Emergency Logistics Vehicle Routing Optimization Model under Uncertain Environment

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Abstract. Against the background of public health events, in the face of demand uncertainty, it is necessary to rationally plan emergency logistics routes to ensure the timely delivery of supplies to disaster-affected areas. Taking a certain area in Wuhan during the epidemic as an example, it was found that there was a lack of reasonable planning for emergency material routes, and the urgency of service at disaster-affected points was not considered during material distribution. An analysis of demand urgency was conducted to address this issue, and a service urgency model was constructed. Simultaneously, a linear goal planning model was established with vehicle distance cost, penalty cost, and fixed operating cost as the objective functions, and with constraints such as vehicle load capacity, delivery time windows, and material demand urgency. The genetic algorithm was employed to solve the model. An example was used to demonstrate the effectiveness of the vehicle routing model considering the urgency of emergency material services.

Keywords: Emergency Logistics, Demand Urgency, Path Optimization.

1 INTRODUCTION

When uncertain situations such as natural disasters and public health incidents occur, the primary task of emergency rescue is to timely deliver rescue materials to the affected areas, to protect the lives and health of the people. In emergencies, the rescue center has limited supplies and often cannot meet the needs of all affected areas at the same time. The delivery process does not consider the urgency of emergency material needs in the affected areas, and transportation routes lack reasonable planning, which to some extent affects the efficiency of rescue efforts in the affected areas. Post-disaster rescue faces the dual pressure of tight material and transportation flows, resulting in an urgent need for medical rescue and daily necessities in the disaster area in a short period.

Domestic and foreign scholars have conducted relevant research on this, and in uncertain emergency environments, material distribution should consider factors such as time windows, priorities, and paths [1]. based on the uncertainty of post-disaster demand. An open emergency material vehicle routing model was established under the

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constraints of fuzzy demand and time window [2]. A new standard for measuring fairness in material distribution has been established based on the proportion of distribution to demand [3]. Considering the need to minimize delivery time when distributing emergency supplies to various disaster-stricken areas in reality, a time window delay delivery penalty mechanism has been added [4]. A multi-objective optimization model was established based on uncertainty theory with the objectives of minimizing total cost and maximizing demand impact rate [5]. and then the vehicle path planning model was solved using a genetic algorithm [6]. Through sorting, it is found that there are many studies on emergency logistics both domestically and internationally, but there is relatively little research on the urgency of demand point services [7]. Therefore, this article focuses on analyzing the urgency of emergency material services in disaster-stricken areas under different service urgency environments, establishing an emergency vehicle path model to optimize the distribution path.

2 ANALYSIS OF SERVICE URGENCY AT DISASTER-AFFECTED POINTS

2.1 Problem Description

In reality, there are differences in the degree of disaster at each disaster-affected point. If material allocation is only based on the demand situation of medical material demand points, it may lead to wrong decisions. Under limited conditions, it is necessary to consider the urgency of emergency material demand. When distributing emergency supplies, it is mainly within a limited area, and the distribution process mainly relies on the driver's familiarity with the roads, which may easily lead to problems such as detours and convection transportation and the path needs to be planned reasonably [8].

2.2 Analysis of Service Urgency Based on Analytic Hierarchy Process

Due to the different situations in each disaster-stricken area, it is necessary to comprehensively consider personnel, materials, and equipment to analyze the urgency of demand to meet emergency needs. The Analytic Hierarchy Process is used to rank and analyze the service urgency. Based on Baidu Baike and the Hubei Provincial Health Commission, the data for this region is shown in Table 1. (Among them, material shortages 5,3,1 are the results of quantifying the data)

Table 1. Basic Information of Disaster Affected Areas

Point	Position	Number of Infected	Number of Medical Staff	Supply Shortage	Open Beds
1	11,43	582	685	5	720
2	9,22	115	415	3	122
3	11,33	389	688	3	389
4	14,27	504	448	5	504
5	10,13	434	386	3	430

6	13,12	196		387	1	196
7	16,33	463		368	3	405
8	10,30		303	264	1	304
9	10.18		347	476	1	340
10	22,27		102	380	1	120
11	9,34		521	553	5	521
12	18,1		318	500	3	300

Using the analytic hierarchy process [9], a structural model is established, and a judgment matrix is constructed using the exponential scaling method. After standardizing and determining the index weights, a consistency check is performed. The results in Table 2 reveal that the degree of material shortage and the number of infected individuals have significant weights, exerting a crucial influence on material allocation.

Table 2. Weights of Various Indicators

Target layer	Criterion layer		Indicator layer		Total weight
	content	weight	content	weight	
Urgency influencing factors	Personnel	0.44	Infrastructure	0.71	0.3124
			Number of medical staff	0.29	0.1276
	Material reserves	0.36	Material shortage	1	0.36
	Infrastructure	0.2	Number of beds invested	1	0.2

The final weight W obtained is $\{0.31, 0.13, 0.36, 0.2\}$

2.3 Evaluation of Service Urgency at Disaster-Affected Points

Analyze the results of section 2.2 using the TOPSIS method [10] and calculate the service urgency of each affected point.

