Incorporating multi-criteria suitability evaluation into multi-objective location–allocation optimization comparison for earthquake emergency shelters

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\textbf{ABSTRACT}  
The optimized location and allocation of earthquake emergency shelters are critical for improving the resilience of communities. However, the existing disaster shelters location–allocation optimization models usually select new shelters from candidate shelters neglecting the existing or planned shelters. The research into comparisons before and after location–allocation optimization between the current planning scenario (CLA scenario) and the supplementary new candidate shelter scenario (SLA scenario) is thus imperative for disaster risk reduction. This article develops a multi-criteria multi-objective multi-scenario supplemental location–allocation optimization model that addresses the concerns related to optimization comparison based on the above two scenarios and provides a higher degree of realism by integrating multi-criteria evaluation and optimization comparison into location–allocation problems. The solutions obtained under the two scenarios are then compared with a case study in Huairou Science City. The results show that the solution under the SLA scenario is superior to the corresponding CLA scenario regardless of the minimal-distance scheme or the minimal-area scheme. The proposed model is proven to be useful for the location–allocation optimization of earthquake emergency shelters, and the presented results can be used as a reference for balancing the interests of the government and residents during the reconstruction and expansion projects of shelters.

\section{1. Introduction}

The frequency and severity of extreme weather events such as droughts, fires, storms, floods, heatwaves are increasing in a warming world (IPCC, 2021). According to the records of Emergency Events Data (EM-DAT), the period 2000–2019 compared with the period 1980–1999, climate-related disasters have nearly doubled (6,681 for

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2000–2019 and 3,656 for 1980–1999), and the number of people affected has increased by nearly 700 million (UNDRR (UN Office for Disaster Risk Reduction)) 2020). However, the number of people killed by climate-related disasters is decreasing from 995,330 in the period 1980–1999 to 510,837 in the period 2000–2019. The decreased mortality could be attributed to the enhanced awareness of risk governance, as well as the improvement of various public service facilities (Shi 2012). As a kind of emergency service facility, disaster shelter plays an important role in reducing disaster risks and improving the communities’ resilience (Ma et al. 2019; Zhao, Chen et al. 2019; Uddin and Matin 2021; He and Xie 2022). Hence, the research on disaster shelters specifically have drawn considerable attention in responding to the frequent natural disasters as well as their impacts on how society copes with emerging risks and recover from disasters.

Our study was undertaken for the Huairou Science City in Beijing, the capital city of China. The work seeks to gain insight into different schemes before and after location-allocation optimization between the current planning scenario (CLA scenario) and the supplementary new candidate shelter scenario (SLA scenario) based on multi-objective location-allocation optimization model and algorithm for disaster shelters. More specifically, the focus is on the incorporation of suitability evaluation (including safety, connectivity, accessibility and general suitability), and comparison of optimization results (including comparison of spatial allocation results and non-inferior solutions under CLA and SLA scenarios) into multi-objective location-allocation problems for earthquake emergency shelters.

The article is organized as follows. First, we review the relevant literature and provide the methods for selecting candidate shelters and evaluating all shelters, as well as methods for developing the location-allocation optimization model and algorithm. Next, to explore the practical usefulness and potential insights that might be derived from multi-objective optimization models, we applied this in a case study in Huairou Science City, Beijing, China. Sections 4.2 and 4.3 present the results as the suitability of disaster shelters and comparison of location-allocation optimization results. This is followed by a discussion on the verification of the results in Section 4.4 and the limitations of the study with regard to suitability evaluation method, evacuation means and influencing factors of evacuation needs in Section 5.

2. Literature review

The analysis of the site selection of disaster shelters is the focus and core of the disaster shelter research, which mainly includes the construction of the suitability evaluation model and the location-allocation optimization model (He and Xie 2022).

