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Optimizing Emergency Supply Location Selection in Urban Areas: A Multi-Objective Planning Model and Algorithm

Chenjun Liu, Zhuang Wu*, Yi Zhang, Yuanyuan Wang, Fangfang Guo, Yating Wang

School of Management Engineering, Capital University of Economics and Business, 100070 Beijing, China

* Correspondence: Zhuang Wu (wuzhuang@cueb.edu.cn)

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Abstract: The scientific location and layout of emergency material storage and rescue points in urban areas are critical aspects of emergency management. In this study, a multi-objective programming optimization model was constructed based on related theories, incorporating multiple goal combinations with different dimensions according to various disaster scenarios and urban emergency needs. The weight factors of emergency timeliness, economy, and safety were considered, and the multi-objective model optimization problem was transformed into a single-objective comprehensive optimization model problem using the weight method. The analysis decision function was utilized to study the transformation and solution method of the urban emergency rescue point location model. Heuristic optimization algorithms were employed to perform average segmentation calculations on the preset neighborhoods, constantly changing and narrowing the neighborhood range until the algorithm termination conditions were met, approaching the domain range of the optimal solution. Additionally, another precision parameter was utilized to control the accuracy of the final solution neighborhood range. The optimization of emergency vehicle scheduling was used to synergistically solve the problem of reserve rescue point location layout and optimization solution. The results of the example demonstrate the feasibility of constructing a multi-objective model with multiple combinations of different dimensions of objectives and the rationality of the Dijkstra heuristic optimization algorithm used. This study provides multiple methodologies and alternative site selection plans for decision-makers to select the required multi-objective reserve rescue point location model based on different urban disaster situations and their own emergency rescue needs.

Keywords: Emergency management; Site selection of urban rescue points; Target dimension; Multi objective model; Dijkstra algorithm

1. Introduction

With the continuous advancement of industrialization, urbanization, and informatization, cities are facing an increasing number of potential risk factors. Various sudden disasters pose a serious threat to the safety of urban residents and increase the difficulty of emergency rescue and disaster reduction work [1]. Therefore, the construction of urban infrastructure must keep pace with urban development to prevent public safety from being greatly threatened due to imperfect disaster prevention and mitigation infrastructure [2]. The reasonable location of urban emergency facilities is crucial for preventing and handling emergencies [3]. The selection and optimization of emergency reserve rescue addresses can significantly improve the effectiveness of cities in responding to various disasters, achieve rapid delivery of emergency supplies, and reduce emergency rescue logistics costs, adapting to the challenges of dynamic new accident risks [4, 5]. This article aims to construct a planning optimization model based on multi-objective planning and related theories. The model takes into account multiple emergency objective dimensions, such as disaster relief scheduling transportation timeliness, economic cost, rescue point safety, and road safety, based on different disaster situations and urban emergency needs. Multiple methodologies and alternative site selection plans are provided for decision-makers to select reserve rescue point location models based on urban disaster situations and their own emergency rescue needs. In summary, this study aims to contribute to the development of a more effective urban emergency public service system by providing a comprehensive and systematic approach to the location and optimization of emergency facilities.

2. Literature Review

In recent years, the issue of location, layout, and optimization has become a focal point of research in emergency management. Various methods have been developed to study reserve location, which can be broadly divided into two categories: quantitative analysis and a combination of qualitative and quantitative analysis.

The first category primarily employs quantitative analysis methods based on intelligent algorithms to address the problem of emergency location selection and the analysis of emergency material reserve optimization decision-making. Song et al. [6-9] considered different scenarios, including dynamic demand, disaster psychology, urban medical needs, and flood disaster risk, and constructed various target models according to their unique characteristics. Algorithmic solutions were applied to determine the location and allocation of material distribution centers and emergency shelters in these scenarios. However, the research frequently overlooks the emergency needs of cities. Xu et al. [10] proposed a dual-objective location model considering effectiveness and economy, and solved the model using a cellular yin-yang balance optimization algorithm. Nevertheless, dual objectives sometimes fail to meet the needs of multi-objective city selection. Yan and Qi [11] created an emergency logistics facility location model, using triangular fuzzy numbers to represent the uncertainty of emergency material demand. The model considered both emergency rescue cost and time objectives and employed genetic algorithms for solving, but it also had insufficient objectives. Feng and Gai [1] developed a dual-objective model for rescue reserve point location based on timeliness and economic factors, and suggested a weight-solving algorithm using the Dijkstra algorithm's system dynamic evolution method. While this approach was extended to multi-objective decision-making, it did not consider the diverse types of urban emergency needs. Luo et al. [12] analyzed and summarized location and transportation factors for emergency supplies, along with the joint model of location and transportation. He suggested that a comprehensive optimization model integrating multiple indicators could be considered in the future, with the exploration of faster and more effective algorithms. However, the objective remains too singular.

The second category mainly employs qualitative and quantitative methods, such as qualitative techniques, the analytic hierarchy process (AHP), and the fuzzy comprehensive evaluation method (FCE), to conduct a comprehensive evaluation of various indicators and ultimately select the optimal location. Li et al. [13-15] utilized the Delphi method and the analytic hierarchy process to quantify relevant impact factors, conducting quantitative evaluation and analysis for country parks in Wuhan and Zhengzhou to obtain alternative plans for emergency medical facility construction. Zhou et al. [16] established an improved Analytic Hierarchy Process (AHP) - Fuzzy Compromise Decision Evaluation Model and introduced a compromise fuzzy decision method to optimize the overall site selection scheme, addressing the issues of lengthy distribution times and limited distribution coverage for urban emergency medical distribution centers. Zhang and Lu [17] developed an evaluation index system for emergency reserve site selection, combining robustness and resilience research. The primary shortcoming of such site selection methods is the presence of many subjective factors that influence the decision-making process. There is a relative lack of objective factors and models that link goals with constraints.

A review of the literature reveals that in constructing and solving urban multi-objective location planning, most current research has inadequately considered urban emergency needs and disaster relief priorities. Additionally, the structural proportional relationship between the importance of multiple target factors has been neglected. Therefore, the reasonable selection of model objectives and the optimization of the weight ratio of objective factors in determining the optimal location scheme have been ignored. The more factors and objectives considered, the greater the impact of target weight ratios on site selection. Consequently, research on target weight ratio selection is of significant importance, and systematic research results are currently lacking in this area.

