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Strategic Distribution of Emergency Resources: A Multi-Objective Approach with NSGA-II and Prioritization of Affected Areas

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Abstract: In recent years, frequent natural disasters and public emergencies have emphasized the importance of emergency material distribution path planning. Aiming at the problems of neglecting the differences in the urgency of the demand at the disaster-stricken points and the lack of distribution fairness in traditional research, this study proposes an emergency material distribution path planning method that integrates the priority assessment of the disaster-stricken points and multi-objective optimization. First of all, a two-level evaluation system is constructed from the dimensions of disaster degree and material demand, including the number of rescue population and other indicators, and the combined weights are calculated by combining the subjective and objective methods of hierarchical analysis (AHP) and entropy weighting, so as to quantify the urgency coefficient of the demand at each disaster site and break through the limitations of the traditional "nearby distribution" mode. On this basis, a vehicle path planning model is established with the dual objectives of minimizing the total distribution cost and vehicle load balance, and the elite strategy non-dominated sorting genetic algorithm (NSGA-II) is introduced to solve the problem. Scenario analysis is carried out with the background of public health emergencies in Jingzhou City, and the effectiveness of the model is verified based on the actual data of 64 medical material demand points. The simulation results show that the total distribution distance and vehicle load balance are optimized after optimization. Finally, it is suggested in conjunction with the current situation of emergency material distribution in China. Through the quantification of demand urgency and multi-objective collaborative optimization, this study provides theoretical basis and practical reference for improving the fairness, timeliness and resource utilization efficiency of emergency logistics, and has important application value for improving disaster relief decision-making.

Keywords: Emergency supplies; NSGA-II; Distribution scheme; Vehicle path planning

1 Introduction

In recent years, a variety of emergencies occur frequently in countries around the world, especially non-climatic and sudden-onset natural disasters may be unpredictable [1], which cause great casualties and economic losses, such as the 2020 New Crown Epidemic, the 2020 Australian forest fires, 2022 Henan Zhengzhou "7-20" special storms, etc. Emergencies have become one of the most pressing major problems in society, which not only cause serious casualties, but also have far-reaching impacts on society and the economy. The frequency of emergencies has become one of the most urgent major problems in the society, which will not only cause serious casualties, but also have a far-reaching impact on the society and economy. Disaster accidents are extremely large-scale events, with the special characteristic of low frequency and sudden tremendous demand for supplies, distinguished from other regular emergency events (e.g., fire stations, medical centers) [2]. Specifically, since 1980, more than 2.4 million people lost their lives to global natural disasters, and the economic losses caused by natural disasters have increased by more than 800% [3], only in 2020, the global losses from 2020 to 210 billion U.S. dollars. In the same year, 138 million people were affected by various natural disasters in China, with 199,577,700 hectares of crops affected, direct economic losses of 370.15 billion RMB, and 591 people lost their lives as a result of the disasters [4]. Although ESC has also played an excellent role in disaster prevention and control, there are still some urgent issues that need to be addressed [5]. Efficient distribution of emergency supplies is the key to meeting the needs of people's survival and life and to reduce disaster losses. Emergency supplies distribution affects the efficiency of the whole emergency response chain, and it is an important link between the affected people and rescue forces. Therefore, we need to make a reasonable allocation of emergency resources and facilities, fully consider the disaster risk of the region, population distribution, transportation conditions and other factors, scientific planning of emergency supplies distribution, to ensure that when a disaster occurs, can carry out rapid and effective rescue, in order to reduce the losses caused by the disaster. Reasonable emergency material distribution plans are the basis for maximizing the safety of people's lives and properties and maintaining social stability and development in the face of emergencies.

Currently, the research on emergency material distribution in the world is relatively mature. Li et al. [6] propose a model that can ensure the fairness of emergency rescue to a certain extent and optimize resource scale while optimizing location. Kemball-Cook and Stephenson [7] pointed out that it is important to establish an emergency management system to carry out emergency rescue operations in a timely and efficient manner. Feng et al. [8] proposes a novel approach based on Multi-Criteria Decision-Making (MCDM) and Geographic Information System (GIS) to solve the ELCs site selection problem. Al Theed and Muaary [9] study not only the distribution of emergency materials but also the evacuation of the injured and the assignment of ambulance personnel from a humanitarian perspective and use split distribution to solve the problem. Barbarosoğlu and Arda [10] considers the uncertainty of supply, demand and road network, and establishes a two-phase stochastic planning model. Weng et al. [11] proposed a hybrid collation programming model with the aim of minimizing the total rescue time from urban distribution centers to temporary distribution stations. Bozorgi-Amiri et al. [12] considered the case of uncertainty in the demand at the disaster site, emergency stockpile centers, and supply, and developed a path optimization model by considering the cost as an uncertain parameter. Florio et al. [13] studied the vehicle path problem with stochastic demand and transportation duration constraints under a given probability and designed new algorithms to solve it. Wang et al. [14] used the WSR methodology as a guide to divide the factors of location selection into "Wuli", "Shili" and "Renli", and proposed the WSR methodology-based multi-criteria decision-making (MCDM) framework for selecting the appropriate location for emergency medical facilities. Bakhshi et al. [15] propose a novel risk-based decision support system for helping disaster risk management planners select the best locations for emergency shelters after an earthquake. Ben-Tal et al. [16] further used the robust optimization theory to quantify the path risk to establish a dual-objective multi-supply positioning-path optimization model and used a genetic algorithm to solve it. Based on AI technology, Xia et al. [17] proposed a novel large-scale emergency medical supply scheduling algorithm to address the problems of inefficient medical supply departures and unbalanced supply point schedules in public health emergencies. Yang et al. [18] proposed a two-stage hybrid component programming model to characterize the location allocation problem in an emergency logistic system to minimize the reduce the total cost.

In summary, most of the existing researches focus on the site selection of the reserve depot and the distribution path selection of emergency supplies, and the research on emergency supplies distribution mainly considers the nearby distribution mode, but less considers the differences of the disaster-stricken points and the extent of the disaster. In this paper, on the basis of considering the differences in the degree of urgency of the demand of each disaster-stricken point, we introduce the parameter of urgency coefficient of the demand of the disaster-stricken point to improve the fairness and reasonableness of the emergency material distribution program, establish a multi-objective emergency material distribution model, and solve it by using the NSGA-II algorithm. The key innovations of this study are highlighted as follows:

• Integration of Priority Assessment and Multi-Objective Optimization. Unlike traditional "nearby distribution" approaches, our method quantifies the urgency coefficient of disaster sites using a hybrid AHP-entropy weighting system, enabling prioritized resource allocation based on disaster severity, material demand, and rescue feasibility.