2.1. Suitability evaluation

A sound methodology to rank suitability of existing and candidate shelters (schools, colleges, open spaces, etc.) can greatly benefit emergency planners in disaster relief and mass care (Kar and Hodgson 2008; Anhorn and Khazai 2015). Consequently, quite a few researches on suitability evaluation have been carried out. Evaluation
indicators and criteria selection may differ but generally include safety, accessibility, connectivity, etc. (Xu et al. 2007, 2008, 2014; Lee et al. 2008; Liu et al. 2011; Tsioulou et al. 2021). The relevant indicators are selected separately, and then related methods such as the analytical hierarchy process (AHP) (Chu and Su 2012; Tsioulou et al. 2021; Uddin and Matin 2021) and TOPSIS (Chu and Su 2012; Yao et al. 2021) are developed to comprehensively evaluate the suitability of existing shelters. However, suitability evaluation and location–allocation optimization of shelters are seldom examined as a whole, even though they are usually closely related tasks in disaster management (Yu et al. 2018).

2.2. Location–allocation optimization

The location–allocation optimization model can be divided into single-objective model and multi-objective model according to the objective types (Ma et al. 2019). A single-objective model is too simplified to effectively address the location–allocation problem for disaster shelters because it cannot cover all important objectives (Xu et al. 2018a). Consequently, the multi-objective location–allocation optimization model has attracted increasing attention for the planning of disaster shelters (Ma et al. 2019), which combine two or more objectives based on single-objective models to jointly determine the location of shelters and evacuation paths for residents, usually choosing to minimize evacuation distance or time, the number of open facilities, facility area or costs, disaster risks and other objectives (Boonmee et al. 2017; Shaw et al. 2022). The multi-objective model has been applied to earthquakes (Ghasemi et al. 2019; Ma et al. 2019), fires (Alcada-Almeida et al. 2009; Coutinho-Rodrigues et al. 2012), tsunamis (Doerner et al. 2009), hurricanes (Yushimito et al. 2012; Qin et al. 2020; Zhao et al. 2020), floods (Nolz et al. 2011; Rodriguez-Espindola and Gaytan 2015) and other disaster types of shelter location–allocation optimization problems. The models are usually solved by genetic algorithm (Zhong et al. 2022), non-dominated sorting genetic algorithm (NSGA) (Hu et al. 2014), NSGA-II algorithm (Doerner et al. 2009; Saadatseresht et al. 2009; Nolz et al. 2011; Zhao and Chen 2015; Zhao et al. 2017; Seraji et al. 2021), non-dominated sorting genetic algorithm–cellular automata (NSGA-II-CA) (Guo et al. 2021), genetic algorithm-simulated annealing algorithm (GA-SA) (Haghi et al. 2017), multi-objective firefly algorithm (MOFA) (Gharib et al. 2022), modified particle swarm optimization algorithm (MPSO) (Bozorgi-Amiri et al. 2012; Samany et al. 2021), particle swarm optimization-simulated annealing algorithm (PSO-SA) (Zhao et al. 2015, 2017; Xu et al. 2018a, 2018b; Ma et al. 2019) and particle swarm optimization-simulated annealing-genetic algorithm (PSO-SA-GA) (Zhao et al. 2019), respectively. However, the above-mentioned single-objective model and multi-objective model usually select new shelters from candidate shelters, without considering the limitation of shelter resources and the objective reality of existing or planned shelters. Hence, the existing location–allocation optimization model is difficult to realize the effective allocation of disaster prevention resources and may even cause the waste of some resources. It is of great practical significance to carry out comparisons before and after
location–allocation optimization between CLA scenario and SLA scenario in actual research, but this part of the work is very lacking.

This article therefore aims to develop a multi-criteria multi-objective multi-scenario supplemental location–allocation optimization model to compare CLA scenario and SLA scenario. This model highlights the importance of integrating multi-criteria evaluation and location–allocation optimization of earthquake emergency shelters. With the help of interleaved PSO-SA-GA, the outputs can additionally help to identify the strengths and weaknesses of different schemes before and after location–allocation optimization between CLA scenario and SLA scenario, hence the model can provide useful further information for planners and decision-makers concerned with the reconstruction and expansion projects of shelters.