Considering the varying disaster situations, disaster relief objectives, and emergency considerations in different cities, this paper aims to achieve the following innovation: constructing a hierarchical system of dual-objective, triple-objective, and multi-objective planning models based on multiple objective dimensions, such as the shortest total distance of urban rescue material transportation, the lowest economic cost, and rescue point safety. Furthermore, it seeks to explore and optimize the weight ratio of influencing factors [18] to balance the impact of factors like distance, cost, and safety on the location of emergency resource reserve points. Secondly, the research will build upon intelligent optimization algorithms [19] and the theory and method of objective model optimization solutions [20-22] to design and improve the value and structure of solution objective weights. Thirdly, this approach will be extended to address location problems in three or more multi-objective models and other areas. Lastly, to simplify the solution, a case study will be conducted using adjacency data matrices to represent the transportation network and adjacency cost matrices to represent the related costs of the transportation network. This will verify the feasibility and rationality of the algorithm that weight optimization can improve the efficiency of reserve point location in multi-objective models.

3. Multi-Objective Programming Model for Location Selection of Rescue Reserves and Rescue Points

3.1 Question Raising

In commercial environments, economic costs are typically the primary consideration for enterprise operations and transportation scheduling. However, in emergency situations such as disasters, the timeliness of disaster relief is the primary concern when it comes to the transportation and scheduling of relief materials [23]. Decision makers in disaster relief situations must consider several factors, including emergency rescue time, which is crucial for saving lives. Shortening rescue time can save more lives and reduce economic losses for disaster victims. Another important consideration is the optimization of the location layout of rescue material storage and exit points. This can reduce the turnover time and total turnover amount of rescue materials, thereby reducing the costs of various types of personnel and property during emergency transportation. It can also save rescue energy consumption and avoid problems such as insufficient rescue capacity caused by excessive concentration of rescue transportation time [2]. Additionally, it is essential to consider the overall safety of alternative rescue points. In the event of sudden disasters, the higher the safety of the reserved rescue points, the smaller the impact of disaster losses can be ensured. Other factors, such as selecting the highest overall safety of the rescue road, should also be considered.

To improve the effectiveness of emergency rescue in the event of a sudden disaster in a city, a multi-objective planning model system that considers different types of factors and constructs different dimensions of objectives can be constructed. By optimizing the weight structure ratio of each objective factor, decision makers can improve the scientificity of the location and layout of rescue material storage and rescue points. In summary, a comprehensive approach that takes into account different factors and dimensions can help decision makers optimize their response to disasters and improve the effectiveness of emergency rescue operations. This is crucial for minimizing the loss of life and economic damage caused by disasters.

3.2 Model Establishment

The location problem of emergency material storage and rescue points can be addressed using a multi-objective programming model in operational research. Based on the analysis above, the model objectives can be set to: first, minimize the transportation and turnover time of emergency rescue materials; second, minimize the economic cost of emergency rescue scheduling. To achieve this, a dual objective equilibrium model for the location of storage and rescue points can be constructed under the constraints of minimizing material turnover time and economic cost. This can help develop a distribution and scheduling plan that reduces the economic cost, energy consumption, and transportation costs of the entire rescue material transportation turnover. Furthermore, if the overall safety of the reserve rescue point is considered to be the highest, a three-goal planning model can be constructed. To account for additional objectives such as the safety of emergency transportation roads and workload at storage points, more than three multi-objective planning models can be constructed.

The model assumption is that mathematical models can be used to solve the location and layout problem without changing its nature. It is further assumed that rescue and rescue points in the city will carry out rescue material scheduling and distribution activities immediately and without delay upon receiving emergency response commands.

To determine the disaster-affected points, a comprehensive evaluation and determination should be conducted using relevant data and materials such as disaster types, emergency levels, frequency and frequency of occurrence, occurrence time characteristics, population size, and social economy in the urban area over a long historical period. Alternative rescue points can be selected according to the emergency location evaluation system based on expert knowledge and emergency location industry planning standards. The relevant model calculation methods in this article can then be used to optimize the solution.

The model description is as follows: i represents the ith disaster demand location, and the disaster point set $I=\{1,2,\ldots,i,\ldots,n\}$. j is the jth emergency rescue resource reserve rescue point, and the set of rescue points $J=\{1,2,\ldots,j,\ldots,m\}$. The city has a total of N material gathering nodes, including m rescue points and n disaster-affected points, which can be obtained as follows: $1\le m$, $n\le N$, and $2\le m+n\le N$. The emergency response coverage matrix for the set of reserved rescue points is represented by a 0-1 mathematical matrix, where x_{ij} indicates whether the reserved rescue point j provides rescue response services for the disaster-affected point i. When $x_{ij}=1$, it indicates that j provides rescue services for the disaster-affected point i. Otherwise, when $x_{ij}=0$. To select P rescue points from m rescue points, $P<m$. The single-objective, dual-objective, three-objective, and multi-objective planning location models can be constructed based on these parameters.

(1) Single Objective Model M1.1 for Finding the Shortest Transportation Path

To effectively respond to emergency situations and plan rescue routes for storage and rescue points, it is essential to determine the shortest path from these points to all possible disaster-affected locations. This can be achieved by constructing a mathematical model for the shortest transportation route based on the shortest path theory of operational research, as shown in Eqns. (1) to (2).

$$\text{Model M1.1} \quad \min S(P) = \sum_{i=1}^{n}\sum_{j=1}^{m} x_{ij} \cdot s_{ij} \tag{1}$$

$$s.t. x_{ij} = \begin{cases} 1, \textit{indicating that } j \textit{ provides rescue services for } i \\ 0, \textit{indicating that } j \textit{ does not provide rescue services for } j. \end{cases} \tag{2}$$

$$x_{ij} \geq 0,\ s_{ij} \geq 0$$

In Eq. (1), s_{ij} represents the shortest rescue distance from reserve rescue point *j* to disaster-affected point *i*. The value of *S*, which is the sum of all actual emergency rescue service routes in kilometers, is determined by the number of rescue points *P* that are ultimately selected.