• Dual-Objective Optimization Model. We simultaneously minimize total distribution cost and vehicle load balance, addressing fairness and efficiency gaps in existing studies.

• Application of NSGA-II with Local Search. We enhance NSGA-II by integrating a 2-opt operator and variable neighborhood search (VNS) to improve convergence speed and solution quality.

2 Demand Point Weighting

When carrying out emergency relief activities, the degree of damage varies from one point of need to another, and the degree of urgency of the emergency needs of each affected area will also be different. In reality, if the amount of materials in the emergency materials reserve is limited, there may be a shortage of materials, in which case the distribution of materials according to the principle of proximity will be unfavorable to the people in the affected areas, who are more severely affected and have more urgent needs. The traffic condition of the disaster-stricken points directly affects the distribution efficiency of emergency supplies. If the roads are seriously damaged and difficult to pass, even if the distance is relatively close, it may be necessary to adjust the distribution priority and give priority to the disaster-stricken points where the traffic is relatively convenient for distribution. Different disaster-stricken points have different types and quantities of emergency supplies. For example, different types of materials such as food, drinking water, and medicine may be urgently needed at the disaster-stricken points, which need to be prioritized according to their specific needs. Therefore, the degree of urgency of the needs of the affected area must be determined, so that emergency supplies can be distributed in a focused and prioritized manner, thus giving full play to the utility of emergency supplies and distributing them in a fair manner.

2.1 Construction of an Indicator System

In emergency disaster relief activities, reasonably determining the weights of demand points is the key to ensuring the efficient allocation of relief resources, so it is necessary to construct a scientific and reasonable indicator system. Factors affecting the degree of urgency of demand at demand points can be divided into two kinds deterministic factors and fuzzy factors. Considering the literature [19] and the literature [20] comprehensively, we establish a system of demand urgency evaluation indexes with the degree of road breakage, the degree of shortage of materials, the demand for materials, the number of affected population, and the loss of the affected emergency as the evaluation indexes. The differences between the indicators are fully considered, and the final weight values are obtained using a combined weight algorithm based on the combination of the hierarchical analysis method (AHP) and entropy weight method. In order to comprehensively assess the priority of the demand points, as shown in Figure 1, we constructed a two-tier indicator system. The first-level indicators include the degree of disaster, the urgency of material demand, the distribution of rescue forces, etc. The selection of the first-level indicators is based on their important influence on the prioritization of the disaster sites. The second-level indicators include the number of people in need of rescue, the number of collapsed houses, the types and quantities of materials in need, and the distribution of rescue teams, etc. The second-level indicators further refine the specific contents of the first-level indicators to make the assessment more precise and comprehensive. By constructing a two-tier indicator system, it can ensure that various factors can be considered comprehensively when prioritizing the demand points, so as to make more scientific and reasonable decisions. This indicator system not only covers the basic situation of demand points but also includes the distribution and utilization efficiency of relief resources, providing a solid foundation for subsequent weight calculation and prioritization.

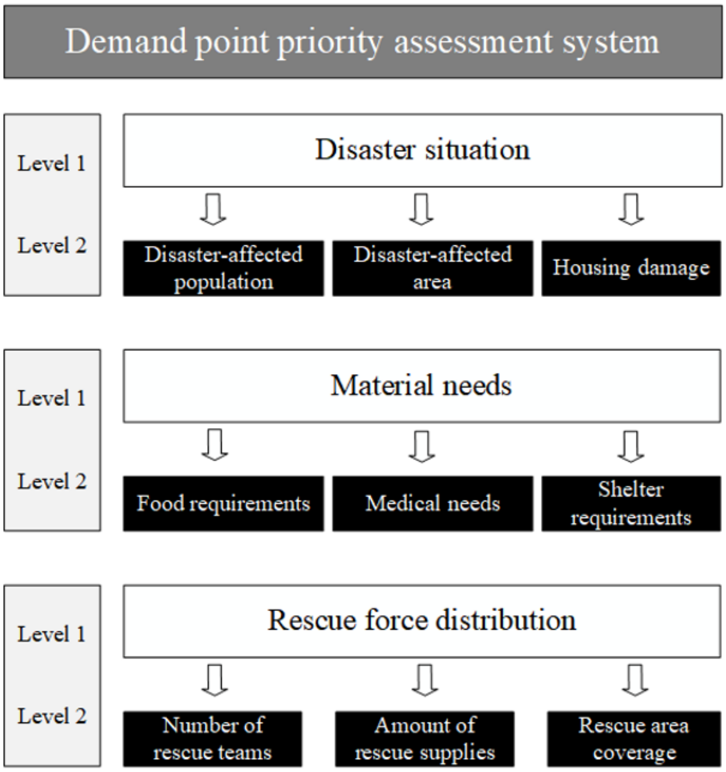

Figure 1. Map of the system for prioritizing and assessing disaster sites

2.2 Calculation of Weights

The relative importance of the indicators was determined by assessing the weights of the first-level indicators using the hierarchical analysis method (AHP). The relative importance of the indicators was determined by constructing a hierarchical model and comparing the indicators in pairs. Experts' relative importance judgments of primary indicators (such as disaster severity and urgency of material demand) are first quantified by constructing a pairwise comparison matrix (Eqs. (1)-(3)), and the weight vector is solved using the eigenvalue method. To ensure the consistency of the judgments, the consistency ratio (CR < 0.1) is further calculated. If the test is failed, the scores are adjusted to eliminate potential contradictions in the experts' subjective perceptions. The entropy weight method focuses on data-driven, objective weight calculation: by normalizing positive/negative indicators (Eqs. (5)-(6)) to eliminate dimensional differences and using the entropy formula (Eqs. (7)-(9)) to assess the information dispersion of secondary indicators (such as the number of people to be rescued and the extent of road damage). The greater the dispersion, the higher the weight. To balance subjective and objective perspectives, a linear combination weighting method (Eq. (11)) is used, with an adjustment coefficient of α = 0.6 (determined through the Delphi method and sensitivity analysis). The subjective weights from AHP and the objective weights from the entropy method are integrated into a 6:4 ratio, which respects expert experience while strengthening data support.

