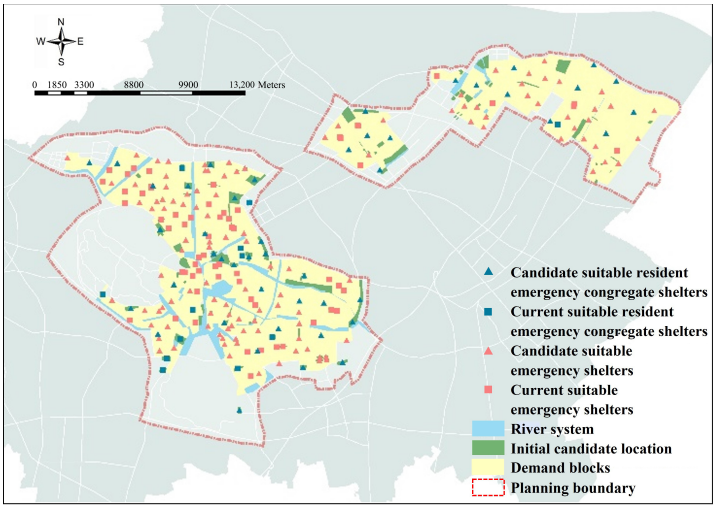


Figure 18. Suitable shelters (built and unbuilt).

3. Results

3.1. The First Hierarchy of Site Selection of Shelters

Because the refuge services of high-level shelters can cover the refuge services of low-level shelters, in the first hierarchy, the service distance and the refuge area per capita of shelters are taken as the criterion of the ESs. The ESs and RSs are regarded as candidate shelters in the first hierarchy.

Through the suitability evaluation of candidate sites, 116 sites are suitable for constructing ESs and 46 sites are suitable for constructing RSs in the study area, and 162 candidate shelters participate in the spatial allocation model in the first hierarchy. In addition, 63 ESs and 12 RSs are regarded as shelters that have already been built (current shelters). According to the designed genetic algorithm, the fitness function value finally converges to 75 (Figure 19). In order to evacuate refugees completely and satisfy the requirements of maximum capacity and service distance, the government administrator should construct at least 75 new shelters.

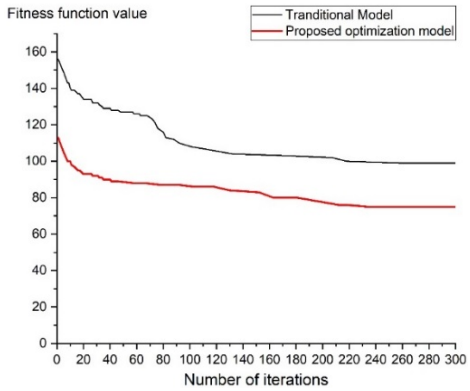


Figure 19. The results of the first phase in the first hierarchy.

In the second phase of the first hierarchy, the enumeration approach is used to determine the practicable spatial allocation schemes from C_{162}^{75} schemes that can satisfy the refugee demands and the restrictive conditions on the maximum capacity and service radius. Then, the overall evacuation times of practicable schemes are compared with each other to determine the optimum scheme with the minimum overall evacuation cost. Figure 20 illustrates the results of shelter location in the first hierarchy. A total of 46 ESs and 29 RSs are selected, with average refugee areas of 1.67 hm^2 and 7.07 hm^2, respectively.

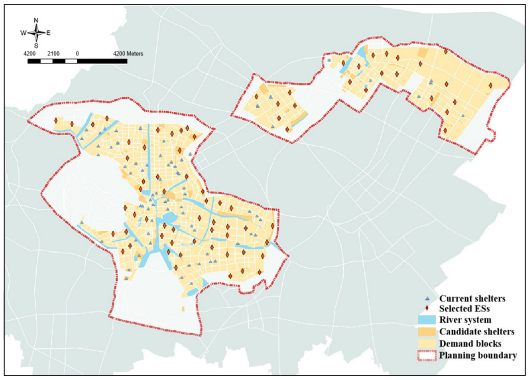


Figure 20. The selected shelters in the first hierarchy.

In the aspect of egress time, it takes 16 min for all refugees to complete evacuation. The average egress time is about 5.2 min. The egress time for 41% of the demand blocks is concentrated between 6 and 8 min. Figure 21 illustrates the egress time of each demand block in the first hierarchy.