(2) Single Objective Model M1.2 for Minimum Economic Consumption

The economic goal of rescue transport economics, based on the concept of high-quality disaster relief and sustainable development, is to minimize the consumption of manpower, material resources, and energy during the transportation process. This objective is closely related to factors such as the length of the transportation path, the smoothness of road traffic, and other factors that affect road conditions, such as the degree of road flatness, the number of potholes, the gradient and number of up and down slopes, the size and number of turning roads, and the number of left turn traffic lights relative to the total number of intersection lights. The economic weight of the corresponding rescue transportation road can be determined by weighing these factors, as shown in Eq. (3).

$$\text{Model M1.2} \quad \min C(P) = \sum_{i=1}^{n}\sum_{j=1}^{m} x_{ij} \cdot \mathrm{c_{ij}} \qquad x_{ij} \geq 0,\ \mathrm{c}_{ij} \geq 0 \tag{3}$$

In Eq. (3), c_{ij} represents the consumption costs of manpower, property, and energy from rescue point *j* to disaster-affected point *i*, while *C* represents the total cost of manpower, property, and energy.

(3) Double Target Model M2

The optimization model for the location of emergency supplies reserve rescue points using dual objective programming is represented as M2, and can be expressed as follows when the average speed of the road from each rescue point to each disaster-affected point in an urban disaster area is v:

$$\text{Model M2} \quad \min T(P) = \sum_{i=1}^{n}\sum_{j=1}^{m} x_{ij} \cdot \left(\mathrm{s_{ij}}/\mathrm{v}\right) \tag{4}$$

$$\min C(P) = \sum_{i=1}^{n}\sum_{j=1}^{m} x_{ij} \cdot \mathrm{c_{ij}} \tag{5}$$

$$\text{s.t.} \ \sum_{j=1}^{m} x_{ij} \geq 1, i = 1,2,\cdots \mathrm{n} \tag{6}$$

$$s_{ij} \leq \mathrm{T_0} \cdot \mathrm{v} \qquad x_{ij} \geq 0, \mathrm{s_{ij}} \geq 0, \mathrm{v}>0, \mathrm{c_{ij}} \geq 0, \mathrm{T_0} \geq 0 \tag{7}$$

Eq. (4) represents the objective of minimizing the total transportation time, which is the sum of the transportation times for each rescue path. In this equation, v is the average transportation speed from all rescue points to disaster-affected points; Eq. (5) is the same as Eq. (3), representing the economic weight of the corresponding rescue transportation road; Equation (6) indicates that each disaster-affected location must have at least one reserve rescue point to provide response services; In Eq. (7), T_0 represents the maximum delivery time from the reserve point to the affected location. This equation ensures that the distribution of goods between rescue point *j* and affected point *i*, with an average vehicle transportation speed v, should be completed within the limited acceptance time (T_0).

(4) Three Objective Model M3

The three-objective planning optimization model for the location of alternative rescue material storage and rescue points in cities can be represented as M3:

$$\text{Model M3} \quad \min T(P) = \sum_{i=1}^{n}\sum_{j=1}^{m} x_{ij} \cdot \left(\mathrm{s_{ij}}/\mathrm{v}\right) \tag{8}$$

$$\min C(P) = \sum_{i=1}^{n}\sum_{j=1}^{m} x_{ij} \cdot c_{ij} \tag{9}$$

$$\max A(P) = \sum_{j=1}^{m} x_j \cdot a_j \tag{10}$$

$$\text{s.t.} \ \sum_{j=1}^{m} x_{ij} \geq 1, i = 1,2,\cdots \mathrm{n} \tag{11}$$

$$\mathrm{S_{ij}} \leq \mathrm{T_0} \cdot \mathrm{V} \qquad x_{ij} \geq 0, \mathrm{s_{ij}} \geq 0, \mathrm{c_{ij}} \geq 0, \mathrm{T_0} \geq 0, \mathrm{v}>0 \tag{12}$$

Eqns. (8) and (9) are the same as Eqns. (4) and (5), respectively, representing the objectives of minimizing total transportation time and economic consumption; Eq. (10) represents the objective of maximizing the safety of alternative reserve rescue points, where a_j represents the safety level of the *j*th alternative reserve rescue point; Eq. (11) ensures that each disaster-affected point is assigned to only one rescue point for response services; In Eq. (12), *v* represents the average speed of disaster relief transportation vehicles, indicating that the distribution of relief materials must be completed within the acceptable maximum time limit T_0. This value can be algorithmically adjusted to meet specific requirements. Eq. (12) ensures that the distance from all rescue points to disaster-affected points meets the maximum time limit proposed by the rescue decision.

(5) Multi-Objective Programming Model MN

In reality, optimizing the location decisions for emergency material storage and rescue points often involves three or more objectives. To simplify the optimization and solution of location and layout problems for multi-objective planning, the weight of objectives can be increased accordingly based on the dual objective optimization algorithm and optimization principle.

Assuming the model has *Z* objectives, if *Z*>3, the Z-objective programming optimization problem can be decomposed into *Z* single objective programming problems. This approach allows for the consideration of various objectives such as road safety, workload of reserve points, in addition to the timeliness and economic cost of emergency relief.

To illustrate the construction of a multi-objective location planning model, MN, this article takes M5 as an example.

Model M5:

$$\min Z_1\,(P) = \sum_{i=1}^{n} \sum_{j=1}^{m} x_{ij} s_{ij} \tag{13}$$

$$\min Z_2\,(P) = \sum_{i=1}^{n} \sum_{j=1}^{m} x_{ij} c_{ij} \tag{14}$$

$$\max Z_3\,\big(A(P)\big) = \sum_{j\in M} x_i \mathrm{a_i} \tag{15}$$

$$\max Z_4\,(P) = \sum_{i=1}^{n} \sum_{j=1}^{m} x_{ij} r_{ij} \tag{16}$$

$$\min Z_5\,(P) = \sum_{i=1}^{n} \sum_{j=1}^{m} a_z x_{ij} \mathrm{z_{ij}} \tag{17}$$

$$\text{s.t. } \sum_{j\in M} \mathrm{x_{ij}} \geq 1, \forall i \in I \tag{18}$$

$$\mathrm{s_{ij}} \leq \mathrm{T_0} \cdot \mathrm{v} \tag{19}$$

In Eq. (16), r_{ij} represents the degree of road safety from reserve point *j* to disaster-affected point *i*. Eq. (17) represents the *z*th objective, such as the maximum workload constraint for disaster relief at the reserve point, from reserve point *j* to disaster-affected point *i*. Other equations are the same as above.