Assuming that the level 1 indicators are, $A_1, A_2, \ldots\ldots, A_n$, construct a pairwise comparison matrix for each indicator A, and construct a pairwise comparison matrix for each indicator A through expert scoring or historical data. For two indicators A_i and A_j, if A_i is more important than A_j, then $a_{ij} > 1$, and vice versa for $a_{ij} < 1$. The judgment matrix A has the following form:

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} \tag{1}$$

The maximum eigenvalue $\lambda_{\max}$ of the judgment matrix A and its corresponding eigenvector are solved using the eigenvalue method, and the weight vector W is obtained after normalization. In addition, the consistency index (CI) and consistency ratio (CR) are calculated to ensure the consistency of the judgment matrix.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{2}$$

$$CR = \frac{CI}{RI} \tag{3}$$

where, RI is the random consistency index, which is found according to the random consistency index table. If $CR < 0.1$, then the judgment matrix has satisfactory consistency, otherwise the judgment matrix needs to be adjusted.

The entropy weight method is used to calculate the weight of each secondary indicator, and the entropy value of each indicator is calculated to determine its weight. First of all, the original data matrix is constructed, assuming that there are m affected points, and each affected point has n indicators, and the original data matrix is constructed Y:

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{bmatrix} \tag{4}$$

Next, the data were normalized to eliminate differences in the scale of different indicators. For positive indicators, the normalization formula is:

$$y_{ij}^* = \frac{y_{ij} - \min(y_{ij})}{\max(y_{ij}) - \min(y_{ij})} \tag{5}$$

For negative indicators, the normalization formula is:

$$y_{ij}^* = \frac{\max(y_{ij}) - y_{ij}}{\max(y_{ij}) - \min(y_{ij})} \tag{6}$$

The entropy value of each indicator is then calculated from the normalized data E_j:

$$E_j = -k \sum_{i=1}^{m} p_{ij} \ln(p_{ij}) \tag{7}$$

where,

$$p_{ij} = \frac{y_{ij}^*}{\sum_{i=1}^{m} y_{ij}^*} \tag{8}$$

$$k=\frac{1}{\ln(m)} \tag{9}$$

Finally, the weight of each indicator is calculated based on the entropy value W_j:

$$W_j=\frac{1-E_j}{\sum_{j=1}^{n}\left(1-E_j\right)} \tag{10}$$

To consider subjective and objective factors comprehensively, the subjective weights obtained by AHP and the objective weights obtained by the entropy weighting method are combined using the combined weighting method. An adjustment coefficient $\alpha\,(0 \leq \alpha \leq 1)$ is set to indicate the degree of trust in subjective opinions. Use the linear combination assignment method to calculate the combination weights:

$$W_{\text{combined}}=\alpha \cdot W_{AHP}+(1-\alpha) \cdot W_{EWM} \tag{11}$$

Among them, W_{AHP} is the subjective weight and W_{EWM} is the objective weight. The combined weights of the indicators provide a scientific basis for subsequent prioritization of disaster sites.

2.2.1 Prioritization of disaster sites

Based on the combination weights, a composite score is calculated for each affected point to prioritize them. The score of each affected point on each indicator is multiplied with the corresponding portfolio weights and summed to obtain the composite score S_i:

$$S_i=\sum_{j=1}^{n} y_{ij}^{*} \cdot W_{\text{combined },j} \tag{12}$$

where, y_{ij}^{*} is the normalized indicator value and $W_{\text{combined},j}$ is the combined weight. The affected sites are ranked according to the combined score S_i, and the higher the score, the higher the priority.

3 Construction of the Model

In this paper, on the basis of determining the priority weight of emergency material distribution at demand points according to the degree of urgency of the demand for emergency materials, a multi-objective model of emergency material distribution is established with the total distribution cost of emergency material distribution vehicles and the load balance of the distribution vehicles as the goal. The problem can be specifically described as a VRP problem in which the demand at each demand point is satisfied, the delivery volume of a single vehicle does not exceed the maximum loading capacity of the vehicle, the demand volume of all orders does not exceed the sum of the maximum loading capacity of all vehicles, the vehicle distribution cost is minimized, and the vehicle load is balanced. The constraints that the delivery weight does not exceed the maximum loading capacity of the vehicle, the starting and ending points are identical, and the demand at each demand point is satisfied need to be considered. Modeling from the actual emergency distribution situation, the following assumptions are made:

1) Distribution centers for emergency supplies are geographically known to the mission point;

2) Distribution of emergency supplies can be mixed into boxes, and there is no taboo on mixing different emergency supplies in boxes;

3) The amount of emergency supplies ordered for each mission site is known;

4) The vehicle loading capacity, number of vehicles, and cost of distribution per vehicle are known;

5) The distribution costs of vehicles are divided into fixed and traveling costs;

6) Requirements per mission point do not exceed the maximum vehicle loading capacity;

7) Does not take into account the diversity of emergency supplies and the diversity of means of transportation.

In addition, the model constraints are as follows, according to the actual situation:

1) The amount of emergency supplies for each mission site must be met;

2) The total order volume of a delivery route does not exceed the maximum loading capacity of the vehicle;

3) The total number of vehicles for distribution cannot exceed the total number of vehicles that can be dispatched from the emergency distribution center;

4) Distribution vehicles depart from the distribution center and return to the center from the last assignment point.

Taking the distribution center as the starting point, the locations of the starting point of the distribution center and the i th task point are indicated by $P_0, P_i(i=1,2,\cdots,N)$, respectively; the demand for emergency supplies at the i th task point is r_i boxes; and the distance between the task point i and j is d_{ij}. The company has a total of L vehicles, and each vehicle has a cost per unit mile traveled of C and a fixed call-out cost of G. The maximum vehicle load is V cases, and each vehicle cannot exceed the maximum load during the distribution process. Each vehicle starts from the distribution center and returns to the distribution center at the end of the distribution, with the same starting and ending points of the vehicles, and the objective is to minimize the total distribution cost of the vehicles and to balance the load of the vehicles. The relevant variables and parameters in the model are defined as follows:

N: Number of mission points;

P_0: Indicates an emergency distribution center, i.e., a driving start and stop point;

P_i: i, j task points;

R_i: Order volume at the i task point;

D_{ij} : Distance from the mission point;

L: Total number of vehicles;

C: Cost per unit mile traveled per vehicle;

C_{ij}: Cost per unit mile traveled from mission point i to mission point j;

G: Fixed call cost per vehicle;

V: Maximum load per vehicle.