Step 1 Standardize the evaluation indicators, which represent the normalized value, as shown in Equation (1)

$$C_{ij} = \frac{X_{ij}}{m(X_j)} \tag{1}$$

Step 2 Multiply C_{ij} by the indicator weight W to construct a weighted decision matrix R_{ij}, Equation (2)

$$R_{ij} = C_{ij} \times W_j \left(i = 1, 2, \cdots n; j = 1, 2 \cdots m\right) \tag{2}$$

Step 3 Determine the positive and negative ideal solutions, R^+, R^- Equations (3) and (4)

$$R^+ = \left(R_1^+, R_2^+, \cdots R_m^+\right), R_j^+ = \max_i R_{ij} \tag{3}$$

$$R^+ = \left(R_1^+, R_2^+, \cdots R_m^+\right), R_j^+ = \max_i R_{ij} \tag{4}$$

Step 4 Calculate the distance from each evaluation objective to the positive and negative ideal solutions, using Equations (5) and (6)

$$d_i^+ = \sqrt{\sum_{j=1}^{m}\left(R_{ij} - R_j^+\right)^2} \tag{5}$$

$$d_i^- = \sqrt{\sum_{j=1}^{m}\left(R_{ij} - R_j^-\right)^2} \tag{6}$$

Step 5 calculates the distance between each evaluation objective and the ideal solution as the urgency value of the demand, using Equation (7)

$$\zeta_i = \frac{d_i^-}{d_i^+ d_i^-} \tag{7}$$

The ranking results of the service urgency of the disaster-stricken areas have been calculated, as shown in Table 3.

Table 3. Ranking of Service Urgency in Disaster stricken Areas

Point	Urgency	Ranking
1	0.998	1
2	0.301	10
3	0.543	4
4	0.814	3
5	0.387	7
6	0.345	8
7	0.401	7
8	0.252	11
9	0.31	9
10	0.051	12
11	0.848	2
12	0.455	5

3 VEHICLE PATH PLANNING MODEL

3.1 Related Assumptions

Emergency logistics has the characteristics of suddenness and urgency. In uncertain environments, a constrained emergency material vehicle routing model based on demand urgency also needs to consider time window constraints, with the main goal of improving material supply rate, action timeliness, and reducing disaster losses as much as possible. The relevant assumptions are as follows:

1) Given the number of vehicles and their loading capacity, each disaster site can only have one vehicle serving.

2) All vehicles must return to the distribution center after completing the delivery task.

3) Taking disinfectant as an example for emergency supplies, the geographical location and quantity of goods at each demand point are known.

4) The vehicle is traveling at an average speed of 30km/h, without considering special circumstances such as vehicle malfunctions.

3.2 Model Construction

The initial service time of the emergency distribution center is 0, and it is required to deliver the materials to the disaster site within 2 hours, with a loading and unloading time of 0.5 hours after the materials arrive. When designing vehicle paths, consideration is given to the fairness of material supply at each disaster site. If rescue vehicles fail to arrive at the disaster site in a timely manner within the specified time, corresponding penalty costs will be incurred. The specific penalty costs are as follows:

$$P(i) = \left(t_i^a / t_i\right)^2 \tag{8}$$

The vehicle path planning model established in this study is shown in equations (9) - (18), with symbols explained in Table 4.

$$\min Z = \sum_{k=1}^{k}\sum_{i=1}^{N}\sum_{j=1}^{N} X_{kij} d_{ij} + \sum_{i=0}^{N} a_i \beta P(i) + \left[\sum_{i=1}^{N} d_i^r / Q\right] C_f \tag{9}$$

$$\sum_{i=1}^{N} d_i^r y_{ki} \le Q, \forall k \in K \tag{10}$$

$$\sum_{i=1}^{N} d_i^r \le Q \sum_{m=1}^{M} \theta_m \tag{11}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{N} X_{ij} = \sum_{i=1}^{N}\sum_{j=1}^{N} X_{ij}, \forall k \in K \tag{12}$$

$$\sum_{m=1}^{M}\sum_{i=1}^{N} X_{kni} = \sum_{m=1}^{M}\sum_{i=1}^{N} X_{kim}, \forall k \in K \tag{13}$$

$$\sum_{k=1}^{k}\sum_{i=1}^{N}\sum_{j=1}^{N} X_{kij} = 1 \tag{14}$$

$$\sum_{i=1}^{M \cup N}\sum_{i=1}^{N} X_{kij} = \sum_{i=1}^{N}\sum_{p=1}^{M \cup N} X_{kjp}, i \ne j \ne p \tag{15}$$

$$\sum_{i=1}^{N} X_{kij} = y_{kj}, \forall j \in N \tag{16}$$

$$\sum_{m=1}^{M} y_{kn} \le 2\theta_m, \forall k \in K \tag{17}$$

$$y_{ki} = y_{kj} = 1, t_i^a > t_j^a \Rightarrow X_{kj} = 0, \forall k \in K \tag{18}$$