It should be noted that emergency decision-makers may need to modify established models based on the specific scenarios of urban sudden disasters. For example, if the city is severely affected and the degree of road damage and the difficulty of material distribution cannot be ignored, reachability cost (AC) may be used instead of transportation cost to characterize disaster relief efficiency [24].

If the *j*th reserve rescue point decides to distribute resources to disaster-affected point *i* during cycle *t*, then x_{ijt}=1, otherwise x_{ijt}=0. The total reachability cost of all disaster-affected points in the planning cycle can be calculated as $Z = \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{t=1}^{T} c_{ij} x_{ijt}$.

4. Algorithm and Solution for Emergency Material Storage and Rescue Point Location Models

The optimal plan for minimizing rescue time and path may not necessarily be the same as the plan for minimizing economic cost. To improve the rationality and practicability of the selected algorithm, and to reduce the complexity of the calculation process, an auxiliary decision analysis function can be introduced. This function takes into account the response time of the manager's decision during emergency rescue, and improves the practicality of the algorithm by considering the influence degree of each objective factor of the model.

4.1 Converting a Multi Objective Model to a Single Objective Model

(1) To solve the optimization of dual objective programming, weights α and 1-α ($\alpha\in$[0,1]) can be introduced to construct the dimensionless function z_{ij} using the weighted method. The dimensionless function z_{ij} can be obtained as follows:

$$z_{ij} = as_{ij} + (1-a)c_{ij}(\alpha \in [0,1]) \tag{20}$$

In Eq. (20), when α=1, only the shortest transportation path is considered. Similarly, when α=0, only the minimization of economic consumption is considered. By setting $\alpha\in[0,1]$, the model can comprehensively consider the timeliness and distance minimization problems.

To solve the multi-objective problem, Eqns. (8) to (9) can be converted into a single objective model solution problem using a weighted sum method, as shown in Eq. (21):

$$\min Z\,(P) = \sum_{i=1}^{n}\sum_{j=1}^{m} x_{ij}z_{ij} = \sum_{i=1}^{n}\sum_{j=1}^{m} a\, x_{ij}\mathrm{s}_{\mathrm{ij}} + \sum_{i=1}^{n}\sum_{j=1}^{m}(1-a)x_{ij}\mathrm{c}_{\mathrm{ij}} \tag{21}$$

The location model represented by Eq. (21) can be solved to find the optimal solution P that satisfies Eqns. (4) to (7) when a reasonable value of α is chosen.

The dual objective programming model is suitable for emergency site selection when cities only focus on or consider the timeliness of emergency relief (or the shortest path) and the minimization of scheduling costs. The weight quantification method between the two factors can be evaluated by an expert group composed of decision-makers and emergency experts, or the weight ratio of the two factors can be optimized based on the construction function relationship for different weight values.

In this article, the latter approach is chosen to determine the weight ratio of the two factors.

(2) To solve the three-objective programming optimization problem, weights α_1, α_2, and α_3 ($\alpha_1+\alpha_2+\alpha_3=1$, α_1, α_2, $\alpha_3 \in [0, 1]$) can be introduced to construct the dimensionless function z_{ij}:

$$\begin{gathered} z_{ij} = a_1 s_{ij} + a_2 c_{ij} + a_3 a_i \\ a_1, a_2, a_3 \in [0,1,]\; a_1 + a_2 + a_3 = 1 \end{gathered} \tag{22}$$

In Eq. (22), when $\alpha_1=1$ and $\alpha_2=\alpha_3=0$, only the shortest transportation path is considered. Similarly, when $\alpha_2=1$ and $\alpha_1=\alpha_3=0$, only the minimization of economic consumption is considered. When $\alpha_3=1$ and $\alpha_1=\alpha_2=0$, only the safety of the rescue point is considered.

By setting α_1, α_2, and α_3 such that α_1, α_2, and $1-\alpha_1-\alpha_2 \in [0, 1]$, the model can comprehensively consider the three aspects of the problem. Eqns. (8) to (10) can be converted into a single objective model solution problem using a weighted sum method, as shown in Eq. (23):

$$\min Z(P) = \sum_{i=1}^{n}\sum_{j=1}^{m} x_{ij}z_{ij} = \sum_{i=1}^{n}\sum_{j=1}^{m} a_1 x_{ij}s_{ij} + \sum_{i=1}^{n}\sum_{j=1}^{m} a_2 x_{ij}c_{ij} - \sum_{j=1}^{m}(1-a_1-a_2)x_j a_j \tag{23}$$

(3) To solve the multi-objective programming optimization problem, weights α_k ($\alpha_k\in[0, 1]$, k=1,2,⋯,z, and $\alpha_1+\alpha_2+\ldots+\alpha_z=1$) can be introduced to construct the dimensionless function z_{ij} using the weighted method.

To address the objectives of maximizing the safety of rescue points and minimizing road safety, two objective functions are introduced: $\min w_3(P) = -\sum_{j\in M} x_j a_j$ and $\min w_4(P) = -\sum_{i=1}^{n}\sum_{j=1}^{m} a_4 x_{ij} r_{ij}$.

Eqns. (13) to (17) in the multi-objective programming model N5 can be transformed as follows:

$$\begin{gathered} \min Z\,(P) = \sum_{i=1}^{n}\sum_{j=1}^{m} a_1 x_{ij}s_{ij} + \sum_{i=1}^{n}\sum_{j=1}^{m} a_2 x_{ij}c_{ij} - \sum_{j=1}^{m} a_3 x_j a_j - \sum_{i=1}^{n}\sum_{j=1}^{m} a_4 x_{ij} r_{ij} + \\ \sum_{i=1}^{n}\sum_{j=1}^{m} a_z x_{ij} z_{ij} \end{gathered} \tag{24}$$

$$\begin{gathered} \text{s.t. } z_{ij} = a_1 s_{ij} + a_2 c_{ij} - a_3 a_i - a_4 r_{ij} + a_5 z_{ij} \quad a_1, a_2, \cdots, a_z \in [0,1] \\ \text{and } a_1 + a_2 + a_3 + a_4 + a_5 = 1 \end{gathered} \tag{25}$$

