Optimizing Network-Constrained Evacuation Paths for Efficient Shelter Allocation after Earthquakes

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Abstract

Allocating emergency shelters after earthquakes is vital to reducing human suffering and ensuring fair access to safety. This study introduces a network-based genetic algorithm (GA) model to assign affected communities to pre-existing shelters by minimizing total evacuation distances. The objective of this work is not to develop new metaheuristic methods; rather, it is to formulate the shelter-allocation problem on realistic networks and demonstrate a practical solution approach. Unlike conventional models that rely on Euclidean distances, the proposed approach integrates GIS-based data—including population blocks, shelter locations, and road networks—into a network-based distance matrix. The GA uses both roulette-wheel and tournament selection strategies and incorporates two-point crossover and uniform mutation to enhance search efficiency and avoid local optima. The model is applied to District 12 of Tehran, involving 1,063 population blocks and 83 shelters. After parameter tuning, the optimal solution achieves a total evacuation distance of 1,991,848 meters within 1,000 generations, using crossover and mutation rates of 0.8 and 0.2, respectively. The results highlight the model's effectiveness in large-scale urban scenarios and its value as a practical, scalable tool for policymakers in disaster preparedness and resilient urban planning.

1. Introduction

Earthquakes can overwhelm urban areas within minutes, disrupting mobility and concentrating demand for safe refuge. Ensuring that residents reach appropriate shelters quickly and fairly is therefore a core requirement of disaster preparedness. We study the emergency shelter–allocation problem: given population blocks, candidate shelters with limited capacities, and a road network that constrains movement, assign each block to exactly one shelter so that the total evacuation distance over the network is minimized. This formulation captures real-world conditions and provides planners with a quantitatively grounded way to balance efficiency (shorter travel) and equity (guaranteed access for all affected communities).

To address this NP-hard optimization problem, a Genetic Algorithm (GA) is utilized. GA is a metaheuristic technique inspired by the principles of natural selection and evolutionary biology. It operates by evolving a population of candidate solutions through iterative processes of selection, crossover, and mutation, which facilitates efficient exploration of high-dimensional, nonlinear solution spaces (Holland, 1992).

The proposed model incorporates key enhancements, including adaptive mutation and crossover rates to mitigate premature convergence and avoid local optima. Additionally, it employs a roulette wheel and tournament selection mechanism to preserve high-fitness individuals across generations. Parameter settings are fine-tuned through sensitivity analysis, optimizing both convergence speed and solution quality. This approach effectively addresses the shelter allocation problem under real-world constraints.

The remainder of this paper is organized as follows: Section 2 reviews previous studies on post-disaster shelter allocation, emphasizing the gaps in addressing urban constraints and computational scalability. Section 3 outlines the proposed methodology, which includes chromosome encoding, the design of the fitness function, and the application of selection, crossover, and mutation operators. Section 4 implements the model in District 12 of Tehran, utilizing metrics such as total evacuation distance and convergence behavior. Finally, Section 5 discusses the implications of our findings for disaster planners, identifies limitations, and suggests directions for future research.

2. Previous Work

Ma and Xu (2019) proposed a multi-objective supplemental location-allocation model for earthquake shelters in Beijing, which prioritizes pre-existing shelters while balancing evacuation distance and resource efficiency. Utilizing a modified Particle Swarm Optimization (PSO) algorithm, the model integrates spatiotemporal population dynamics and seismic risk scenarios, demonstrating that prioritizing designated shelters can reduce the total shelter area by 18–30%.

Hu and Xu (2012) developed a modified PSO algorithm to address the earthquake emergency shelter allocation problem in the Zhuguang Block of Guangzhou, China. The model tackled the complexities of discrete solution spaces and stringent constraints, such as shelter capacity and service radius, by incorporating a feasibility-based rule along with a simulated annealing (SA) component to escape local optima. This algorithm optimized both the number and locations of shelters, demonstrating superior performance compared to other hybrid methods in terms of computational efficiency and solution quality. However, the model assumed Euclidean evacuation distances, which limits its realism in dynamic disaster contexts.

Xu and Yin (2016) developed a GIS-supported multi-criteria model for shelter location in Yangzhou, China, which integrates population density, accessibility, and spatial coverage. The model employed Lagrangian relaxation and heuristic algorithms, yielding balanced urban planning outcomes.