Define the 0-1 variables as follows:

$$X_{ij}^l \begin{cases} 1, \text{ denote the } l- \text{ th vehicle's movement from task point i to task point } j \\ 0, \text{ otherwise} \end{cases}$$

After specifying the model objectives and constraints, its objective function can be expressed as follows:

Objective function 1:

$$\min Z = \sum_{l=1}^{L} \left[\left(\sum_{i=0}^{N} \sum_{j=0}^{N} X_{ij} C_{ij} D_{ij} \right) + G \right] \tag{13}$$

Objective function 2:

$$\min W = \max_{l=1}^{L} \sum_{i=0}^{N} \sum_{j=1}^{N} D_{ij} \cdot x_{ij}^l \tag{14}$$

The constraints are as follows:

$$\sum_{j=0}^{N} \sum_{l=1}^{L} X_{ij} = 1 \quad i \in \{1, 2, \cdots, N\} \tag{15}$$

$$\sum_{i=0}^{N} \sum_{l=1}^{L} X_{ij} = 1 \quad j \in \{1, 2, \cdots, N\} \tag{16}$$

$$\sum_{i=0}^{N} X_{ij} - \sum_{i=0}^{N} X_{ji} = 0 \quad j \in \{1, 2, \cdots, N\} \quad l \in \{1, 2, \cdots, L\} \tag{17}$$

$$\sum_{i=1}^{N} X_{0i}^l = \sum_{j=1}^{N} X_{0j}^l \leq 1 \quad l \in \{1, 2, \cdots, L\} \tag{18}$$

$$\sum_{i=0}^{N} \sum_{j=0}^{N} r_i X_{ij}^l \leq V_l \quad l \in \{1, 2, \cdots, L\} \tag{19}$$

$$\sum_{j=0}^{N} X_{0j}^l \leq L \quad l \in \{1, 2, \cdots, L\} \tag{20}$$

The above model is explained below:

Eq. (13) is the objective function 1 of the model, which is to find the minimum value of the total cost of distribution, the first term is the cost of driving the vehicle, which is linearly related to the distance traveled, and the second term is the fixed cost of calling the vehicle;

Eq. (14) is the objective function of the model.2 The load balancing objective is to make the distribution load of each vehicle relatively uniform, i.e., to ensure that there is little difference in the distance traveled by all vehicles. Load balancing is achieved by minimizing the maximum difference in distance traveled by vehicles.

Eq. (15) and Eq. (16) indicate that each mission point can only be serviced once, and Eq. (15) indicates that a vehicle can only exit a mission point once; Eq. (16) indicates that each mission point can only be accessed by one vehicle;

Eq. (17) indicates that the vehicle must leave after it has finished delivering to a particular task point;

Eq. (18) indicates that all vehicles start from the distribution center and all return to the starting point after the distribution is completed, i.e., the vehicles have the same starting and stopping points, which is a closed-loop route;

Eq. (19) indicates that the sum of the emergency supply order requirements for the mission points on each distribution route is not greater than the maximum load capacity of the vehicles on that route;

Eq. (20) indicates that the number of vehicles departing from the distribution center is not greater than the total number of vehicles that can be dispatched from the emergency distribution center.

4 NSGA-II

The research of this paper is a multi-objective optimization problem, for the multi-objective optimization problem, this paper chooses the Non-dominated Sorting Genetic Algorithm with Elite Retention Strategy (NSGA-II) to solve the model. This algorithm enables the genetic evolution of elite individuals, which has better convergence and stability compared with traditional genetic algorithms [21] and is also superior in terms of performance, with good convergence and robustness. The basic idea of NSGA-II can be described as follows: generate an initial population randomly, and obtain the offspring population through selection, crossover and mutation operations after non-dominated sorting; connect the parent population merged with the child population to perform fast non-dominated sorting, and the congestion is performed on the sorted individuals, and a new parent population is selected and generated according to the non-dominated relationship and the congestion degree of the individuals; the above two steps are repeated until the end condition is satisfied. The program flow of NSGA-II is shown in Figure 2.

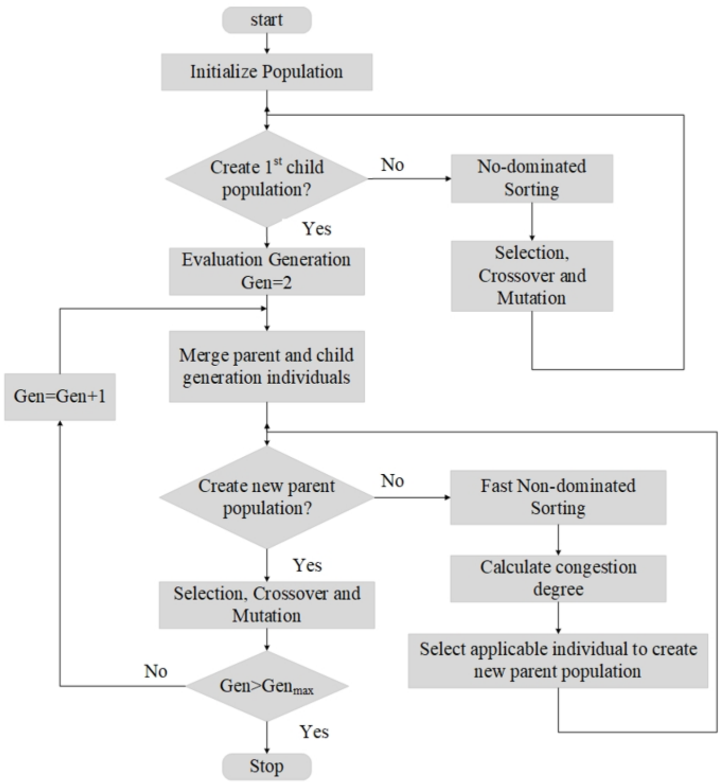

Figure 2. Program flow chart of NSGA-II

The first step is coding and initial program design. Real number coding was chosen to randomly generate the initial population. In our approach, real-number encoding is used to represent vehicle routes, ensuring a smooth and continuous representation of the solution space.

In the second step, the crowding degree is calculated. First, the nondominated class is calculated based on the objective function value of each individual, and then the crowding degree is calculated for each class of individuals.