4.2 Transforming Model Forms and Constructing Auxiliary Analysis Functions

To determine the values of various weight parameters and model solutions for different disaster relief scenarios and emergency situations in cities, an α decision optimization analysis function can be constructed for the independent variable in the dual objective programming model M2. This function can be represented by the variable z_k, which is a weighted independent variable that has a one-to-one correspondence with the weight coefficient α.

$$z = z_k(a), a \in [0,1]\;\; k \in \{1,2,\cdots,X\} \tag{26}$$

Given a solution that satisfies the constraints of the model, denoted by P_α, two single auxiliary decision analysis functions based on distance and cost can be constructed by decomposing the weighted independent variable z

according to distance and cost dimensions. These functions are denoted by $z_{1k}(a) = as_{ij}(a)$ and $z_{2k}(a) = (1 - a)c_{ij}(a)$, respectively, where $\alpha \in [0, 1]$ and $k \in \{1, 2, \ldots, X\}$. Here, $z_{1k}(\alpha)$ and $z_{2k}(\alpha)$ represent the corresponding relationship between weight and road distance and between weight and economic cost, respectively, and $z_k(a) = z_{1k}(a) + z_{2k}(a)$.

The auxiliary decision analysis function has the following monotonic properties: $z=z_{1k}(\alpha)$ is an incremental function of α, and $z=z_{2k}(\alpha)$ is a decreasing function of α. The function $z=z_{1k}(\alpha)$ takes the maximum value at $\alpha=1$ and the minimum value at $\alpha=0$, while $z=z_{2k}(\alpha)$ takes the maximum value of 0 at $\alpha=0$ and the minimum value at $\alpha=1$. Therefore, $Z(P)$ increases with the increase of s_{ij} and decreases with the increase of c_{ij}. $Z(P)$ is the superposition of the functions of s_{ij} and c_{ij}, and $Z(P)$ may have a maximum value at some value of α, as shown in Figure 1.

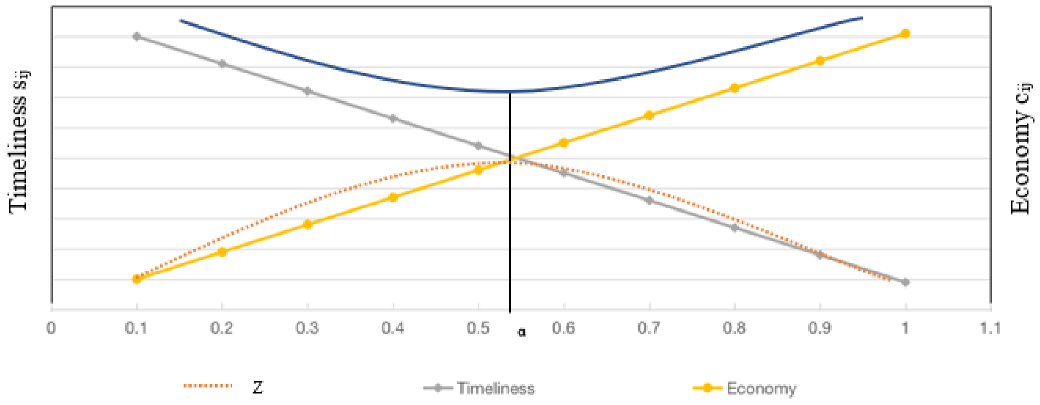

Figure 1. Schematic diagram of property analysis of auxiliary decision analysis function

4.3 Algorithm Design

In order to obtain the optimal reserve rescue point from the alternative reserve rescue points that meet the requirements of both Eq. (4) and Eq. (5), the Dijkstra optimization algorithm can be used to solve the s_{ij} in the model. Based on the monotonicity of the decision analysis function, the interval $[\lambda, \beta]$ can be divided into N parts, and the median value of each group can be taken to verify whether the constraint Eq. (7) can be satisfied. If a point that does not meet the constraint condition is found, the search range can be modified, and the location of the interval can be changed.

Specifically, the interval $[\lambda, \beta]$ can be divided into N parts, where $\alpha=k(\beta-\lambda)/N$ $(k=1, 2,..., N)$. The value of α is divided into N parts, and the unit increase value during each iteration calculation is $(\beta-\lambda)/N$. When the value of α satisfies the constraint Eq. (7), λ and β can be reassigned to search for new locations. The parameter N is set to 10 to balance the trade-off between algorithm efficiency and accuracy. When the interval length is less than a given accuracy value ε (in this article, ε is set to 0.001), a more accurate interval $[\lambda_k, \beta_k]$ can be obtained, and the feasible solution satisfying the model constraints can be obtained as $\alpha=(\lambda_k+\beta_k)/2$. Once the value of α is obtained, the z_{ij} function can be determined according to Eq. (20).

At this point, the dual objective programming model can be transformed into a single objective programming optimization problem, as shown in Eq. (21). Using the Matlab optimization calculation toolbox, the x_{ij} can be calculated, which represents the distance data correspondence between the emergency supplies reserve rescue point and the disaster affected point in an $n \times m$ data matrix.

4.4 Multi-Objective Programming Model Optimization Location Algorithm

When optimizing a single objective programming solution, it is often possible to subdivide the interval [0,1] into several parts to obtain a series of local optimal solutions Pi that satisfy the single objective, where $i=1,2,...,N$, and then obtain a global optimal solution P that satisfies all objectives simultaneously.

For three or more multi-objective plans, the overall goal optimization is achieved when each goal plan meets all constraints. In some cases, there may be multiple optimal solutions for the optimization results of multi-objective plans. In such cases, the optimal solution is the feasible solution that meets multiple goals and constraints simultaneously within the feasible region. If the feasible solution region is an empty set, it is necessary to reduce the constraint constraints or the model accuracy ε and perform iterative operations again to find a feasible optimal solution. If there are multiple optimal solutions in the feasible region, that is, they form an optimal solution set, then there are multiple plans to choose from.

The multi-objective programming model optimization location algorithm can help decision-makers to identify the optimal solution that best meets the needs and constraints of the problem. By considering multiple objectives or criteria, the algorithm can help decision-makers to identify the trade-offs between different objectives and to select the most appropriate solution based on the specific needs of the problem. The subdivision of the interval into several parts can help to identify local optimal solutions, and the iterative operations can help to refine the solution and find the optimal solution that meets all objectives and constraints simultaneously.