3. Methods

3.1. Suitability evaluation method

In order to ensure the validity of the results, it is necessary to analyze and evaluate the suitability of planned shelters and candidate sites before the start of location–allocation optimization, so as to select candidate shelters and evaluate all shelters through scoring. In accordance with the planning principles of earthquake emergency shelters, three evaluation indicators were selected. The first is safety. Earthquake emergency shelters should be far away from dangerous zones such as fault zones and the slope should not be too high. The second is connectivity. Earthquake emergency shelters should be as close as possible to fire stations, hospitals, disaster supply warehouses, etc. The third is accessibility. The evacuation distance or time for residents to reach the corresponding emergency shelter should be as short as possible. In addition, land use that did not meet the requirements was eliminated accordingly. Figure 1 shows the suitability evaluation process of earthquake emergency shelters. The calculation of the suitability score is shown in Equations (1)–(5).
\( R = \sum_{k=1}^{3} F_k \).  

(1)

where \( R \) is the suitability score of the evaluation unit as an earthquake emergency shelter, and \( F_k \) \((k = 1, 2, 3)\) is the score of the \( k \)th factor that affects the rationality of the shelters. Candidate shelters with a safety score of 1 will be eliminated. The higher the \( R \) score, the more reasonable it is as an emergency shelter. The maximum score is 8, which means that the safety, connectivity and accessibility of the shelter are all very suitable.

\[
F_1 = \min(a_1, a_2, \ldots, a_i, \ldots, a_n),
\]

(2)

where \( F_1 \) is the comprehensive evaluation score of the safety of the shelter, and \( a_i \) \((i = 1, 2, \ldots, n)\) is the single-factor score of the safety of a certain location. Score of 1 indicates that it is not safe as a shelter. Once a score of 1 is achieved, the corresponding candidate shelters should be eliminated. A score of 2 indicates medium safe, and a score of 3 indicates safe (Table 1).

\[
F_2 = \sum_{i=1}^{m} b_i,
\]

(3)

where \( F_2 \) is the comprehensive evaluation score of the connectivity of the shelter, and \( b_i \) \((i = 1, 2, \ldots, m)\) is the single-factor score of the connectivity of a certain location. In the evaluation, the scores of each factor will be added together. A score of 1 or 0.5 indicates that the connectivity of the factor as a shelter is good, and a score of 0 indicates that the connectivity is poor. The specific scoring criteria are shown in Table 2.

\[
F_3 = \begin{cases} 
1 & \sigma_i \geq \text{Med}, \\
0 & \sigma_i < \text{Med}, 
\end{cases}
\]

(4)

\[
\sigma_i = \frac{S_i}{S},
\]

(5)

where \( F_3 \) is the evaluation score of the accessibility of the shelter. \( \sigma_i \) is the coverage area ratio of shelter \( i \), \( \text{Med} \) is the median of the coverage area ratio, \( S_i \) is the coverage area of shelter \( i \) within its road evacuation reachable range of 3000 m as shown in

| ID | Factor | Criteria | Score | ID | Factor | Criteria | Score |
|----|-------|----------|-------|----|-------|----------|-------|
| 1  | Seismic fault zone | Distance ≤ 15 m | 1 | 4  | Gas supply pipeline | Distance ≤ 25 m | 1 |
|    | 15 ~ 30 m | 2 |     |    | 25 ~ 50 m | 2 |
|    | >30m | 3 |     |    | >50 m | 3 |
| 2  | Slope | >30° | 1 | 5  | Liquid ammonia tank station | Distance ≤ 50 m | 1 |
|    | 15 ~ 30° | 2 |     |    | 50 ~ 100 m | 2 |
|    | ≤15° | 3 |     |    | >100 m | 3 |
| 3  | Gas station | Distance ≤ 50 m | 1 | 6  | River | On the water | 1 |
|    | 50 ~ 100 m | 2 |     |    | Distance ≤ 30 m | 2 |
|    | >100 m | 3 |     |    | >30 m | 3 |
Figure 5, and $S$ is the total area of the study area. A score of 1 indicates that the earthquake emergency shelter has high accessibility, and a score of 0 indicates that the earthquake emergency shelter has low accessibility.