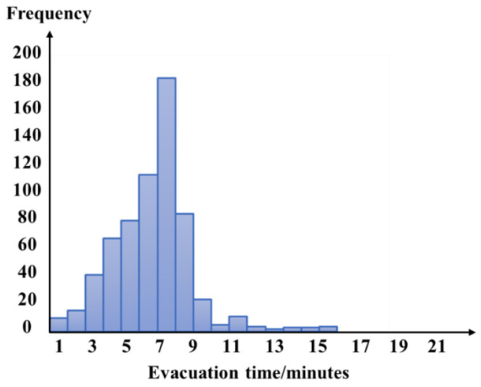


Figure 21. Frequency distributions of egress time in the first hierarchy.

3.2. The Second Hierarchy of Shelter Location

In addition to the 29 RSs already selected in the upper hierarchy, the remaining 17 suitable shelters enter the spatial allocation in the second hierarchy. The selected shelters in the first hierarchy are regarded as the demand blocks in the second hierarchy.

The number of new RSs is determined to be eight in the second hierarchy through the designed genetic algorithm (Figure 22). The optimal location scheme with the minimum overall evacuation cost is determined from C_{17}^{8} schemes by the enumeration approach, as illustrated in Figure 23. Each RS can accommodate 36,012 refugees on average.

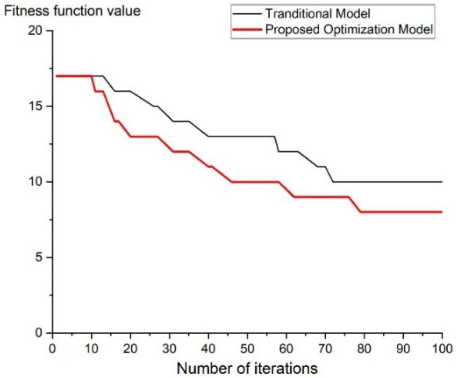


Figure 22. The results of the first phase in the second hierarchy.

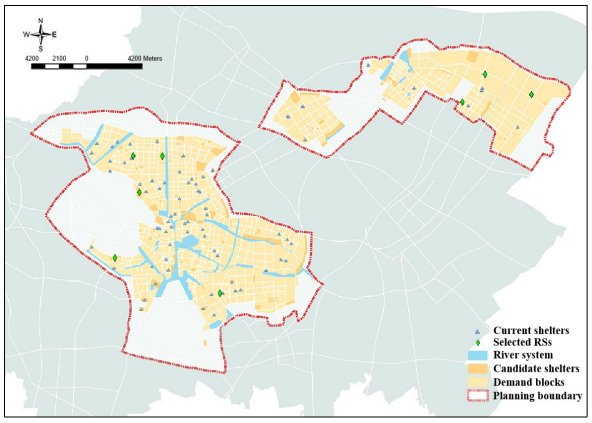


Figure 23. The selected shelters in the second hierarchy.

In terms of egress time, it takes 24 min for all refugees to complete evacuation. The average evacuation time is about 13.9 min. The evacuation time for 68% of the demand blocks to reach the RSs is concentrated between 13 and 17 min. Figure 24 illustrates the evacuation time for each demand block in the second hierarchy.

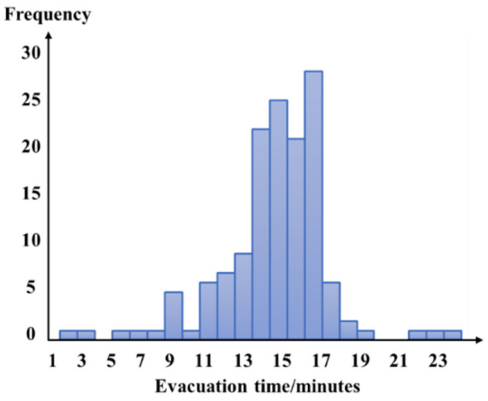


Figure 24. Frequency distributions of evacuation time in the second hierarchy.

In general, all selected shelters in the two-hierarchy spatial allocation model are demonstrated in Figure 25, with a total of 46 ESs and 37 RSs to be built. Compared with the results of the conventional approach, which requires building 109 new shelters, the proposed methodology reduces the number of newly built shelters by 31.3%.