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Chen and Chen (2013) proposed a hierarchical shelter system that incorporates temporal phases (immediate and long-term) while considering budget constraints.

Yin and Zhao (2023) proposed an Improved Quantum Genetic Algorithm (IQGA) to optimize large-scale evacuation planning by integrating principles of quantum computing with traditional GA operations. The model minimized the total evacuation distance while enforcing constraints related to spatial continuity and shelter capacity. It featured a quantum-inspired chromosome encoding scheme that facilitated efficient exploration of the solution space, as well as a spreading operation that dynamically disperses clustered evacuees from high-risk zones. When validated against urban seismic scenarios, IQGA demonstrated a convergence rate that was 20–30% faster and achieved total evacuation distances that were 15% lower compared to Voronoi diagram-based and network-flow models.

Zhao and Xu (2017) developed a multi-objective optimization framework to address the earthquake shelter location-allocation problem, explicitly quantifying the trade-offs between evacuation efficiency and infrastructure costs. Utilizing a modified PSO algorithm, the study aimed to minimize Total Weighted Evacuation Time (TWET) by incorporating factors such as route distance, population density, and pedestrian speed, as well as Total Shelter Area (TSA), while adhering to capacity and distance constraints. Validated in Jinzhan Town, Beijing, the analysis revealed a power-law relationship indicating diminishing returns in evacuation time reduction as the shelter area expands. Importantly, the size of the evacuation population demonstrated a linear positive correlation with both minimum TSA and minimum TWET, suggesting that population growth disproportionately increases evacuation time more than the costs associated with the shelter area.

However, most previous studies utilized Euclidean distance rather than actual road network distance, which does not facilitate more realistic evacuation routing. Our research significantly advances the field by integrating network-based constraints with distance minimization, thereby addressing critical gaps in both spatial realism and scalability that earlier studies have overlooked.

3. The Proposed Methodology

The proposed method applies a genetic algorithm (GA)—one of the most conventional and widely used metaheuristic techniques—to optimize emergency shelter allocation by minimizing total evacuation distance. While other algorithms may, in some settings, offer higher efficiency, we adopt GA for its robustness, simplicity, and straightforward integration with network-based geographic data. Our purpose is not to develop or identify the best-performing metaheuristic; rather, we focus on modelling the shelter-allocation problem on realistic networks and demonstrating a practical solution workflow. The model is designed to enhance both the efficiency and equity of post-disaster response by ensuring fair and timely access to designated shelters. Its core is an objective function (Equation 1) that minimizes the sum of evacuation distances over the road network, thereby promoting rapid accessibility. In addition, a constraint (Equation 2) enforces that each community is assigned to one—and only one—shelter, maintaining logistical consistency and exclusivity under real-world spatial conditions.

$$Z = \sum_{i=1}^{n} \sum_{j=1}^{m} d_{ij}\, x_{ij} \tag{1}$$

s.t.

$$\sum_{i=1}^{n} x_{ij} = 1 \quad \forall i \in I \tag{2}$$

where I is set of communities (population blocks) $\{1, 2, 3, \ldots, n\}$, x_{ij} is a binary variable (1 if community i is assigned to shelter j; 0 otherwise). Also, n and m are the number of population blocks and the number of candidate shelters, respectively.

In this paper, network-based distances are used to calculate evacuation distances. Unlike Euclidean distance, which assumes straight-line travel, network-based distance reflects real-world evacuation routes by measuring paths along road networks. To calculate optimal evacuation distances, the road system is modelled as a weighted graph $G = (V, E)$, where nodes V represent intersections, communities, or shelters, and edges E encode road segments with weights corresponding to their lengths. The shortest-path distance d_{ij} between community i and shelter j is computed using Dijkstra's algorithm, ensuring the shortest route under normal conditions. Precomputed best route distances between all communities and shelters are stored in a matrix for efficient GA fitness evaluation, while GIS tools validate path accuracy and connectivity.

The proposed method employs GA to address the NP-hard problem of optimally assigning population communities to post-earthquake shelters under specific constraints. GAs are a class of metaheuristic optimization techniques inspired by the principles of natural selection and genetics. They are particularly well-suited for solving complex and nonlinear optimization problems where traditional exact methods may be computationally infeasible. GAs mimic natural selection by evolving a population of candidate solutions (chromosomes) through iterative cycles of selection, crossover, and mutation. By leveraging the exploration power of GAs, the model effectively navigates complex, constrained solution spaces and generates near-optimal allocation strategies that are both computationally tractable and operationally feasible (Wei and Le, 2023).