### 3.2. Location–allocation optimization model and algorithm

In order to compare CLA scenario and SLA scenario, a multi-objective multi-scenario supplemental location–allocation optimization model for temporary earthquake emergency shelters, with the objectives of minimizing the total shelter area and minimizing the total evacuation distance was developed as follows (Equations (6) and (7)).

$$
\min f_1 = \sum_{i=1}^{N} A_i^s Y_i^s \forall j \in J \forall s \in S, \\
\min f_2 = \sum_{j=1}^{M} d_{ji}^s B_{ji}^s \forall i \in I^s \forall s \in S,
$$

The model is subject to constraints of shelter capacity and service distance (Equations (8) and (9)).

$$
\sum_{j=1}^{M} N_j L B_{ji}^s \leq A_i^s Y_i^s \forall i \in I \forall s \in S, \\
d_{ji}^s B_{ji}^s \leq D_j \forall i \in I \forall j \in J \forall s \in S,
$$

$$
\sum_{i=1}^{N} Y_i^s = 1 \forall j \in J \forall s \in S,
$$

$$
B_{ji}^s = \begin{cases} 
1, & \text{community } j \text{ selects shelter } i \text{ as emergency shelter}, \\
0, & \text{others,}
\end{cases}
$$

| ID | Factor                  | Criteria                          | Score |
|----|-------------------------|-----------------------------------|-------|
| 1  | Fire station            | Distance $\leq 2000$ m            | 1     |
| 2  | Hospital                | Distance $\leq 2000$ m            | 1     |
| 3  | Disaster supply warehouse | Distance $\leq 2000$ m         | 1     |
| 4  | Substation              | Distance $\leq 2000$ m            | 0.5   |
| 5  | Water plant             | Distance $\leq 2000$ m            | 0.5   |

Table 2. Scoring criteria for connectivity evaluation of disaster shelters.
The sets, variables and parameter definitions in this model are as follows:

* $S$ is the set of scenarios: $S = \{\text{CLA, SLA}\}$; $I^s$ is the set of earthquake emergency shelters in scenario $s$: $I^s = \{1, 2, \ldots, i, \ldots, N\}$, in our case, $N = 57$ in scenario CLA and $N = 89$ in scenario SLA; $J$ is the set of demand points: $J = \{1, 2, \ldots, j, \ldots, M\}$; $A_i^s$ is the area of earthquake emergency shelter $i$ in scenario $s$; $d_{ji}^s$ is the length of the shortest path between demand point $j$ and shelter $i$ in scenario $s$; $N_j$ is the number of evacuees in demand point $j$; $L$ is the smallest refuge area per capita (1 m²/person); $D_j$ is the maximal evacuation distance for evacuees in demand point $j$, which is set to 3 km to ensure that it can be reached within 1 h on foot.

Equation (6) is used to calculate the minimum value of the total shelter area, and Equation (7) is used to calculate the minimum value of the total evacuation distance. Equation (8) is the capacity constraint to ensure that the areas of the shelters satisfy the demand of the evacuees in the surrounding blocks, and Equation (9) is the distance constraint, which guarantees the distance from the demand point to the selected shelter is less than the maximum evacuation distance. Equation (10) ensures that only one shelter is selected per demand. Equations (11) and (12) define the decision variables in the model.