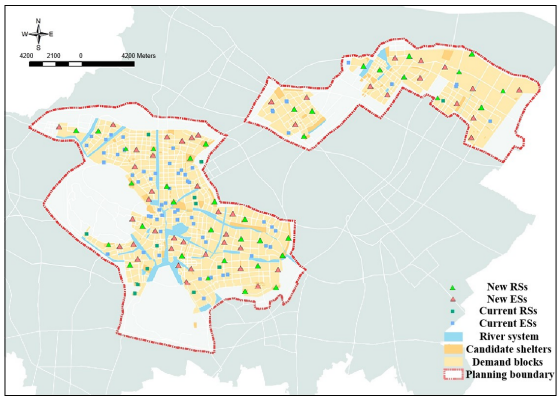


Figure 25. All selected ESs and RSs.

4. Discussion

After analyzing the deficiency of the conventional spatial allocation model of shelters regarding refuge demands and the hierarchy of the evacuation distribution pattern, this study proposes a two-hierarchy and two-phase spatial allocation methodology for shelters. The first hierarchy aims to evacuate refugees from demand blocks to both ESs and RSs, while the second hierarchy aims to transfer refugees from selected shelters in the first hierarchy to RSs. Each hierarchy contains two phases of optimization calculations. The optimization objectives for the first and second phases are minimizing the number of new shelters and the overall evacuation time, respectively. This methodology represents an advancement over the conventional optimization approach in four main respects:

(1) In the conventional hierarchical model, refuge demands are determined based on the resident population, which cannot reveal the spatio-temporal changes in refuge demands. This study considers the differences in population distribution between daytime and nighttime separately through Chinese mobile phone signaling data, which can address disaster scenarios with uncertain occurrence times more reasonably and satisfy the refugee demands of residents during the entire period. Meanwhile, this study couples the damage status of buildings with population data to accurately determine the number of refugees at the building dimensions.

(2) The conventional approaches assume that one demand block corresponds to only one shelter, which does not align with the actual evacuation process. The assumption that refugees from one demand block are assigned to the same shelter will result in congestion or the waste of refugee resources due to the mismatch between the number of refugees and the capacity of the shelters. This study hypothesizes that multiple demand blocks correspond to multiple shelters, meaning refugees from one demand block have the option to choose different shelters rather than strictly following the assignment. This study proposes a cyclic assignment evacuation model based on the gravity model, which allows refugees from the same demand block to enter different shelters within the limitations of service distance and maximum capacity. The cyclic assignment evacuation model can evacuate all refugees and make full use of all shelters.

(3) This study considers the allocation of evacuation traffic flow in shelter location. The evacuation routes are important for the location of shelters, as they strongly influence evacuation time. To simulate authentic evacuation roads and avoid problems such as the longer time required for dynamic traffic allocation, multiple input parameters, high accuracy requirements, and difficulties in iteration convergence [38], this study uses a deterministic user equilibrium problem [39]. The user equilibrium model assumes that no evacuees can shorten their evacuation time by changing their evacuation route [39]. Traditional spatial configuration models of shelters neglect the evacuation process and traffic flow. Evacuation routes and traffic flow determine evacuation time. For spatial configuration models of shelters that take minimum evacuation time as the objective function, evacuation traffic flow is a vital factor. This study applies the user equilibrium model to reflect evacuation traffic flow allocation, which improves the scientific accuracy of the shelter location model.

(4) Based on the Code for Design of Disasters Mitigation Emergency Congregate Shelter [40], shelters are categorized into two hierarchies, each with different limitations for service distances and maximum capacity. This study proposes a two-hierarchy and two-phase site selection model for shelters, with the minimization of the overall evacuation cost and shelter quantity as optimization objectives.

In the first hierarchy, all shelters are considered emergency shelters. In the second hierarchy, refugees are transferred from the selected shelters in the first hierarchy to resident emergency congregate shelters, which offer more refuge area per capita and better service facilities. The two-hierarchy spatial allocation model aligns more closely with the hierarchical changes in refuge demands that occur over time after a disaster. Additionally, the

two-phase model within each hierarchy effectively reduces the computational complexity of the multi-objective shelter location model.

Meanwhile, due to limitations in data acquisition and computational complexity, this study has some deficiencies that could be improved in future research:

(1) This study focuses solely on earthquakes, but modern cities may encounter various disasters, such as floods, fires, and multi-hazard scenarios. How to design the spatial layout of shelters for multiple disasters requires further research.
(2) The average speed is used in the evacuation process of refugees, but in an authentic scenario, the evacuation velocity of special groups, such as the elderly and the disabled, is much lower than the average. Future studies could provide a more detailed analysis of population distribution and evacuation characteristics, for example, by examining differences in the spatial distribution and evacuation velocity of refugees by age and gender in order to improve the scientific basis of the spatial layout of shelters.