The crowding degree of an individual X in a non-dominated class shows how crowded its neighborhood is. The calculation of the crowding degree helps keep the population diverse. Individuals with a higher crowding degree are more likely to be chosen for the next generation because they are in less crowded areas of the solution space. This promotes exploration and stops the algorithm from quickly converging to a sub-optimal solution.

The third step is the genetic operation. For selection, we employ tournament selection based on Pareto rank and crowding distance, which helps maintain diversity and ensures that individuals with better trade-offs between objectives are chosen for reproduction. The crossover operation is based on sub-path crossover, a method designed to preserve the continuity of the vehicle routes, thereby maintaining the feasibility and integrity of the solution. For mutation, we incorporate two distinct operators: 2-opt, which performs local optimization to refine the routes, and Variable Neighborhood Search (VNS), which facilitates global exploration by avoiding local optima and exploring diverse solution spaces. The 2-opt optimization operator improves the convergence speed and then adds the variable neighborhood intelligent search algorithm to converge to the global optimal solution quickly.

The fourth step is parameter design. To justify the parameters used in NSGA-II, we selected a population size of 50 and set the number of iterations to 120. These values strike a balance between computational efficiency and solution quality, allowing the algorithm to converge within a reasonable time while maintaining the quality of the solutions. When compared to traditional Genetic Algorithms (GA), NSGA-II demonstrates superior performance in terms of convergence. This is primarily due to the use of elitism, which retains the best solutions over generations, and the preservation of diversity, which helps the algorithm avoid premature convergence. Overall, NSGA-II proves to be a more effective approach for solving the multi-objective optimization problem in vehicle routing.

5 Scenario Response Analysis

5.1 Scenario Construction

Based on the characteristics of major public health emergencies, medical supplies are needed at the point of need in all areas of the city. Emergency medical supplies are characterized by the joint participation of government and social resources, such as social fund-raising and assistance from provinces and other countries. Distribution centers for supplies are usually established. The local government may select a fire and rescue detachment to transport emergency medical supplies from the distribution center to each demand point and then return to the distribution center. The location of the demand point and the need for medical supplies are known. Considering the constraints such as the load of the distribution vehicle, the distribution time window and the urgency of the demand for medical supplies, the distribution path is rationally optimized, while minimizing the total distribution cost. The distribution path of emergency medical supplies in the medical distribution network is shown in Figure 3.

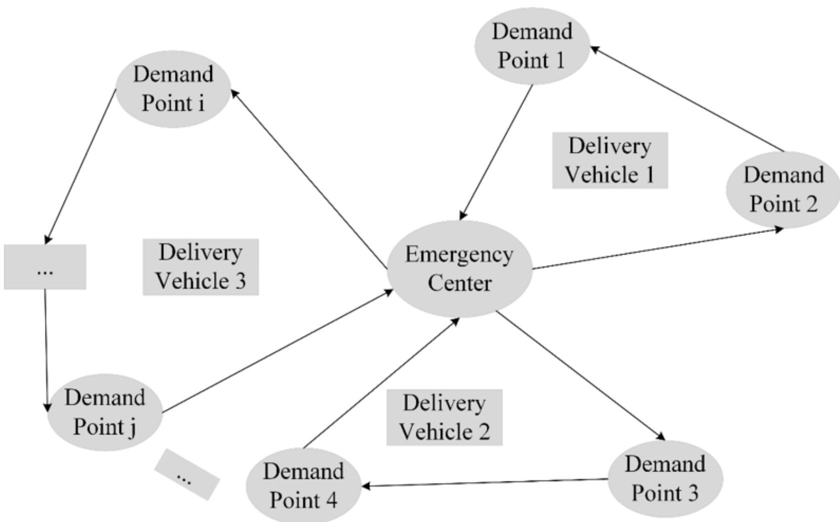

Figure 3. Emergency medical supplies distribution path

Assuming that after a major public health emergency occurs in Jingzhou city, the relevant departments of the local government react quickly and count the disaster information in each jurisdiction of the city in a timely manner, with reference to the scale of medical treatment, geographic location, and medical supplies in each jurisdiction of the city, which will be divided into 64 medical supplies demand points, and formulate a scientific distribution program for the medical supplies. Some of the raw data of the 64 medical supplies location information is shown in Table 1. For data sources, the geographic coordinates of demand points are extracted from the Jingzhou City GIS, ensuring accurate spatial distribution.

Table 1. Selected location information data for medical supplies

Serial Number	Distribution Point	Longitude and Latitude	Serial Number	Distribution Point	Longitude and Latitude
0	Jingzhou Rescue Detachment	112.233314, 30.331995	6	Jingzhou Hospital of Traditional Chinese Medicine	112.273529, 30.310358
1	Jingzhou Central Hospital	112.193479, 30.353793	7	People's Government of Shad City	112.252005, 30.326651
2	Jingzhou First People's Hospital	112.259461, 30.310805	8	Jingzhou Public Security Bureau, Shashi City Branch	112.241859, 30.332731
3	Jingzhou Second People's Hospital	112.252927, 30.319777	9	Jingzhou Fire and Rescue Detachment Shacheng District Brigade	112.270574, 30.308372
4	Jingzhou Municipal Public Security Bureau Jingzhou District Branch Bureau	112.188897, 30.353016	10	Lixin Pharmacy	112.203961, 30.352921
5	Jingzhou Third People's Hospital	112.300949, 30.284137	11	Jingbei Road Pharmacy	112.191422, 30.356771

Jingzhou Rescue Detachment as the emergency material reserve depot and vehicle starting and ending points, through the literature research and expert evaluation of the way to get the evaluation index data of the demand point, which the degree of shortage of materials data by the expert evaluation of the evaluation level of very serious, serious, general, light and very light, this paper was used 9, 7, 5, 3 and 1 will be transformed into the weight of each demand point, Table 2 for the part of the evaluation of the demand point. Through the method of 2.2, we can get the demand urgency coefficient value of each demand point, as shown in Table 3.

