Research on Emergency Material Dispatching Model for Multi-disaster Sites Under Natural Disasters

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Abstract. Natural disasters pose a serious threat to society and people's lives, and the timely dispatch of emergency supplies has become a key link in mitigating the impact of disasters and safeguarding the basic livelihood of affected people. However, the diversity, uncertainty and infrastructure destruction of the affected areas make the dispatch of emergency supplies face great challenges. In this paper, a multi-objective optimisation model is developed that integrates the dispatching cost and time. The model aims to find the optimal material dispatch solution under multiple uncertain scenarios. It is validated by a major flood disaster in Hebei Province, China in 2023 as a case study. Under uncertainty conditions, this paper uses a fuzzy algorithm based on two-dimensional Euclidean distance objective assignment to analyse the multi-objective emergency resource scheduling model. By weighing the two components of the multi-objective and determining the weights, the model is transformed into a single-objective model, which is then solved using the LINGO software to obtain the basic data of resource scheduling. The results show that the model and method of this study can cope with the complexity and uncertainty of actual disaster scenarios, provide decision makers with scientific and reasonable suggestions for material dispatch, and maximise the efficiency of disaster relief in disaster-stricken areas and the life safety of the affected people.

Keywords: natural disaster; emergency supplies; dispatch optimisation; multi-objective decision making; fuzzy mathematics

1 INTRODUCTION

Natural disasters often have devastating effects and seriously threaten human life and social development. In the aftermath of a disaster, the effective dispatch of relief supplies becomes a key link in mitigating the impact of the disaster and safeguarding the basic livelihood of the affected population. However, the dispatch of emergency supplies faces great challenges due to the diversity of factors such as the geographical distribution of the affected region, the extent of the disaster and the demand for resources, as well as the potential damage to logistics, communications and infrastructure. In addition, the uncertainty and complexity in disaster response further increase the difficulty

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of dispatching emergency supplies. Therefore, how to achieve rapid, accurate and efficient dispatch of emergency supplies in a complex and volatile post-disaster environment is an important issue that needs to be addressed urgently.

Emergency material dispatch plays a crucial role in responding to natural disasters, and scholars both domestically and internationally have conducted extensive and in-depth research on this topic. These studies mainly focus on demand forecasting for emergency materials, resource allocation, optimization of transportation routes, and the development of decision support systems. For example, Barbarosoglu et al. [1] proposed a two-stage stochastic programming model to balance relief efficiency and costs, ensuring that emergency materials are delivered quickly and economically to disaster-affected areas. Fiedrich et al. [2] studied the uncertainty and dynamics in earthquake disaster development by establishing dynamic and stochastic models to better achieve optimal distribution of post-earthquake emergency materials. Sheu et al. [3] proposed a hybrid fuzzy clustering optimization method based on demand forecasting for emergency materials and constructed a dynamic rescue demand management model under conditions of incomplete information in large-scale natural disasters. Guo et al. [4] introduced the method of triangular fuzzy numbers to establish a fuzzy optimization model for scheduling materials with the shortest time, aiming to improve the accuracy of emergency material scheduling decisions. Gao et al. [5] used the expert scoring method to convert disaster points into disaster factors and established a multi-objective model based on time and cost to determine emergency material supply points and quantities. Kang et al. [6] proposed a multi-level emergency rescue method, coordinating actions to improve rescue efficiency, reduce losses, maximize resource utilization, and provide important strategies for disaster response. Yuan et al.[7] proposed a multi-stage emergency material multimodal transportation scheduling framework and used a heuristic hybrid algorithm combining genetic algorithm and simulated annealing for solution. Zhu [8] conducted some preliminary explorations by applying advanced intelligent technology and constructing emergency logistics information platforms to improve the intelligence level of emergency material scheduling. Zhang et al. [9] considered the disaster situation and decision-maker risk preferences, constructed preference matrices, and designed a second-generation non-dominated sorting genetic algorithm for optimal scheduling of emergency resource dispatch events with multiple distribution points and disaster points. Wang et al. [10] studied and resolved the disturbances caused by large-scale emergencies on people's physiological and psychological well-being. Through an improved grey wolf optimization algorithm with the introduction of reverse learning, differential evolution, and nonlinear convergence strategies, the model was validated using data from the 2008 Sichuan earthquake case. The improved algorithm can provide more fair and efficient scheduling solutions, effectively addressing emergency material distribution issues in fuzzy demand scenarios. Liu et al. [11] focused on handling the uncertainty of emergency material allocation, dividing the emergency rescue process into black box period and gray box period based on the level of disaster information. They studied emergency material allocation schemes after earthquakes.