5. Conclusions

The planning and construction of shelters require a scientific and reasonable layout optimization methodology. How to assign refugees to shelters effectively and improve the efficiency of residents' evacuation is a global disaster prevention issue that needs to be solved urgently.

This study proposes a two-hierarchy shelter location model with two phases. The first hierarchy aims to evacuate refugees from demand blocks to both ESs and RSs, while the second hierarchy aims to transfer refugees from selected shelters in the first hierarchy to RSs.

Each hierarchy includes two phases of optimizing calculation. The optimization objectives for the first phase and second phase are to minimize the overall evacuation cost and the number of new shelters, respectively. The improved genetic algorithm is used to determine the solution of model solving for the first phase, and the exhaustive approach is used for the second phase. An evacuation assignment based on the gravity model rule is proposed to evacuate refugees from demand blocks to different shelters. This study also differentiates evacuation demands by distinguishing the population between daytime and nighttime using mobile signaling data, thereby improving accuracy from the plot scale to the building scale.

In the empirical study of the main urban area of Changshu City, the suitability evaluation of candidate sites identified 116 sites for ESs and 46 sites for RSs as suitable locations. In the first hierarchy, it takes 16 min for all refugees to complete the evacuation. The average egress time is about 5.2 min, with the egress time for 41% of the demand blocks concentrated between 6 and 8 min. The minimum number of new shelters required is 75, based on the restrictive conditions of service distance and maximum capacity. In the second hierarchy, it takes 24 min for all refugees to complete the evacuation. The average egress time is about 13.9 min, with the egress time for 68% of the demand blocks to arrive at the RSs concentrated between 13 and 17 min. The number of new RSs is determined to be 8. In total, 46 ESs and 37 RSs are selected as the optimal location scheme with a minimum number of shelters and evacuation time. Compared with the conventional approach, which requires 109 new shelters, the proposed methodology reduces the number of newly built shelters by 31.3%. The egress time for each demand block in each hierarchy does not exceed 25 min. The proposed methodology reduces the construction cost of shelters and the evacuation cost effectively.

Author Contributions: Conceptualization, Yujia Zhang, Wei Chen, and Guangchun Zhong; methodology, Yujia Zhang; software, Guangchun Zhong; validation, Yujia Zhang and Guangchun Zhong; formal analysis, Yujia Zhang; investigation, Wei Zhai; resources, Wei Chen; data curation, Guangchun Zhong; writing—original draft preparation, Yujia Zhang; writing—review and editing, Guangchun Zhong and Wei Chen; visualization, Yujia Zhang and Guangchun Zhong; supervision, Guofang Zhai; funding acquisition, Wei Chen. All authors have read and agreed to the published version of the manuscript.