The original PSO algorithm, which is characterized by fast convergence, high effectiveness and strong robustness, has become an important tool in solving facility location–allocation problem (Bozorgi-Amiri et al. 2012). In addition, as artificial intelligence algorithms, GA and SA algorithm also has been widely used in addressing location–allocation issue (Haghi et al. 2017). To solve the complex and discrete optimization problem for earthquake emergency shelters more effectively, an interleaved PSO-SA-GA was developed (Zhao et al. 2019). First, the SA algorithm is used as a local search for each particle’s individual optimum and local optimum by combining PSO and SA. Then, the algorithm continuously interleaves the execution of the PSO-SA algorithm and the GA algorithm until the convergence of the Pareto sets is met simultaneously by both algorithms. In this study, the interleaved PSO-SA-GA was used to solve the multi-objective model for earthquake emergency shelter location–allocation problem in the CLA scenario and the SLA scenario.

### 4. Case study in Huairou Science City, Beijing

#### 4.1. Study area and data

#### 4.1.1. Study area

Huairou Science City (HSC), covering an area of 68.4 square kilometers, is located in the northeast of Beijing (Figure 2). As a Key National Science Centre in Beijing, this region is affected by the Huangzhuang-Gaoliying seismic fault zone (Figure 3). In addition, there are some industrial parks in this region, which contain liquid ammonia and other hazardous materials. Therefore, the region is threatened by multiple hazards.
4.1.2. Data
The research data in this paper mainly include the hazard identification data, seismic fault zone distribution data, surrounding supporting facilities data, disaster prevention zones and the number of evacuees, earthquake emergency shelter data, and evacuation road data. The first three types of data are mainly used for the suitability evaluation of earthquake emergency shelters, and the latter three are mainly used for the location–allocation optimization of earthquake emergency shelters. The data details and sources are shown in Table 3.

Figure 2. Huairou Science City, Beijing.
Estimation of the number of evacuees. The resident population of 840 blocks in 11 disaster prevention zones is calculated with the area ratio as the weight, thus the evacuation demands of the disaster prevention zones are refined to the block scale (Figure 2). The total population often exceeds the total amount of evacuees. If the total population is used as the base of evacuation demand to plan disaster shelters, it will inevitably lead to excessive planning and construction of shelters, resulting in a lot of waste of resources. The planning standard for earthquake emergency shelters in Beijing clearly requires that the size of evacuees should be set at 30% of the
permanente population (Zhao et al. 2014). Therefore, the number of evacuees of each demand point is set to 30% of the resident population in this paper. The total number of evacuees was estimated at 62,700.

**Earthquake emergency shelters.** Planned shelters. A total of 44 parks, green spaces, schools and playgrounds are planned as earthquake emergency shelters within the study area (Figure 2), covering a total area of 3.90 km² and accommodating 173,400 persons. Candidate shelters. In accordance with the requirements of the earthquake emergency shelter (outdoor) program guidelines (OPG) for the central area of Beijing, 31 candidate shelters with an area of more than 2,000 square metres, covering a total area of 1.06 km² and accommodating 265,400 people, were selected based on the planned land use types such as park green land, education land, sports land and cultural activity facility land (Figure 2). According to OPG’s recommendations, each shelter used in the model has a capacity of 60% of its total area, excluding surface water area.

**Evacuation roads.** Combined with the disaster relief evacuation passage plan in the study area, the disaster relief evacuation road was digitized by fully considering the distribution of internal block units as shown in Figure 2.

### 4.2. Suitability evaluation results of earthquake emergency shelters

#### 4.2.1. Safety evaluation

This article designs a safety evaluation criteria based on the topography and geo-hydrological conditions and danger sources around the emergency shelters. Most of the landslides occurred on slopes steeper than 15° (Liu et al. 2011), and the sites should keep away from seismic fault zones and flood hazards (breaking of river or
reservoir dykes) (Chu and Su 2012). In addition, the emergency shelters close to danger sources may cause secondary disasters (Ji and Gao 2014). By analyzing the influence of geological conditions (including seismic fault zones, slopes, and rivers) and danger sources (including gas stations, gas supply pipelines, and liquid ammonia tanks) on the distribution of earthquake emergency shelters, unsafe candidate shelters are excluded, and a certain number of candidate shelters are selected. The safety of the distribution of planned shelters and the selected candidate shelters were evaluated based on the scoring criteria in Table 1 and Equation (2), and the evaluation results are shown in Figure 3. Among the influencing factors, the most important factor affecting the safety of HSC is the seismic fault zone, followed by gas supply pipelines and rivers. Other unsafe factors do not affect the shelters. Specifically, among the 45 planned shelters, there is only one unsafe shelter (score of 1) with the evacuation site is less than 15 m away from the seismic fault zone. Most of the planned shelters (84.09%) have the highest safety score (3 points). In addition, 64.52% of the 31 candidate shelters have the highest safety score (3 points) excluding unsafe shelters that scored 1 point.