Table 2. Selected point-of-need evaluations

Demand Point	Level of Material Shortages	Material Requirements	Number of People to be Rescued/Person	Economic Support Required/ $10,000
Jingzhou Central Hospital	9	147.5	800	500
Jingzhou First People's Hospital	9	32	800	480
Jingzhou Second People's Hospital	5	27	700	230
Jingzhou Third People's Hospital	5	37	125	50
Jingzhou Hospital of Traditional Chinese Medicine	7	85	150	175
Jingzhou Fire and Rescue Detachment Shacheng District Brigade	3	12	100	40

Table 3. Demand urgency factors for selected distribution points

Demand Point	Demand Point Urgency Factor
Jingzhou Central Hospital	0.124
Jingzhou First People's Hospital	0.113
Jingzhou Second People's Hospital	0.111
Jingzhou Third People's Hospital	0.11
Jingzhou Hospital of Traditional Chinese Medicine	0.113
Jingzhou Fire and Rescue Detachment Shacheng District Brigade	0.107

There is only one type of distribution vehicle, Wuling LZW6443BTY, with a total of 10 vehicles, each with a maximum load capacity of 500kg; each vehicle costs $1 per kilometer for fuel; each driver of is paid $150 per day, while there are also $10 loading and unloading handling costs when unloading; the emergency response center needs to lose $20 for the maintenance and depreciation of the vehicle for each vehicle issued. This choice aligns with China's grassroots emergency logistics standards and avoids delivery delays from overloading. Cost parameters are based on the 2022 Hubei Province emergency logistics survey, ensuring realistic economic assumptions. The 63 demand points are all in Jingzhou District and Shashu City District of Jingzhou City, which have a larger flow of people than other counties and districts and are distributed once a day. The geographic locations of the emergency response center and the demand points are shown in the preceding section.

5.2 Distribution Path Results

Combining the previous model and related parameters, NSGA-II is used to solve the vehicle path optimization problem by setting the parameters, cross probability of 0.9, variance probability of 0.05, initial population size of 50, and the number of iterations is 120. The results of running the iterations on a laptop with the operating system Windows 10 using PyCharm software are shown in Figure 4 and Figure 5. To verify the superiority of the proposed NSGA-II algorithm, we conduct a systematic experimental comparison with the traditional Genetic Algorithm (GA) in emergency-material path-planning scenarios. In the experimental design, the traditional GA uses a single-objective optimization framework, minimizing total distribution cost, with solutions generated via roulette-wheel selection, single-point crossover, and random mutation. Parameters are uniformly configured in Python 3.9: a population size of 50, 120 maximum iterations, crossover probability of 0.9, and mutation probability of 0.05, ensuring a fair comparison. The results obtained by using the traditional Genetic Algorithm are shown in Figure 6 and Figure 7.