Funding: Funder's name: the National Natural Science Foundation of China, Grant ID: 52108053. Funder's name: the Social Science Foundation of Jiangsu Province, Grant ID: 20ZZC001.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Aly, A.A.; White, J.A. Probabilistic Formulation of the Emergency Service Location Problem. *J. Oper. Res. Soc.* **1979**, *29*, 1167–1179. [CrossRef] [PubMed]
2. Church, R.; Velle, C.R. The Maximal Covering Location Problem. *Pap. Reg. Sci.* **1974**, *32*, 101–118. [CrossRef]
3. Tsai, C.H.; Yeh, Y.L. The Study of Integrating Geographic Information with Multi-Objective Decision Making on Allocating the Appropriate Refuge Shelters: Using Kengting National Park as an Example. *Nat. Hazards* **2016**, *82*, 2133–2147. [CrossRef]
4. Hakimi, S.L. Optimum Locations of Switching Centers and the Absolute Centers and Medians of a Graph. *Oper. Res.* **1964**, *12*, 450–459. [CrossRef]
5. Wang, J.; Shen, D.; Yu, M. Multiobjective Optimization on Hierarchical Refugee Evacuation and Resource Allocation for Disaster Management. *Math. Probl. Eng.* **2020**, *20*, 8395714. [CrossRef]
6. Gama, M.; Santos, B.F.; Scaparra, M.P. A Multi-Period Shelter Location-Allocation Model with Evacuation Orders for Flood Disasters. *EURO J. Comput. Optim.* **2015**, *4*, 299–323. [CrossRef]
7. Hu, F.; Xu, W.; Li, X. A Modified Particle Swarm Optimization Algorithm for Optimal Allocation of Earthquake Emergency Shelters. *Int. J. Geogr. Inf. Sci.* **2012**, *26*, 1643–1666. [CrossRef]
8. Praneetpholkrang, P.; Huynh, V.N.; Kanjanawattana, S. A Multi-Objective Optimization Model for Shelter Location-Allocation in Response to Humanitarian Relief Logistics. *Asian J. Shipp. Logist.* **2021**, *37*, 149–156. [CrossRef]
9. Sherali, H.D.; Carter, T.B.; Hobeika, A.G. A Location-Allocation Model and Algorithm for Evacuation Planning under Hurricane/Flood Conditions. *Transp. Res. Part B Methodol.* **1991**, *25*, 439–452. [CrossRef]
10. Zhang, N.; Huang, H.; Su, B.N. Analysis of Dynamic Road Risk for Pedestrian Evacuation. *Phys. A Stat. Mech. Its Appl.* **2015**, *430*, 171–183. [CrossRef]
11. Doerner, K.F.; Gutjahr, W.J.; Nolz, P.C. Multi-Criteria Location Planning for Public Facilities in Tsunami-Prone Coastal Areas. *OR Spectr.* **2009**, *31*, 651–678. [CrossRef]
12. Barzinpour, F.; Esmaeili, V. A Multi-Objective Relief Chain Location Distribution Model for Urban Disaster Management. *Int. J. Adv. Manuf. Technol.* **2014**, *70*, 1291–1302. [CrossRef]
13. Alçada-Almeida, L.; Tralhão, L.; Santos, L. A Multiobjective Approach to Locate Emergency Shelters and Identify Evacuation Routes in Urban Areas. *Geogr. Anal.* **2009**, *41*, 9–29. [CrossRef]
14. Zhao, L.; Li, H.; Sun, Y.; Huang, R.; Hu, Q.; Wang, J.; Gao, F. Planning Emergency Shelters for Urban Disaster Resilience: An Integrated Location-Allocation Modeling Approach. *Sustainability* **2017**, *9*, 2098. [CrossRef]
15. Xu, J.; Yin, X.; Chen, D.; An, J.; Nie, G. Multi-Criteria Location Model of Earthquake Evacuation Shelters to Aid in Urban Planning. *Int. J. Disaster Risk Reduct.* **2016**, *20*, 51–62. [CrossRef]
16. Zhang, X.; Yu, S.; Zhang, X. Optimized Location Model of Resident Emergency Congregate Shelter based on Multi-Objective Constraints. *Urban Dev. Stud.* **2020**, *27*, 59–66.
17. Kongsomsaksakul, S.; Yang, C.; Chen, A. Shelter Location-Allocation Model for Flood Evacuation Planning. *J. East. Asia Soc. Transp. Stud.* **2005**, *6*, 4237–4252.
18. Li, H.; Zhao, L.; Huang, R.; Hu, Q. Hierarchical Earthquake Shelter Planning in Urban Areas: A Case for Shanghai in China. *Int. J. Disaster Risk Reduct.* **2017**, *22*, 431–446. [CrossRef]
19. Yi, W.; Ozdamar, L. A Dynamic Logistics Coordination Model for Evacuation and Support in Disaster Response Activities. *Eur. J. Oper. Res.* **2007**, *179*, 1177–1193. [CrossRef]
20. Mollah, A.K.; Sadhukhan, S.; Das, P.; Anis, M.D. A Cost Optimization Model and Solutions for Shelter Allocation and Relief Distribution in Flood Scenario. *Int. J. Disaster Risk Reduct.* **2018**, *13*, 1187–1198. [CrossRef]
21. Fan, C.; Zhai, G.; Zhou, S.; Zhang, H.; Qiao, P. Integrated Framework for Emergency Shelter Planning Based on Multihazard Risk Evaluation and Its Application: Case Study in China. *Nat. Hazards Rev.* **2017**, *18*, 103–118. [CrossRef]
22. Ma, Y.; Xu, W.; Qin, L.; Zhao, X. Site Selection Models in Natural Disaster Shelters: A Review. *Sustainability* **2019**, *11*, 399–412. [CrossRef]
23. Ng, M.; Park, J.; Waller, S.T. A Hybrid Bilevel Model for the Optimal Shelter Assignment in Emergency Evacuations. *Comput. Aided Civ. Infrastruct. Eng.* **2010**, *25*, 547–556. [CrossRef]
24. Sugimoto, T.; Murakami, H.; Kozuki, Y.; Nishikawa, K.; Shimada, T. A Human Damage Prediction Method for Tsunami Disasters Incorporating Evacuation Activities. *Nat. Hazards* **2003**, *29*, 587–602. [CrossRef]
25. Chou, J.S.; Ou, Y.C.; Cheng, M.Y.; Lee, C.M. Emergency Shelter Capacity Estimation by Earthquake Damage Analysis. *Nat. Hazards* **2013**, *65*, 2031–2061. [CrossRef]
26. Chen, Z.; Chen, X.; Li, Q.; Chen, J. The Temporal Hierarchy of Shelters: A Hierarchical Location Model for Earthquake-Shelter Planning. *Int. J. Geogr. Inf. Sci.* **2013**, *27*, 1612–1630. [CrossRef]