4.2.2. Connectivity evaluation

In order to analyze the connectivity between the earthquake emergency shelters and surrounding fire stations, hospitals, and disaster supply warehouses, etc., the road impedance model based on the Network Analysis-Service Area Analysis tool in ArcGIS was used to simulate the connectivity range of all emergency supporting facilities within a service area of 2000 m. In addition, the connectivity of the distribution of earthquake emergency shelters was evaluated in accordance with the scoring criteria in Table 2 and Equation (3), and the evaluation results are shown in Figure 4. About 52.00% of shelters have high connectivity (score of 2–4), and 37.33% are moderately connected (score of 1–2). In terms of spatial distribution, the three shelters with poor connectivity (score of 0) are scattered, two are located outside the disaster prevention zone near farmland, and one is located in the bq disaster prevention zone in the north. The seven shelters with high connectivity (score of 3–4) are concentrated, all located in nq-01 disaster prevention zone, where various supporting facilities are complete.

4.2.3. Accessibility evaluation

To explore the accessibility of planned shelters and candidate shelters, the above-mentioned road impedance model based on ArcGIS was used to simulate the reachable range of all earthquake emergency shelters within two service areas of 500 m and 3000 m, and the accessibility of all shelters was evaluated according to Equations (4) and (5). The simulation results are shown in Figure 5. On the whole, the earthquake emergency shelter can basically cover all construction land under the service radius of 3000 m. Due to the limitation of the extension of the road, almost all shelters with poor accessibility are located in the outer area of HSC. In contrast, most of the shelters located in the inner area of HSC are highly accessible due to good traffic conditions. A few shelters with poor accessibility are affected by natural geographic locations such as rivers and farmland.
4.2.4. Suitability evaluation

On the basis of safety evaluation, connectivity evaluation and accessibility evaluation, the suitability scores of all shelters are calculated according to Equation (1) as shown in Figure 6. The results show that the suitability of the 11 disaster prevention zones is relatively high. In addition, the suitability score of candidate shelters is generally superior to that of planned shelters, because unsafe sites have been eliminated during the process of selecting candidate shelters. In more detail, the suitability of all shelters in the study area is relatively high except for the two disaster prevention zones of

Figure 4. Connectivity of emergency shelters.
zx-03 and zx-04. The zx-03 area is adjacent to farmland in the east and green space in the west with few supporting facilities. The zx-04 area is adjacent to the mountainous area in the northwest, with higher terrain and fewer supporting facilities.

4.3. Comparison of optimization results under CLA and SLA scenarios

4.3.1. Comparison of spatial allocation results

There are three main reasons for the generation of cross lines on the spatial location-allocation maps: poor road connectivity, the existence of capacity constraints, and
the cross result obtained is a non-inferior solution rather than an optimal solution. In the multi-objective programming, a non-inferior solution means that in the given set of alternative solutions, there is no solution that can improve each objective function. However, the set of non-inferior solutions produced by each run is often different, because the optimization algorithm is not good enough to get close to the optimal solution. So, the last one is often the main reason for the generation of cross lines (Xu et al. 2018a). As shown in Figure 7, the spatial location-allocation results corresponding to the minimal-distance and minimal-area solutions of the multi-objective model in the CLA scenario and the SLA scenario do not produce a cross line. This
result shows that the interleaved PSO-SA-GA is a promising method to solve the multi-objective location–allocation model based on the macro spatial allocation results. In addition, the allocation schemes with the smallest area and the shortest distance in the two scenarios have cross-regional evacuation, and the cross-regional evacuation in the SLA scenario has been alleviated.