Equation (9) is the objective function of the model. The first term is the vehicle path cost, the second term is the penalty cost caused by rescue delay, and the third term is the fixed usage cost of the vehicle. Equation (10) represents the load constraint of the vehicle. Equation (11) indicates that the total demand is not greater than the total amount of materials (12) and (13) represents the access constraints between the disaster-stricken area and the emergency distribution center. Equation (14) represents the uniqueness constraint for accessing the affected point. Equation (15) requires vehicles to leave the affected area. Equation (16) represents the constraint on vehicle access to the affected point. Equation (17) represents the constraint on the number of times vehicles can access the emergency distribution center. Equation (18) represents the time window constraint for node access.

Table 4. Symbol Description

M	Emergency Distribution Center	α_1	Penalty coefficient for material oversupply
N	Set of disaster points	α_2	Penalty coefficient for insufficient supply
K	Transport vehicle collection	β	Penalty coefficient for delayed assistance
θ_m	Number of available vehicles in M	C_f	Vehicle fixed usage cost
x_{kij}	Vehicle k travels from disaster point i to disaster point j	t_i	The latest service time for point i affected by the disaster
x_{kj}	Disaster point i is served by vehicle k	t_i^a	The latest service time for i
d_i^r	Distribution amount of point i materials	a_i	Delayed rescue takes 1; Otherwise, take 0
Q	Total amount of materials	F	Service urgency

At present, there is no unified plan and standard for the distribution of emergency supplies. Therefore, this article proposes a material distribution model based on the distribution of basic supplies and the urgency of services. Q' is set as the total amount of materials at the disaster site, and the basic distribution amount is 60% of the emergency supplies in the distribution center divided by the number of disaster sites. The allocation of materials based on demand urgency is to allocate the remaining 40% of materials based on service urgency

$$Q' = \frac{60\%Q}{N} + \frac{40\%QF}{\sum_{n=1}^{N} F} \tag{19}$$

According to the calculation, the distribution of materials at each disaster site is shown in Table 5:

Table 5. Total allocation of emergency supplies for each disaster-stricken area

Point	1	2	3	4	5	6	7	8	9	10	11	12
Quantity/t	1.2	0.71	0.88	1.07	0.77	0.74	0.78	0.68	0.72	0.53	1.1	0.82

4 CASE ANALYSIS

4.1 Case Background

There is currently one emergency logistics distribution center (Position 0,27) as a single distribution center, mainly focusing on optimizing vehicle paths for 12 nearby disaster-stricken areas around this emergency distribution center. The relevant information of the emergency distribution center is shown in Table 6, and the information of the affected areas is shown in Table 1.

Table 6. Basic Information of Emergency Distribution Center

Parameters	Value	Parameters	Value
Emergency supplies (tons)	10	Fixed operating cost (yuan/time)	700
Number of vehicles	6-7	Insufficient supply cost (yuan/time)	500
Vehicle load capacity (tons)	1.8	Oversupply cost (yuan/time)	200
Unit operating cost (yuan/km)	3.9	Delay penalty cost (yuan/time)	500

4.2 Result Analysis

This article uses a genetic algorithm for solving, with the following parameter settings: mutation probability pm=0.1, crossover probability pc=0.9, and maximum iteration count maxgen=300. The disaster site's emergency logistics vehicle routing problem was solved and optimized using MATLAB software. As the number of iterations increased, the number of vehicles decreased and tended to stabilize. The objective function value gradually approached the minimum, and the optimized distribution and transportation route were finally output. The optimization process is shown in Figure 1.

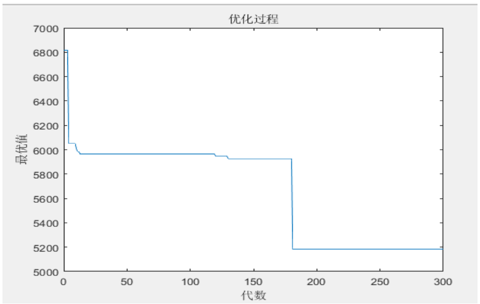

Fig. 1. Optimization process

As a result, the optimal driving route for the vehicle routing problem at the disaster site was generated, as shown in Table 7

Table 7. Optimal Driving Route

	Route1	Route2	Route3	Route4	Route5	Route6
Route nodes	0-1-10-0	0-11-8-0	0-2-4-0	0-3-7-0	0-5-9-0	0-12-6-0
Delivery volume/t	1.73	1.78	1.78	1.66	1.49	1.56

Number of vehicles used: 6, total cost: 5182.7857yuan

5 CONCLUSION

This article optimizes vehicle paths based on the urgency of emergency material services and develops material allocation plans by analyzing the urgency of services at various disaster-stricken points. Subsequently, a multi-cost emergency logistics path model was established, and the optimal path was solved using a genetic algorithm. The effectiveness of the model was verified through examples.

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