4.5 End Condition and Excellence Analysis of Algorithm Solution

When solving the location of emergency material storage points, it is important to obtain the optimal solution within a limited time frame while maintaining the solution's quality. Multi-objective optimization and its algorithm problems can be particularly complex [1]. In situations where multiple optimal solutions exist, the algorithm can provide emergency decision-makers with multiple location plans. However, it is important to add algorithm termination precision constraints to the cyclic operation process to ensure that the algorithm can terminate within a certain accuracy range in a timely manner. For example, adding constraints such as β-λ<ε, where, ε is an appropriate value can ensure that the solution algorithm can terminate within a certain accuracy range.

Selecting an appropriate N value can also help to reduce the iteration time. A large N value can lead to too narrow and too many intervals for each operation, resulting in longer search times, more iterations, and reduced computational efficiency. This may also result in multiple adjacent feasible solutions that can complicate the decision-making process. On the other hand, a small N value can lead to too few intervals and increase the search calculation time, potentially resulting in the loss of some optimal solutions. In practice, the N value can be determined through multiple simulations and comparisons to find an appropriate balance between computational efficiency and solution quality.

Overall, it is crucial to balance solution quality and computational efficiency when solving location problems for emergency material storage points. By adding termination precision constraints and selecting an appropriate N value, decision-makers can obtain the optimal solution within a limited time frame, while ensuring the solution's quality and maintaining computational efficiency.

5. Solving Model and Example Analysis

5.1 Solving Model

To verify the rationality and effectiveness of the Dijkstra heuristic algorithm in solving emergency rescue location problems, a double objective programming model is selected as an example, using the transportation network and roads in the urban area of the H mega city as the emergency rescue simulation data network. The spatial distance between disaster demand points and between disaster-stricken points and rescue points can be obtained by querying the geographic information system (GIS), and the relevant distance matrix data can be obtained from an .xls file or imported from a database system (DBS).

As shown in Figure 2, the algorithm involves the following steps:

(1) Set parameters for average rescue speed and rescue response time based on actual needs. The maximum rescue distance parameter of the rescue point in this article is set to 75 km.

(2) Set algorithm precision parameters ε, which control the size of the algorithm's final neighborhood range and the accuracy of the resulting lambda. In this article, ε is set to 0.001.

(3) Determine the neighborhood search range and times of N by setting parameters α, β, and k.

(4) Compare the distance obtained through Dijkstra with the actual demand. If it does not meet the requirements, proceed to the next neighborhood search and execute step 5.1. If it meets the requirements, set the current neighborhood as the search range of the algorithm and execute step 5.2.

(5.1) If the algorithm meets the search frequency, output λ. If not satisfied, enter a new neighborhood.

(5.2) If the algorithm meets the accuracy, output λ. If not satisfied, enter a new neighborhood.

(6) By determining λ, calculate the evaluation function of the algorithm under different target numbers and ultimately obtain the problem solution.

The correctness of the monotonic nature of the auxiliary analysis function can be verified by analyzing the obtained solution and comparing it with the actual demand. The timeliness efficiency of the solution can also be evaluated based on the time required to obtain the solution.

By using this algorithm, decision-makers can effectively determine the optimal location of emergency material storage points within a limited time frame while considering multiple objectives and constraints. The Dijkstra heuristic algorithm can help to improve the efficiency and accuracy of the optimization process, making it a useful tool for emergency response planning and management.

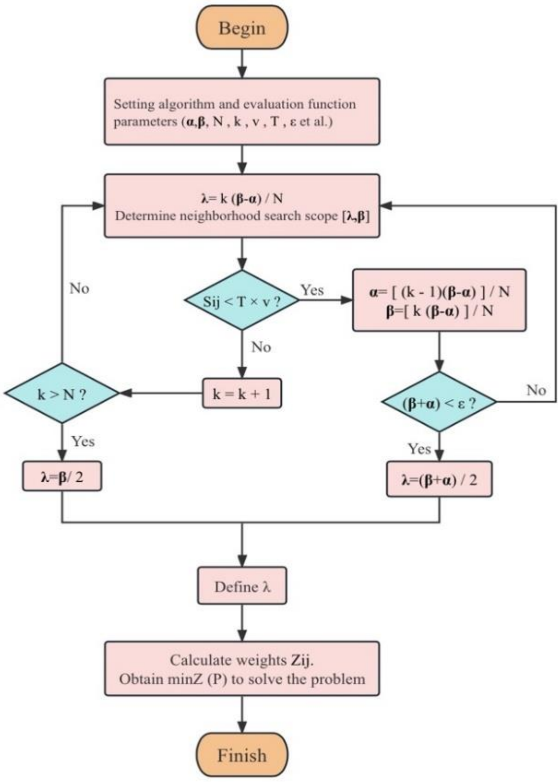

Figure 2. Algorithm diagram

Table 1. Distance data relation matrix between alternative reserve rescue points and disaster-affected points