27. Li, A.C.Y.; Nozick, L.; Xu, N.; Davidson, R. Shelter Location and Transportation Planning under Hurricane Conditions. *Transp. Res. Part E Logist. Transp. Rev.* **2012**, *48*, 715–729. [CrossRef]
28. Widener, M.J.; Horner, M.W. A Hierarchical Approach to Modeling Hurricane Disaster Relief Goods Distribution. *J. Transp. Geogr.* **2011**, *19*, 821–828. [CrossRef]
29. Teixeira, J.C.; Antunes, A.P. A Hierarchical Location Model for Public Facility Planning. *Eur. J. Oper. Res.* **2008**, *185*, 92–104. [CrossRef]
30. Şahin, G.; Süral, H. A Review of Hierarchical Facility Location Models. *Comput. Oper. Res.* **2007**, *34*, 2310–2331. [CrossRef]
31. Şahin, G.; Süral, H.; Meral, S. Locational Analysis for Regionalization of Turkish Red Crescent blood services. *Comput. Oper. Res.* **2007**, *34*, 692–704. [CrossRef]
32. Ma, Y.; Xu, W.; Qin, L.; Zhao, X.; Du, J. Emergency Shelters Location-Allocation Problem Concerning Uncertainty and Limited Resources: A Multi-Objective Optimization with a Case Study in the Central Area of Beijing, China. *Geomat. Nat. Hazards Risk* **2019**, *10*, 1243–1267. [CrossRef]
33. Chen, Z.; Li, Q.; Chen, J. Study on Hierarchical Location of Urban Emergency Shelters (II): Three-Hierarchical Location Models. *J. Nat. Disasters* **2010**, *19*, 13–19.
34. Lee, Y.; Keum, H.; Han, K.; Hong, W. A Hierarchical Flood Shelter Location Model for Walking Evacuation Planning. *Environ. Hazards* **2021**, *20*, 432–455. [CrossRef]
35. Zhao, X.J.; Chen, J.G.; Xu, W.; Lou, S.Y.; Du, P.; Yuan, H.Y. A Three-Stage Hierarchical Model for an Earthquake Shelter Location-Allocation Problem: Case Study of Chaoyang District, Beijing, China. *Sustainability* **2018**, *11*, 4561. [CrossRef]
36. Zhao, X.J.; Coates, G.; Xu, W. Hierarchical mathematical model of the earthquake shelter location-allocation problem solved using an interleaved MPSO-GA. *Geomat. Nat. Hazards Risk* **2019**, *10*, 1712–1737. [CrossRef]
37. Jiang, X.; Song, J.; Lin, Y.; Gong, Y. A Practical Approach to Constructing Hierarchical Networks for Urban Hazard Mitigation Planning Using GIS: The case of Futian, Shenzhen. *Int. J. Disaster Risk Reduct.* **2018**, *28*, 629–639. [CrossRef]
38. Long, J.; Guo, J. Review and prospect of dynamic traffic assignment research. *J. Transp. Syst. Eng. Inf. Technol.* **2021**, *21*, 125–138. (In Chinese)
39. Sheffi, Y. *Urban Transportation Networks*; Prentice-Hall: Englewood Cliffs, NJ, USA, 1985.
40. *GB 51143-2015*; Code for Design of Disasters Mitigation Emergency Congregate Shelter. Ministry of Housing and Urban-Rural Construction of the People's Republic of China: Beijing, China; China Architecture & Building Press: Beijing, China, 2015.
41. Fan, C. The Integrated Framework for Emergency Shelter Planning for Multi-Hazard Risks. Ph.D. Thesis, Nanjing University, Nanjing, China, 2016.
42. *GB 50413-2007*; Standard for Urban Planning on Earthquake Resistance and Hazardous Prevention. Ministry of Housing and Urban-Rural Construction of the People's Republic of China: Beijing, China; China Architecture & Building Press: Beijing, China, 2007.