From the spatial allocation results of the minimal-distance solution (Figure 7a and b), it can be seen that (1) in both scenarios, all demand points can be evacuated to their nearest shelters without exceeding the capacity limit of the shelters; (2) almost all planned shelters and candidate shelters in the disaster prevention zones under the two scenarios have been selected; (3) the layout of planned shelters in the nq-01 disaster prevention zone is more reasonable with the short spatial allocation line, that is, the per capita evacuation distance is shorter. The layout of planned shelters in the zx-02 disaster prevention zone is relatively poor, but there are suitable candidate shelters nearby. Therefore, the spatial allocation results under the SLA scenario have been significantly improved, which is manifested as the allocation line is significantly shortened.

From the spatial allocation results of the minimal-area solution (Figure 7c and d), it can be seen that (1) the number of shelters selected by the demand points in the two scenarios is drastically reduced compared with the minimal-distance solution, and one of the shelters in some disaster prevention zones can satisfy all of the evacuation demand of the area; (2) due to the limitation of capacity constraints, the solution of the smallest area is more difficult than that of the shortest distance, and the optimization result of the CLA scenario is not the optimal solution, for example, the three shelters selected in the nq-02 disaster prevention zone in Figure 7c can be reduced to two in Figure 7d.

4.3.2. Comparison of non-inferior solutions
The associated non-inferior solutions obtained using the multi-objective model under different scenarios is shown in Figure 8. We construct none capacity constraints scenario (NC scenario) as reference, and a capacity-constrained scenario (CC scenario) in the multi-objective model. Each feasible non-inferior solution is represented by one point in the figure and corresponds to a particular spatial location–allocation result. The four spatial location–allocation schemes in Figure 7 correspond to the four points at the beginning and the end of the scatter diagram in the CLA CC scenario and the SLA CC scenario in Figure 8. Table 4 presents a further comparison of the solutions of minimal-distance and minimal-area schemes corresponding to the four scenarios in Figure 8.

It is worth noting that the solutions differ significantly between scenario NC and CC (blue and red scatter points in Figure 8), followed by scenario CLA and SLA (hollow and solid points of the same color). According to Table 4, the same minimal-distance scheme can be obtained regardless of the capacity constraint, but the capacity constraint greatly restricts the further optimization of the minimal-area scheme. In addition, the solution under the SLA scenario with or without capacity constraints is superior to the corresponding CLA scenario regardless of the minimal-distance scheme or the minimal-area scheme. For example, the average evacuation distance per person (AEDP) of the minimal-distance scheme in the CLA scenarios exceeds 500 m, and the corresponding value in the SLA scenario is 457, which can ensure
Figure 7. Spatial location-allocation results corresponding to the minimal-distance (a, b) and minimal-area (c, d) solutions obtained using the multi-objective model for the CLA scenario (a, c) and the SLA scenario (b, d).
that the evacuation time per person on foot is less than 10 minutes. In addition, the average shelter area (ASA) and the number of selected shelters (NSS) under the minimal-area scheme in the SLA scenarios are both greatly reduced, especially in scenario SLA CC.

### 4.4. Verification

Figure 9 shows the changes of the two objective function values (AEDP and ASA) of the multi-objective model with the number of iterations to further verify the correctness of the results. The changes in minimum, medium and maximum AEDP and ASA for evacuation schemes under the CLA NC, CLA CC, SLA NC and SLA CC scenarios are illustrated, respectively. For the high-dimensional complex problem of the actual case in this study, the algorithm converges to the optimal solution at about 20,000 times.