Panel point	J1	J2	J2	J4	J5	J6	J7	J8	J9	J10
1	7.33	6.72	10.68	6.79	10.32	7.51	6.7	9.09	2.3	2.19
2	11.0	7.4	11.92	9.64	2.14	4.0	5.95	4.78	10.44	2.52
3	6.38	9.42	4.16	4.58	8.56	11.91	10.0	3.16	11.97	2.78
4	5.9	7.25	11.52	5.56	8.46	8.87	9.09	10.97	3.76	3.06
5	9.21	4.82	13.86	9.74	6.82	10.25	8.54	8.92	9.18	4.37
6	3.38	11.60	7.31	2.87	2.94	6.44	11.61	6.16	5.98	4.26
7	6.18	6.1	6.94	7.83	7.17	2.29	17.93	5.08	8.87	3.38
8	10.11	3.03	8.62	4.41	4.1	9.36	14.08	3.39	3.83	10.03
9	6.95	2.43	10.51	10.18	2.54	4.58	9.18	3.49	3.93	10.13
10	9.55	3.15	8.39	2.28	3.23	4.04	10.53	7.52	1.47	8.13
11	8.59	7.67	8.58	11.08	10.15	8.66	8.04	6.04	7.93	6.76
12	7.06	3.09	9.83	6.60	8.91	7.3	10.52	2.72	5.5	12.04
13	3.67	10.63	9.8	10.27	3.62	8.68	8.43	9.02	5.72	9.32
14	7.86	7.55	10.54	11.19	8.74	7.88	2.3	2.21	7.3	3.97
15	10.03	4.02	11.04	4.08	5.62	7.23	8.37	4.14	9.79	10.34
16	7.46	6.59	9.79	5.35	16.33	6.46	7.61	3.57	4.36	8.27
17	7.81	8.15	9.06	5.85	10.17	8.5	4.49	6.51	8.93	6.78
18	8.5	6.19	6.33	8.66	10.16	8.23	7.74	12.11	8.16	4.33
19	10.11	6.56	2.98	9.38	14.13	9.01	8.69	5.25	2.45	2.86
20	11.02	5.65	5.19	14.25	4.27	4.08	7.03	2.25	6.5	7.42
21	9.61	8.79	2.34	2.44	2.88	5.66	8.03	8.5	2.22	12.02
22	6.71	6.91	6	9.41	4.7	2.12	6.67	3.45	8.94	11.18
23	10.4	10.38	9.63	4.49	1.67	11.05	5.07	8.45	4.02	5.33
24	8.07	6.9	9.84	4.11	6.32	4.42	10.72	10.81	7.14	7.66
25	6.93	2.36	3.90	3.96	4.46	4.07	8.9	9.77	10.74	8.33
26	9.25	2.32	3.18	4.45	2.85	11.7	4.5	11.76	5.42	6.42
27	9.88	9.74	6.76	5.78	3.18	4.08	7.16	4.78	8.06	2.18
28	10.98	5.94	7.52	7.58	10.15	9.56	8.52	4.78	8.66	7.44
29	11.14	9.56	5.28	9.36	7.88	6.18	2.38	7.95	5.45	2.38
30	9.76	3.18	3.22	9.54	5.78	8.72	2.36	7.08	7.66	2.48
31	11.81	10.99	4.54	4.64	5.08	7.86	10.23	10.7	4.42	14.22
32	8.81	9.01	8.1	11.51	6.8	4.22	8.77	5.55	11.04	13.28

Table 1 provides the distance (s_{ij}) data matrix between 32 disaster relief demand points (numbered 1-32) and 10 alternative reserve rescue points (numbered J1-J10) in H city. The distances between these points are essential for determining the optimal location of reserve rescue points while considering the timeliness and economic cost of emergency response operations.

Table 2. Economic cost data matrix between alternative reserve rescue points and disaster-affected points

Panel point	J1	J2	J2	J4	J5	J6	J7	J8	J9	J10
1	2.44	2.24	3.56	2.26	3.44	2.50	2.23	3.03	0.77	0.73
2	3.67	2.47	3.97	3.21	0.71	1.33	1.98	1.59	3.48	0.84
3	2.13	3.14	1.39	1.53	2.85	3.97	3.33	1.05	3.99	0.93
4	1.97	2.42	3.84	1.85	2.82	2.96	3.03	3.66	1.25	1.02
5	3.07	1.61	4.62	3.25	2.27	3.42	2.85	2.97	3.06	1.46
6	1.13	3.87	2.44	0.96	0.98	2.15	3.87	2.05	1.99	1.42
7	2.06	2.03	2.31	2.61	2.39	0.76	5.98	1.69	2.96	1.13
8	3.37	1.01	2.87	1.47	1.37	3.12	4.69	1.13	1.28	3.34
9	2.32	0.81	3.50	3.39	0.85	1.53	3.06	1.16	1.31	3.38
10	3.18	1.05	2.80	0.76	1.08	1.35	3.51	2.51	0.49	2.71
11	2.86	2.56	2.86	3.69	3.38	2.89	2.68	2.01	2.64	2.25
12	2.35	1.03	3.28	2.20	2.97	2.43	3.51	0.91	1.83	4.01
13	1.22	3.54	3.27	3.42	1.21	2.89	2.81	3.01	1.91	3.11
14	2.62	2.52	3.51	3.73	2.91	2.63	0.77	0.74	2.43	1.32
15	3.34	1.34	3.68	1.36	1.87	2.41	2.79	1.38	3.26	3.45
16	2.49	2.20	3.26	1.78	5.44	2.15	2.54	1.19	1.45	2.76
17	2.60	2.72	3.02	1.95	3.39	2.83	1.50	2.17	2.98	2.26
18	2.83	2.06	2.11	2.89	3.39	2.74	2.58	4.04	2.72	1.44
19	3.37	2.19	0.99	3.13	4.71	3.00	2.90	1.75	0.82	0.95
20	3.67	1.88	1.73	4.75	1.42	1.36	2.34	0.75	2.17	2.47
21	3.20	2.93	0.78	0.81	0.96	1.89	2.68	2.83	0.74	4.01
22	2.24	2.30	2.00	3.14	1.57	0.71	2.22	1.15	2.98	3.73
23	3.47	3.46	3.21	1.50	0.56	3.68	1.69	2.82	1.34	1.78
24	2.69	2.30	3.28	1.37	2.11	1.47	3.57	3.60	2.38	2.55
25	2.31	0.79	1.30	1.32	1.49	1.36	2.97	3.26	3.58	2.78
26	3.08	0.77	1.06	1.48	0.95	3.90	1.50	3.92	1.81	2.14
27	3.29	3.25	2.25	1.93	1.06	1.36	2.39	1.59	2.69	0.73
28	3.66	1.98	2.51	2.53	3.38	3.19	2.84	1.59	2.89	2.48
29	3.71	3.19	1.76	3.12	2.63	2.06	0.79	2.65	1.82	0.79
30	3.25	1.06	1.07	3.18	1.93	2.91	0.79	2.36	2.55	0.83
31	3.94	3.66	1.51	1.55	1.69	2.62	3.41	3.57	1.47	4.74
32	2.94	3.00	2.70	3.84	2.27	1.41	2.92	1.85	3.68	4.43

Table 2 shows the economic cost (c_{ij}) data matrix between alternative reserve rescue points and disaster-stricken points. This information is crucial for decision-makers to calculate the cost of emergency response operations and to determine the optimal location of reserve rescue points in H city.

To address the emergency rescue needs of H city, a total of 7-9 reserve rescue points are selected from the alternative reserve points for calculation. A reasonable P-value needs to be ultimately optimized and selected based on the model to ensure the timeliness and economic cost of emergency response operations.