In this paper, a GA is employed to address the shelter allocation problem (see Figure 1). The chromosome structure is represented as a list, where each gene corresponds to the shelter ID assigned to a specific community. The fitness function is defined by the total evacuation distance, guiding the optimization process toward solutions that minimize overall travel costs. For the selection mechanism, both tournament selection and roulette wheel selection methods are utilized and compared to enhance solution quality. Additionally, a two-point crossover operator is applied to recombine parent solutions, while a uniform mutation operator introduces diversity to prevent premature convergence. The termination criterion for the algorithm is established as a fixed number of generations, ensuring computational consistency across experimental runs.

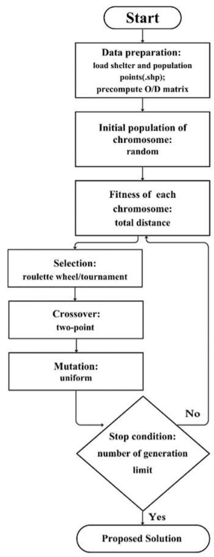

Figure 1. Proposed method

3.1 Chromosome Encoding and Initial Population Construction

The proposed method utilizes a GA to solve the NP-hard problem of assigning population communities to post-earthquake shelters under specific constraints. As a metaheuristic inspired by natural selection, GA is well-suited for addressing complex, nonlinear problems where exact methods become computationally infeasible. Through iterative processes of selection, crossover, and mutation, GAs evolve a population of candidate solutions, enabling the model to explore constrained solution spaces effectively and generate near-optimal, computationally feasible allocations (Wei and Le, 2023).

In this study, GA is tailored for shelter allocation (see Figure 1), using a chromosome structure where each gene represents the shelter ID assigned to a particular community. The fitness function, defined by total evacuation distance, drives the search toward cost-minimizing solutions. Both tournament selection and roulette wheel selection are implemented and compared to enhance performance. Genetic diversity is maintained using a two-point crossover and uniform mutation, while a fixed number of generations is used as the termination condition to ensure consistent execution. The integer-vector encoding simplifies genetic operations and preserves spatial coherence, enabling a balance between solution quality and computational efficiency during exploration.

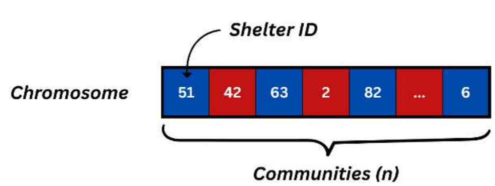

Figure 2. Chromosome encoding

3.2 Fitness Function Calculation

The fitness function is a critical component that evaluates the optimality of a candidate solution (individual) in addressing a specific problem. It assigns a numerical score (fitness value) to each individual in the population, guiding the selection, crossover, and mutation processes toward improved solutions over successive generations. In this study, the fitness function assesses each potential shelter allocation solution (chromosome) based on the total evacuation distance. The primary objective is to minimize the sum of evacuation distances across the road network for all communities. The final fitness value is inverted (1/objective) to align with the maximization paradigm of GAs, ensuring that solutions with shorter distances and fewer violations receive higher fitness scores.

3.3 Selection

Selection is a vital component of GAs, guiding which individuals are chosen for reproduction. This study compares tournament and roulette wheel selection methods. Roulette wheel selection assigns probabilities based on fitness, giving higher chances to stronger candidates while maintaining diversity. Tournament selection selects the fittest individual from a randomly chosen subset, offering strong selection pressure while preserving diversity by occasionally accepting weaker solutions (Razali and Geraghty, 2011). Evaluating both methods helps improve convergence quality and maintain a balanced exploration–exploitation trade-off in the shelter allocation process.

3.4 Crossover

Crossover, a fundamental genetic operator, merges genetic material from two parent solutions to produce offspring, thereby enhancing the exploration of the solution space. In this paper, we employ a two-point crossover method, which involves selecting two random positions within the parent chromosomes and exchanging the intermediate gene segments.