By comparing Figure 9a, c, e, and g with Figure 9b, d, f, and h, it can be seen that the AEDP value converges faster than the ASA value in any scenario, which further proved that the solution for the smallest area is more difficult than that of the shortest distance due to the limitation of capacity. By comparing the results with and

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**Table 4. Comparison of solutions of minimal-area and minimal-distance schemes for different scenarios.**

| Scenarios | Minimal-distance scheme | Minimal-area scheme |
|-----------|-------------------------|---------------------|
|           | AEDP | ASA | NSS | AEDP | ASA | NSS |
| CLA NC    | 542  | 635 | 48  | 1201 | 68  | 14  |
| CLA CC    | 542  | 635 | 48  | 917  | 254 | 22  |
| SLA NC    | 457  | 1209| 75  | 1172 | 61  | 14  |
| SLA CC    | 457  | 1209| 75  | 1468 | 190 | 16  |

Notes: AEDP, average evacuation distance (m) per person; ASA, the average shelter area (m²) for each block; NSS, number of selected shelters. Bold represents the solution about distance in the minimal-distance scheme or about area in the minimal-area scheme. The grey entries represent the solution of the SLA scenario is superior to the CLA scenario.
Figure 9. Variation of AEDP and ASA of multi-objective model with the number of iterations.
without capacity constraints, it is found that the AEDP values are the same both in the CLA and SLA scenarios, while the ASA values are significantly different. In both CLA scenario and the SLA scenario, the ASA values converge more slowly in the case of scenario CC, which confirms that the capacity constraints greatly restrict the further optimization of the minimal-area scheme.

In addition, by comparing Figure 9a–d with Figure 9e–h, it can be found that the values in the latter four graphs are better than the former four, which further verifies that the solution under the SLA scenario with or without capacity constraints is superior to the corresponding CLA scenario regardless of the AEDP or the ASA.

5. Discussion and conclusion

This study developed a multi-criteria multi-objective multi-scenario supplemental location–allocation optimization model for earthquake emergency shelters that addresses the concerns related to optimization comparison based on the CLA and SLA scenarios. The developed model incorporates the suitability evaluation of planned shelters and candidate sites before the start of location–allocation optimization into the location–allocation problem for earthquake emergency shelters. With the help of interleaved PSO-SA-GA, the results of the model analysis can provide effective planning strategies for the reconstruction and expansion projects of shelters, and substantially increase resilience in communities confronted with potential environment risks and disasters.

However, this study came with several limitations. First, the safety, connectivity and accessibility indicators were simply added to evaluate the suitability of earthquake emergency shelters. The suitability evaluation method can be refined by using AHP and TOPSIS methods for determining weights of different indicators to derive a comprehensive suitability score in future research. In addition, due to the complexity of the location–allocation optimization of disaster shelters and the unavailability of relevant data, we also made some relevant assumptions in the construction of the model, e.g., it was assumed that the number of evacuees at each demand point was 30% of the resident population, and the evacuation method was set as foot evacuation, etc. However, in the actual process, these assumptions are difficult to meet, which increases the uncertainty of the model analysis results. Hence, in the future, it is necessary to carry out extensive research on the influencing factors of evacuation needs, including objective factors such as critical infrastructures damage affected by the earthquake (Ghasemi and Khalili-Damghani 2021) and daily dynamic changes of population (Xu et al. 2018a), as well as subjective factors such as willingness to evacuate to designated shelters (shelter evacuees) (Ma et al. 2019), non-shelter evacuees (Li et al. 2012), the residents’ evacuation behaviours (Tai et al. 2010), the public-shelter users’ satisfaction (Mayunga 2012; Ki nay et al. 2018), government trust problems caused by rumours (Fraser et al. 2021), etc.

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Data availability statement

Seismic data were collected from China Earthquake Administration. Hazard identification data, surrounding supporting facilities data, earthquake emergency shelter data and evacuation road data were collected from Emergency Management Bureau. Land use data were derived from Huairou Science City Planning and modified through field research. Derived data supporting the findings of this study are available from the corresponding author [B.L] on request.

Disclosure statement

No potential conflict of interest was reported by the authors.

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