Assuming that all emergency reserve points are designed in accordance with industry or national standards and are not affected by the disaster, the space distance (s_{ij}) and economic cost (c_{ij}) between every two nodes in the rescue road network can be represented by a 32×10 mathematical matrix. The average rescue speed (v) in the urban road H after a sudden disaster is assumed to be 50 km/h, and the maximum rescue response time (T_0) is set to 1.5 hours. The maximum rescue distance of the rescue point is set to 75 km.

The dual objective programming model constructed in this study utilizes the Dijkstra algorithm to construct the shortest path data matrix and economic cost data matrix from each disaster relief point to each material reserve rescue point. This algorithm calculation can obtain the quantitative relationship between α and Z. The data analysis shows that the trend of change in the timeliness and economy of emergency rescue is consistent with the theoretical analysis trend in Figure 1.

In practical emergency rescue operations, decision-makers can determine the maximum rescue time and economic cost based on the actual rescue scenario. Then, a reasonable range of values for α can be calculated through the algorithm, within which multiple emergency plans can be generated for decision-makers to choose from.

5.2 Result Analysis

When α is set to 0.5, the corresponding disaster demand points for emergency material storage and rescue points, as well as the cost and distance of each storage and rescue point, were obtained. The following conclusions were drawn based on the comprehensive comparison of the results:

(1) If 7 out of 10 backup rescue points are selected, the total emergency cost is 32.63 units, the total distance is 97.85 kilometers, and the comprehensive value is 65.24, as shown in Table 3.

(2) If 8 out of 10 backup rescue points are selected, the total cost is 32.51 units, the total distance is 97.47 kilometers, and the comprehensive value is 64.99, as shown in Table 4.

(3) If 9 out of 10 backup rescue points are selected, the total cost is 32.51 units, the total distance is 97.47 kilometers, and the comprehensive value is 64.99. This conclusion is consistent with the result of selecting 8, as the number of disaster demand points served by the third rescue point is 0 (omitted in the table).

Based on the comprehensive comparison results, it can be concluded that setting up 8 emergency material storage and rescue points in H city is the most reasonable option, with a comprehensive value of 64.99. These points are J2, J4, J5, J6, J7, J8, J9, and J10, as shown in Table 4. This approach can help decision-makers to effectively allocate resources and improve the efficiency and effectiveness of emergency response planning and management in H city.

Table 3. Response zoning, distance, and cost of 7 rescue points and 32 disaster-affected points

Rescue point number	Disaster demand point number	Distance /km	Cost/10000 yuan	Comprehensive value
J2	8, 9, 15, 25, 26	14.16	4.72	9.440
J5	2, 6, 13, 23	10.37	3.46	6.915
J6	7, 22, 24, 32	13.05	4.35	8.700
J7	17, 30	6.85	2.29	4.570
J8	11, 12, 14, 16, 20, 28	21.57	7.19	14.38
J9	10, 19, 21, 31	10.56	3.52	7.040
J10	1, 3, 4, 5, 18, 27, 29	21.29	7.10	14.195
Sum	—	97.85	32.63	65.240

Table 4. Response zoning, distance, and cost of 8 rescue points and 32 disaster-affected points

Rescue point number	Disaster demand point number	Distance /km	Cost/ 10000 yuan	Comprehensive value
J2	8, 9, 15, 25, 26	14.16	4.72	9.440
J4	6, 24	6.98	2.33	4.655
J5	2, 13, 23	7.43	2.48	4.955
J6	7, 22, 32	8.63	2.88	5.755
J7	17, 30	6.85	2.29	4.570
J8	11, 12, 14, 16, 20, 28	21.57	7.19	14.38
J9	10, 19, 21, 31	10.56	3.52	7.040
J10	1, 3, 4, 5, 18, 27, 29	21.29	7.10	14.195
Sum	—	97.47	32.51	64.990

5.3 Analysis

Based on the data presented in Tables 3 and 4, it can be concluded that in the event of a sudden disaster, the workload of each reserve rescue point for rescue and disaster reduction is not evenly distributed. This means that the response relationship between the emergency rescue reserve rescue point and the disaster relief demand point is not evenly distributed. Due to the constraints of timeliness and cost, the number of disaster demand points for rescue point services varies, and the efficiency of disaster relief varies. Therefore, it is important to carefully optimize the zoning of rescue points.

In some cases, it may be necessary to establish a target for the workload of each rescue point. This can be achieved by using Eq. (17) and optimizing the location based on the constructed target model and related algorithms. By doing so, the timeliness and economy of emergency rescue can be better met, and the rescue time, transportation distance, and transportation cost during the emergency rescue process can be reduced to an acceptable range. This approach can provide multiple sets of excellent alternative reserve location plans for urban emergency management decision-makers.

6. Conclusions

In this study, a multi-objective model was established for the location and response scheduling zoning of urban regional rescue material reserve rescue sites, considering the timeliness, economy, and safety of emergency rescue, among other different dimensional goals. An auxiliary decision analysis function was constructed using objective weight factors, and the value of the objective weight factor was gradually changed to search for the scope of the optimal solution. This approach provided multiple location models and response zoning schemes for decision-makers. A numerical example was used to verify the feasibility of the combination model with different target dimensions and the rationality of the selected algorithm.

A heuristic algorithm was used to perform average segmentation calculations on the preset neighborhood, continuously changing and narrowing the neighborhood range before the algorithm termination conditions were met, approaching the domain range of the optimal solution. The algorithm accuracy parameters ε were set to control the accuracy of the final solution's neighborhood range. The example verified the correctness and advantages of the algorithm, as well as the correctness of the solving efficiency and auxiliary function properties. Scientifically selecting 8 reserve points from the alternative reserve rescue points in H city demonstrated the good application prospects of the model and algorithm for selecting the location of rescue points based on multi-dimensional urban rescue material reserves.

Based on multiple different dimensional objectives of rescue material storage and rescue points in urban areas, a multi-objective location planning and coordination optimization problem for material rescue vehicle scheduling and allocation was constructed. This approach is also applicable to optimization problems such as location selection (such as shelters, etc.) and response zoning layout in emergency rescue and disaster reduction operation management, considering different dimensional objective combinations in urban disaster emergencies.

In conclusion, the proposed multi-objective model and algorithm have the potential to optimize the allocation of resources and improve the efficiency and effectiveness of emergency response planning and management in urban areas. Further research can explore the applicability of this approach to other emergency management contexts and expand the range of objectives considered in the decision-making process.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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