3.5 Mutation

Mutation introduces controlled randomness in GAs to preserve diversity, explore new solutions, and avoid local optima. This study uses uniform mutation, where each gene (community-shelter assignment) has a chance to be reassigned to another shelter, encouraging the use of less-populated shelters. This enhances population diversity (Chang and Huang, 2010). Unlike traditional methods, GAs are effective for large-scale problems. By combining mutation for exploration and crossover for exploitation, GAs find near-optimal solutions efficiently. This makes them scalable and robust—essential qualities for fast, adaptive urban disaster response systems.

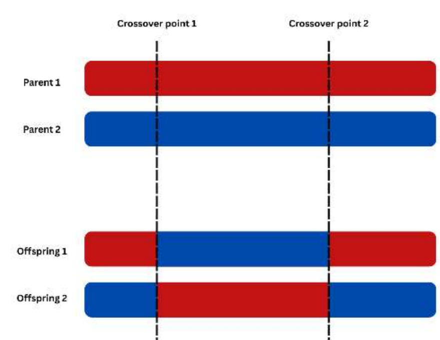

Figure 3. Two-point crossover

3.6 Stop Condition

In GAs, the termination criterion is essential for balancing optimization quality with computational efficiency. In the proposed shelter allocation model, a maximum generation limit is established as the stopping condition to prevent excessive runtimes. This approach ensures that the GA operates for an adequate number of iterations to effectively explore the solution space. The generation limit is empirically adjusted to reduce the risk of premature convergence in problem instances while maintaining practical execution times.

4. Implementation and Results

This section specifically addresses the emergency shelter allocation problem, detailing its implementation within the study area. The methodological framework is applied to real-world spatial and demographic data, and the resulting allocation outcomes are analyzed to evaluate the effectiveness and operational feasibility of the proposed method.

4.1 Case Study

The proposed network-based emergency shelter allocation model is applied to District 12 of Tehran, Iran, an urban area characterized by a high seismic risk due to its proximity to multiple active fault lines. As the capital and most populous city of Iran, Tehran hosts approximately 14 million residents daily, making it a critical focal point for disaster preparedness planning. District 12, situated in the city's historical and commercial core, includes the Tehran Grand Bazaar, a major economic hub that further enhances the area's strategic importance in urban crisis management. According to the demographic data utilized in this study, District 12 has a residential population of 239,611 spread across approximately 16 square kilometers.
According to the Tehran City Crisis Management Organization, there are 83 designated emergency shelters in this district, which include 33 open spaces, such as parks and sports fields, and 50 school facilities adapted for emergency accommodation, as illustrated in Figure 4. The implementation of the model utilized detailed spatial and demographic data collected from 1,063 population blocks, allowing for a comprehensive analysis of shelter accessibility and evacuation logistics.

4.2 Implementation Details

The model is developed using Python 3.9 and leverages specialized libraries for spatial data analysis, network analysis, and evolutionary computation algorithms. Geopandas is utilized to process spatial data, read population community polygons (representing population demand points), and calculate the centroids of each polygon for optimal route computations. Road networks are modeled with NetworkX, which facilitates shortest-path calculations through Dijkstra's algorithm to determine evacuation distances between population communities and shelters. The GA is implemented using DEAP (Distributed Evolutionary Algorithms in Python), which offers tools for chromosome initialization, fitness evaluation, and evolutionary operators, including roulette wheel selection, tournament selection, two-point crossover, and uniform mutation. The integration of these libraries ensures seamless handling of geospatial, network, and optimization components.
The implementation of the proposed model begins with the construction of an origin-destination (O/D) matrix, which captures the shortest paths between all supply points (candidate emergency shelters) and demand points (population communities). Using Dijkstra's algorithm, the shortest travel distance from the centroid of each demand polygon to every shelter is calculated across the urban road network. The GA is then initialized by defining a chromosome structure as an integer list, with a length equal to the number of demand points; each gene within the chromosome represents the ID of the assigned shelter for that specific demand location.

The optimization process involves formulating a fitness function designed to minimize the total weighted evacuation distance, as well as implementing crossover and mutation operations to evolve the solution population.