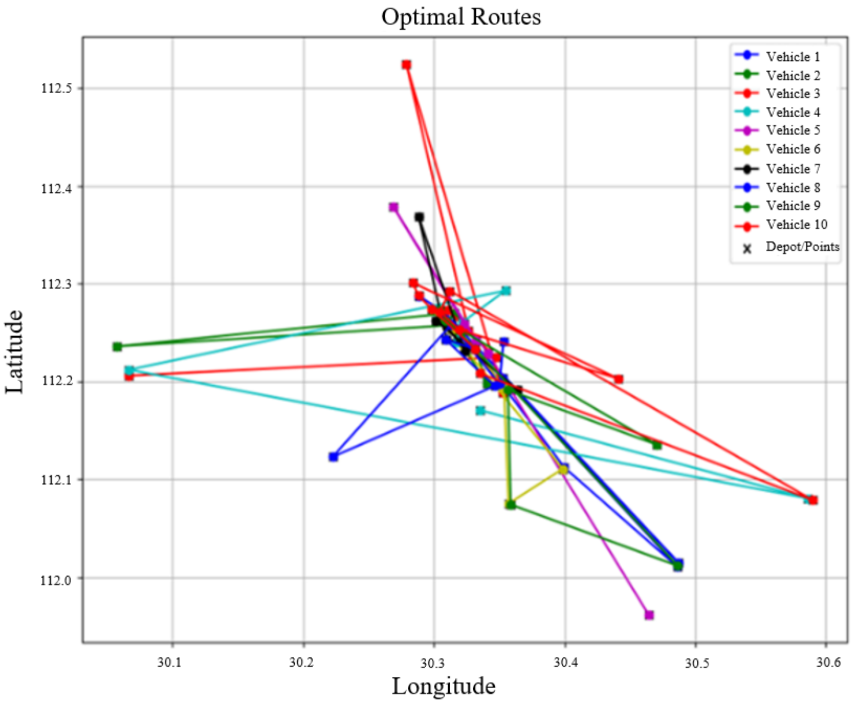

Figure 4. Graph of optimal distribution scheme of NSGA-II algorithm

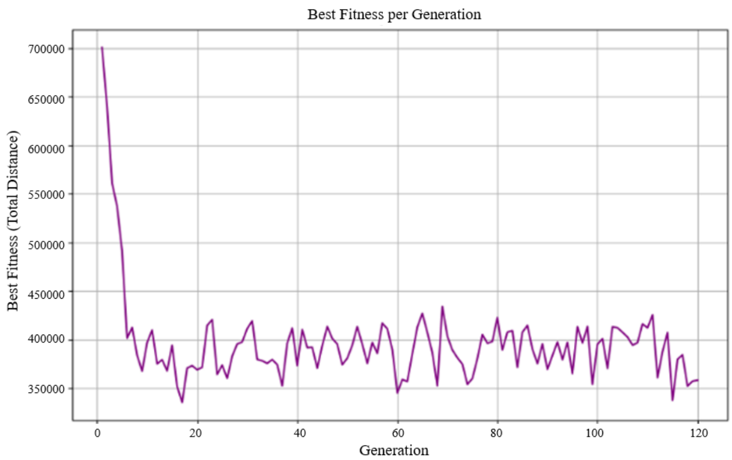

Figure 5. Iterative process of NSGA-II algorithm

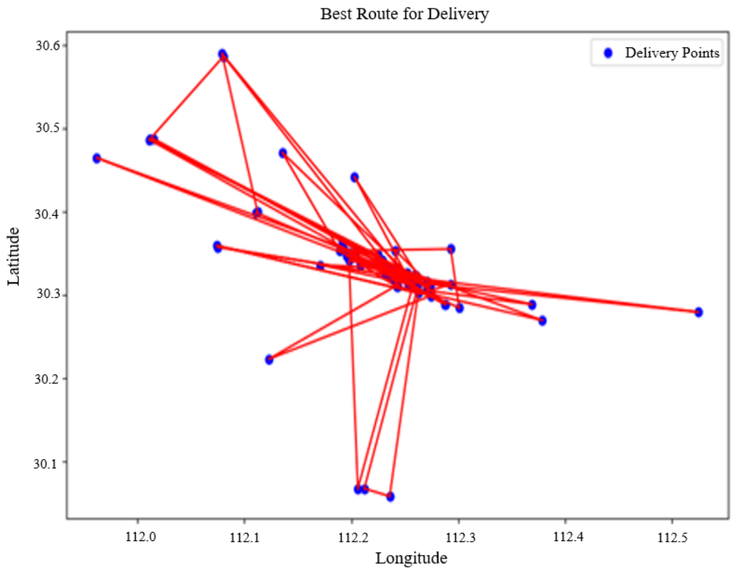

Figure 6. Graph of optimal distribution scheme of GA algorithm

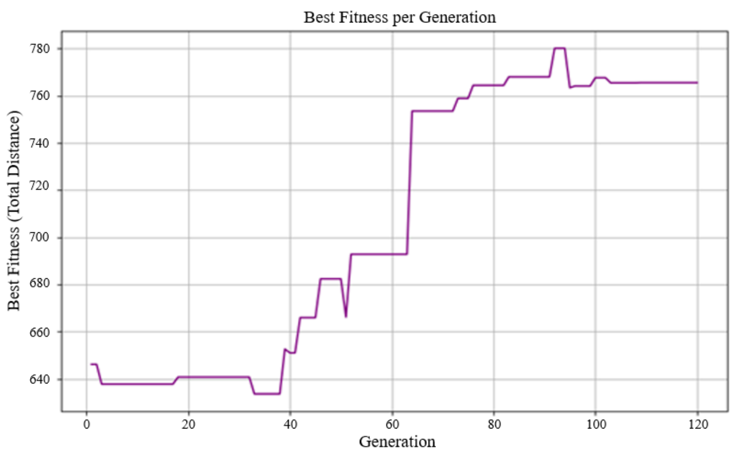

Figure 7. Iterative process of GA algorithm

Total distance: 357933.58330581436 m
Vehicle 1 Path: [0, 60, 38, 10, 34, 9, 57,0]
Vehicle 2 path: [0, 19, 2, 35, 48, 17, 41,0]

Vehicle 3 Path: [0, 4, 28, 7, 6, 59, 16,0]
Vehicle 4 Path: [0, 21, 37, 62, 30, 54, 20,0]
Vehicle 5 Path: [0, 45, 8, 33, 61, 52, 27,0]
Vehicle 6 Path: [0, 1, 39, 44, 13, 14, 23,0]
Vehicle 7 Path: [0, 18, 36, 63, 12, 26, 22,0]
Vehicle 8 Path: [0, 58, 29, 43, 46, 31, 53,0]
Vehicle 9 Path: [0, 55, 50, 11, 42, 47, 15,0]
Vehicle 10 Path: [0, 25, 56, 5, 32, 3, 51, 40, 49, 24,0]
The results of the runs were organized and the results are shown in Table 4.

Table 4. Emergency material distribution routes and costs

Traffic	Travel Route	Traveling Distance/m	Transportation Cost/$
1	$0, 60, 38, 10, 34, 9, 57, 0$	84130.21769770086	251
2	$0, 19, 2, 35, 48, 17, 41, 0$	12653.09768852364	183
3	$0, 4, 28, 7, 6, 59, 16, 0$	44996.118692755656	215
4	$0, 21, 37, 62, 30, 54, 20, 0$	24564.511352393623	195
5	$0, 45, 8, 33, 61, 52, 27, 0$	26987.49534519012	197
6	$0, 1, 39, 44, 13, 14, 23, 0$	17314.11398193529	187
7	$0, 18, 36, 63, 12, 26, 22, 0$	44254.95983724478	214
8	$0, 58, 29, 43, 46, 31, 53, 0$	23385.17003138485	193
9	$0, 55, 50, 11, 42, 47, 15, 0$	39300.58942710399	209
10	$0, 25, 56, 5, 32, 3, 51, 40, 49, 24, 0$	53165.49531803529	223

Table 5. Comparison between NSGA-II algorithm and GA algorithm

Indicator	NSGA-II	GA	Improvement Rate
Total distribution distance (m)	357933	765588	53%
Total Distribution Cost ($)	2067	2728	32%

From Figure 4, it can be seen that the NSGA-II algorithm can converge quickly in the beginning stage and find a relatively better solution, although it falls into fluctuation in the later stage, which makes it difficult to further reduce the optimal fitness, and needs to be further optimized for convergence and stability, but it still achieves a certain degree of optimization compared to the initial higher value, and obtains a relatively better solution. The transportation cost of each vehicle is obtained from Table 4 and it can be observed that the transportation cost of each vehicle does not differ much, i.e., the load balancing of vehicles has also achieved relatively good results, which verifies the effectiveness of the algorithm. From Table 5, it can be seen that the NSGA-II algorithm significantly reduces the distribution distance and total distribution cost. Moreover, the results indicate that the NSGA-II, through its multi-objective optimization and diversity-preservation mechanisms, has achieved two major breakthroughs: Global optimization - It avoids the premature convergence problem of the traditional Genetic Algorithm (GA) caused by focusing on a single objective; Decision - making flexibility - Its Pareto front contains various trade-off solutions between cost and load balance, enabling emergency commanders to dynamically adjust strategies according to real - time disaster situations. In summary, NSGA-II outperforms traditional GA in these aspects.

At the same time, our research also has certain limitations. In practical applications, obtaining real-time data is crucial for optimizing the distribution routes of emergency supplies, but it often poses difficulties. To address this issue, it is recommended to construct a local database that includes static data such as the geographical locations of each demand point and the demand for supplies. Additionally, a data sharing mechanism should be established with traffic management departments, meteorological departments, etc., to obtain real-time traffic conditions and weather information. Meanwhile, leveraging Internet of Things (IoT) technology and mobile communication networks, GPS and sensors should be equipped on distribution vehicles to transmit dynamic data such as the vehicle's location, driving speed, and load in real-time, enabling full-process monitoring of the distribution process.

Regarding the problem of dynamically changing traffic conditions, it is recommended to reserve a certain proportion (such as 10%-15%) of alternative routes during route planning and establish a mechanism for real-time updates of traffic information. By collaborating with traffic management departments and map service providers, traffic condition information should be updated every 15 to 30 minutes. Prediction algorithms should be used to forecast traffic flow, accident risks, etc., and adjust the distribution routes in advance. Furthermore, an emergency response mechanism should be established. In the event of sudden traffic control, natural disasters, or other situations that render roads impassable, the alternative routes should be immediately activated or new routes should be replanned to ensure the smooth completion of the distribution tasks.