43. *CJJ 37-2012*; Code for Design of Urban Road Engineering. Ministry of Housing and Urban-Rural Construction of the People's Republic of China: Beijing, China; China Architecture & Building Press: Beijing, China, 2016. (In Chinese)
44. *GB/T 51328-2018*; Standard for Urban Comprehensive Transport System Planning. Ministry of Housing and Urban-Rural Construction of the People's Republic of China: Beijing, China; China Architecture & Building Press: Beijing, China, 2018. (In Chinese)
45. Chen, M.; Zhu, D. Real-Time Path Planning for a Robot to Track a Fast Moving Target Based on Improved Glasius Bio-Inspired Neural Networks. *Int. J. Intell. Robot. Appl.* **2019**, *3*, 186–195. [CrossRef]
46. Wardrop, J.G. Road paper. some theoretical aspects of road traffic research. *Proc. Inst. Civ. Eng.* **1952**, *1*, 325–362. [CrossRef]
47. Beckmann, M.; McGuire, C.B.; Winsten, C.B. *Studies in the Economics of Transportation*; Yale University Press: New Haven, CT, USA, 1956.
48. Bureau of Public Roads. *Traffic Assignment Manual*; Department of Commerce: Washington, DC, USA; Urban Planning Division: Washington, DC, USA, 1964.
49. Li, W.; Zhai, G.; Chen, W. Research Review on Multi-Objective Model with Constraint Condition of Shelter Location. *Urban Probl.* **2021**, *3*, 107–114.
50. *GB 50011-2010*; Code for Seismic Design of Buildings. Ministry of Housing and Urban-Rural Construction of the People's Republic of China: Beijing, China; China Architecture & Building Press: Beijing, China, 2010. (In Chinese)
51. Dijkstra, E.W. A Note on Two Problems in Connection with Graphs. *Numer. Math.* **1959**, *1*, 269–271. [CrossRef]
52. Wu, Z.; Ye, Z. Research on Urban Spatial Structure Based on Baidu Heat Map: A Case Study on the Central City of Shanghai. *City Plan. Rev.* **2016**, *40*, 33–40.
53. Wang, D.; Ren, X. Distribution and Composition of Actual Population in Urban Space from Daily Human Mobility View. *Urban Plan. Forum* **2016**, *40*, 33–40.
54. Zuo, J.; Shi, J.; Li, C.; Mu, T.; Zeng, Y.; Dong, J. Simulation and optimization of pedestrian evacuation in high-density urban areas for effectiveness improvement. *Environ. Impact Assess. Rev.* **2021**, *87*, 106521. [CrossRef]
55. Chen, H.; Li, J.; Qin, C.; Liu, G.; Sun, J. Study on Spatio-Temporal Distribution of Residents' Nocturnal Activities of Xi'an Based on Micro-Blog. *Hum. Geogr.* **2015**, *30*, 57–63.
56. Changshu Municipal Bureau of Statistics. *Changshu Statistical Yearbook 2021*; China Local Records Publishing: Beijing, China, 2021.

57. Zhong, G.; Zhai, G.; Chen, W. Optimization of Shelter Location Based on a Combined Static/Dynamic Two-Stage Optimization Methodology: A Case Study in the Central Urban Area of Xinyi City, China. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 262–287. [CrossRef]
58. Gao, J.; Feng, Q.; Zhang, H. Simulation Method for Earthquake Damage of Urban Group Structures. *Technol. Earthq. Disaster Prev.* **2007**, *2*, 193–200. (In Chinese)
59. Yin, Z.; Li, S.; Zhao, Z. A Method for Prediction and Classification of Earthquake Disasters. *Earthq. Res. China* **1991**, *7*, 9–19. (In Chinese)
60. Zhou, Y.; Liu, M. Risk Assessment of Major Hazards and Its Application in Urban Planning: A Case Study. *Risk Anal.* **2012**, *32*, 566–577. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.