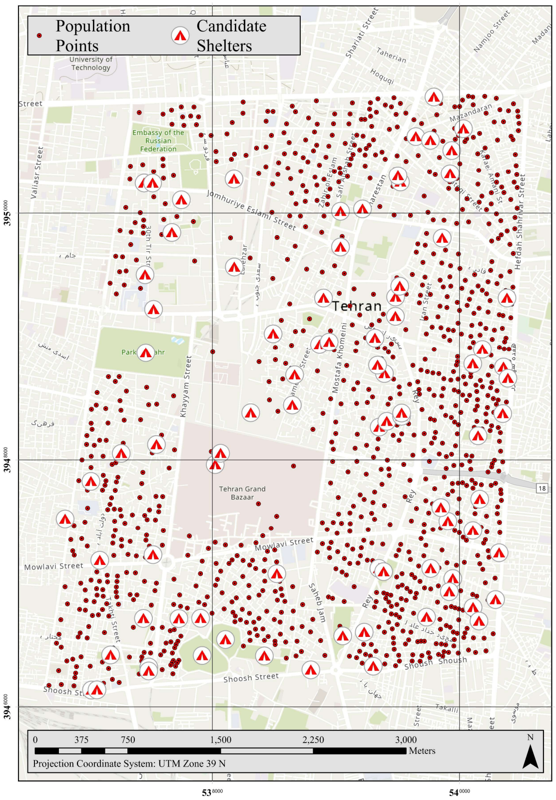

Figure 4. Case area with all the candidate shelters' locations

4.3 Parameter Tuning Results

To enhance both computational efficiency and solution quality, a systematic parameter tuning process is implemented. The algorithm is executed multiple times under different configurations to evaluate its performance based on two primary criteria: total evacuation distance and convergence behavior.
Initial values are established for core GA parameters, including population size, number of generations, crossover rate, and mutation rate. During the tuning process, critical GA parameters are meticulously adjusted: the crossover rate is varied between 0.8 and 0.9, the mutation rate is tested at 0.05, 0.1, 0.15, and 0.2, and the number of generations is examined within the range of 500 to 1000. Additionally, a population size of 200 individuals is utilized, and in the tournament selection method, five subsets of individuals are randomly chosen from the population. This systematic evaluation facilitates the identification of parameter combinations that achieve an effective balance between solution accuracy and computational efficiency. The results obtained using the tournament selection method are summarized in Table 1, while those employing the roulette wheel selection method are presented in Table 2, enabling a comparative analysis to highlight trade-offs and identify optimal parameter configurations.
The results indicate that the optimal solution is achieved using the roulette wheel selection method, with a crossover rate of 0.8 and a mutation rate of 0.2, over 1,000 generations. Under these parameters, the best solution results in a total evacuation distance of approximately 1,991 km for the assignment of 1,063 population blocks to 83 candidate shelters. Figures 5 and 6

illustrate the convergence curve and the emergency shelter allocation for the proposed solution, respectively. While increasing the number of generations generally improved solution quality—evidenced by reduced total evacuation distances—this improvement came at the expense of longer execution times. However, an analysis of the convergence curves revealed a saturation point beyond which further increases in generation count yielded diminishing returns. Specifically, the additional computational effort did not result in significant improvements in the objective function after reaching a certain threshold, indicating an efficiency-optimal trade-off point for parameter selection.

Table 1. Genetic parameter tuning results using the tournament selection method

	Population Size	Number of Generations	Crossover Rate	Mutation Rate	Total Distance (km)
Run 1	200	500	0.8	0.05	2251.94
Run 2	200	500	0.8	0.1	2342.16
Run 3	200	500	0.8	0.15	2370.34
Run 4	200	500	0.8	0.2	2384.07
Run 5	200	1000	0.8	0.05	2051.36
Run 6	200	1000	0.8	0.1	2355.42
Run 7	200	1000	0.8	0.15	2514.87
Run 8	200	1000	0.8	0.2	2462.64
Run 9	200	500	0.9	0.05	2444.81
Run 10	200	500	0.9	0.1	2473.60
Run 11	200	500	0.9	0.15	2531.66
Run 12	200	500	0.9	0.2	2514.57
Run 13	200	1000	0.9	0.05	2330.63
Run 14	200	1000	0.9	0.1	2382.85
Run 15	200	1000	0.9	0.15	2403.07
Run 16	200	1000	0.9	0.2	2308.60

Table 2. Genetic parameter tuning results using the Roulette wheel selection method