6 Conclusions

This study constructs a priority evaluation system for demand points, determines the weights of demand points by combining the Analytic Hierarchy Process (AHP) and the entropy weight method, establishes an emergency material distribution path planning model with the goals of minimizing the total distribution cost and balancing the vehicle load, and uses the NSGA-II algorithm to solve it. This effectively optimizes the emergency material distribution path and improves the distribution efficiency and fairness. However, this study still has certain limitations, which point out the direction for future research. In terms of algorithm optimization, although the NSGA-II algorithm has achieved certain results in this study, it fluctuates in the later stage of convergence, making it difficult to further reduce the optimal fitness. The stability and adaptability of the algorithm still need to be improved. Future research can consider introducing an adaptive parameter adjustment mechanism, enabling the algorithm to dynamically adjust parameters according to the complexity of the problem and changes during the solution process, and enhancing the performance of the algorithm. At the same time, improve the local search strategy, for example, combine it with more efficient neighborhood search algorithms to improve the algorithm's ability to search for the optimal solution and enhance the convergence and stability of the algorithm. In terms of the transformation to practical applications, the results of this study need to be further implemented in practice. In the future, in-depth cooperation with government departments can be carried out to conduct practical case studies. By participating in real emergency material distribution scenarios, the effectiveness of the model and algorithm can be tested, and the model can be adjusted and improved according to the actual situation to make it more suitable for practical needs. In addition, developing corresponding decision support systems is also an important future research direction. This system can integrate various types of emergency material data, geographical information, traffic conditions, etc., and use the models and algorithms of this study to provide real-time distribution path planning and decision-making suggestions for emergency commanders, improving the efficiency and accuracy of emergency responses. The following are our recommendations for the distribution of emergency supplies.

1) Building an informatization platform

At present, China's emergency logistics system is deficient in disaster response. Although relevant science and technology are constantly developing, the existing early warning systems for various disasters are slow to respond due to unpredictability and the outstanding characteristics of unpredictability and complexity of earthquakes and other natural disasters [22]. In the disposal of public emergencies, the low level of informatization often leads to difficulties in efficiently coordinating material requirements, capacity deployment, command and coordination, and information docking. Informatization platform can use the Internet of Things and other technologies to balance and schedule resources in each link, to achieve the overall improvement of the efficiency of management synergy, to ensure that the procurement of materials, transportation, storage, loading and unloading, handling, packaging, and distribution activities are carried out smoothly, and to respond quickly to emergency needs. And most pharmaceutical enterprises only through the traditional information management system and personnel management, resulting in low information processing efficiency, difficulty in carrying out real-time monitoring of data, information technology construction lags behind, and difficulty for the city's nearly 1,000 logistics enterprises to provide a centralized development and integration platform. The overall level of informatization still has high room for improvement, and it is necessary to build a modern information platform to promote the development of pharmaceutical logistics in Jingzhou City. The information platform is not only part of the emergency management system, but also an important link between disaster relief and disaster reduction [23], the key point of effective rescue is to rationally design the vehicle routes and determine the amount of emergency supply and path optimization as a key component of the optimization algorithm, focusing on planning the best driving path for the vehicle, which is expected to be significantly improved [24].

2) Building an emergency management system

China is one of the countries with the most serious natural disasters in the world, and various types of natural disasters such as earthquakes, floods, and typhoons occur frequently. After a disaster occurs, the disaster environment system, the disaster-causing factor system and the disaster-affected system are coupled with each other, and this interconnection triggers a series of chain reactions, forming a continuous or concurrent disaster chain [25]. At the same time, all kinds of hidden accidents and security risks are intertwined and overlapped, and incidents such as mine accidents, chemical explosions, and traffic accidents are prone to occur more and more frequently, and public security is facing increasing risks. In this context, the construction of a perfect emergency management system is particularly important. Emergency management systems can effectively enhance the prevention, response and recovery capabilities of various types of disasters and accidents, and minimize casualties and property losses. For different types of emergencies, such as earthquakes, floods, epidemics, etc., a detailed and targeted emergency plan should be developed. The emergency response process should be clearly defined in the plan, including key links such as material demand assessment, deployment orders, distribution task allocation, etc., and the division of responsibilities among departments and personnel should be determined, so as to avoid confusion caused by unclear responsibilities.

A sound emergency management system not only helps to improve the scientific nature of the government's emergency decision-making, the rationality of resource deployment and the efficiency of departmental coordination, but also enhances the emergency response capability of society as a whole. In logistics operations, all parties involved should communicate regularly and share information freely to ensure that they are on the same page and working towards the same goals. Integration of logistics, management and technology is critical, meaning that logistics operations should be guided by management strategies and supported by technological approaches [26]. Through this integration, optimal allocation and efficient use of resources can be achieved. Thus, rapid response and precise deployment can be achieved in the event of a disaster to guarantee the timely supply of emergency supplies and maintain social stability and the safety of people's lives and property.

3) Material stocks and procurement

Material stockpiling and procurement play an irreplaceable and crucial role in emergency management and are the core links in safeguarding people's lives and property, maintaining social stability and effectively responding to emergencies. A scientific and reasonable material stockpiling and procurement strategy can target the stockpiling of corresponding materials according to the disaster risk characteristics of different regions, and ensure that appropriate material support can be provided quickly in all kinds of disasters and emergencies. The establishment of an emergency material reserve and the signing of long-term procurement agreements with reliable suppliers are key measures to ensure the stability of material supply. In the event of disruption of supply channels or emergencies, the emergency stockpile can provide the necessary buffer to ensure the continued supply of essential materials. At the same time, long-term suppliers are able to respond quickly in emergencies and replenish the stockpile in a timely manner, thus reducing the negative impact of supply disruptions.

Especially in the face of emergencies such as public health events, natural disasters, or pandemics, safeguarding the public's food supply and food safety has become a top priority. Fresh produce, due to its short shelf-life and perishability, places greater demands on the timeliness and efficiency of the supply chain. It is therefore important to ensure that fresh produce can be distributed from storage centers to distressed populations in the shortest possible time. For example, studies on the rapid distribution and accurate delivery of emergency supplies during public health events have shown that efficient supply chain management is essential for securing the basic livelihoods of residents [27]. The supply of emergency fresh produce not only meets the daily needs of residents but also stabilizes social sentiment and enhances the public's sense of security during a crisis.

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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 no conflict of interest.

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