	Population Size	Number of Generations	Crossover Rate	Mutation Rate	Total Distance (km)
Run 1	200	500	0.8	0.05	2321.43
Run 2	200	500	0.8	0.1	2307.81
Run 3	200	500	0.8	0.15	2196.62
Run 4	200	500	0.8	0.2	2042.70
Run 5	200	1000	0.8	0.05	2318.71
Run 6	200	1000	0.8	0.1	2188.16
Run 7	200	1000	0.8	0.15	2081.12
Run 8	200	1000	0.8	0.2	1991.85
Run 9	200	500	0.9	0.05	2331.75
Run 10	200	500	0.9	0.1	2226.05
Run 11	200	500	0.9	0.15	2141.37
Run 12	200	500	0.9	0.2	2047.69
Run 13	200	1000	0.9	0.05	2338.00
Run 14	200	1000	0.9	0.1	2161.04
Run 15	200	1000	0.9	0.15	2145.53
Run 16	200	1000	0.9	0.2	2007.51

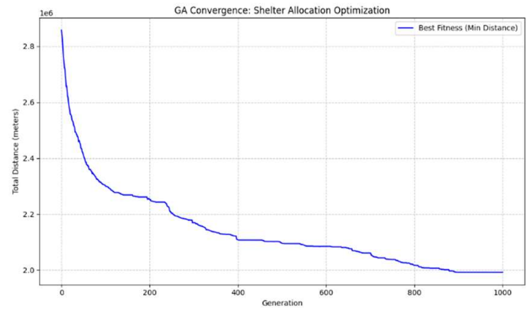

Figure 5. Convergence curve in the proposed solution

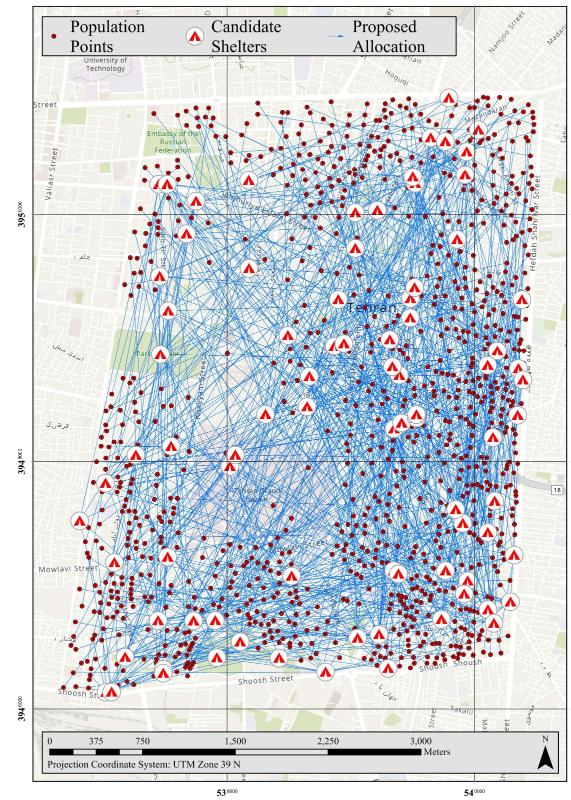

Figure 6. Result of shelter allocation in the study area

5. Conclusion

This study developed a network-based GA model to address the post-earthquake emergency shelter allocation problem in dense urban environments. By integrating GIS-based demographic data, road networks, and shelter locations, the model prioritizes minimizing total evacuation distance through realistic network-based routing rather than Euclidean assumptions. The GA employs a robust evolutionary strategy—including roulette wheel and tournament selection, two-point crossover, and uniform mutation—to efficiently explore the solution space and avoid premature convergence.

Applied to District 12 of Tehran, the model successfully allocated 1,063 population blocks to 83 pre-identified shelters. After parameter tuning, the optimal configuration (crossover rate of 0.8, mutation rate of 0.2, 1,000 generations) yielded a minimized evacuation distance of approximately 1,991 km. The algorithm demonstrated convergence stability, scalability, and suitability for large-scale urban disaster response scenarios.

The proposed approach offers urban planners and disaster managers a practical and computationally efficient decision-

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support tool for resilient evacuation planning. Despite assuming fixed shelter capacities and static demand points, the framework provides a solid foundation for more dynamic, constraint-aware extensions. Future work may incorporate time-based evacuation modeling, shelter capacity constraints, and multi-hazard risk scenarios, as well as comparisons with other metaheuristic algorithms like ACO or PSO. This model also shows potential for integration into IoT-enabled smart city platforms to support real-time evacuation guidance and adaptive planning.

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