This study aims to explore an optimisation model for emergency material dispatch based on multi-objective decision-making and fuzzy mathematical theory to cope with complex scenarios in natural disaster situations. First, by analysing the needs and characteristics of multiple affected sites in different natural disaster scenarios, we identify the key issues and challenges in emergency material dispatch. Then, we introduced the fuzzy mathematical theory to deal with the uncertainty information in emergency dispatching, and established a multi-objective optimisation model that integrates the dispatching cost and time. Through case validation, the models and methods in this study can not only effectively deal with the complexity and uncertainty of actual disaster scenarios, but also provide decision makers with scientific and reasonable material dispatching solutions to maximise the efficiency of disaster relief in disaster-stricken areas and the life safety of the affected people. The main contribution of this paper is to propose a novel optimisation method for emergency material dispatch, which integrates multi-objective decision-making and fuzzy mathematical theory, and makes up for the shortcomings of traditional methods in dealing with complexity and uncertainty in disaster response. Our findings have significant theoretical and practical value for improving the efficiency of natural disaster response, optimising resource allocation and guiding practical operations.

2 MODELLING OF EMERGENCY RESOURCE DISPATCH AT MULTI-DISASTER SITES

2.1 Description of the Problem

Assume that there are m ($m \geq 1$) kinds of emergency supplies that need to be mobilised at the affected points, and denote the nth kind of supplies by Zn ($1 \leq n \leq m$). The total storage capacity of various emergency supplies should be greater than the sum of the demand of each affected point. pi (i=1,2,3...a) is the number of emergency supplies out of the rescue point, and Hj (j=1,2,3...b) is the number of the affected point.

It is now known that the actual supply of Zn in the salvage point Pi is p(Zn) i, the actual storage of Zn in the salvage point Pi is M(Zn)i, the actual demand for the material Zn in the affected point Hi is h(Zn) j, the emergency material dispatched from the salvage point Pi to the affected point Hj is x(Zn) ij, the required unit cost is C(Zn) ij,, and the unit time for the delivery is tij, when Pi=0, it means that Pi is not involved in the rescue.

According to the different degree of urgency of the demand for different emergency supplies in different affected points, the dispatch of m kinds of supplies from each rescue point to each affected point can be divided into k ($k \geq 1$) stages. Let the importance degree of emergency supplies θn, then the importance degree ratio of m kinds of supplies is θ1: θ2: θ3... θm, the demand urgency coefficient of supplies:

$$\lambda_n = \frac{x(Z_n)_{ij}}{\theta_n},\ \theta_n \neq 0 \tag{1}$$

If λn are different, then it can be divided into n stages, if there are β identical values in λn: k = m'-β, where m' denotes the number of types of scheduling materials from Pi to Hj and m' = m-c, and c denotes the number of times X(Zn) ij is zero.

Taking the minimum demand urgency coefficient minλ(k) for λ(k) at stage k, the number of first stages in which material Zn is dispatched from a single outgoing rescue point to a single disaster point is:

$$x(Z_n)_{ij} = \lambda(k)\theta_n \tag{2}$$

The value of λ(k) is then re-determined based on the type and quantity of supplies left at that salvage point to determine the type and quantity of supplies to be dispatched in the next phase. The process is repeated until the point of dispatch is complete.

2.2 Model Building

When a natural disaster strikes, the information of material demand, dispatching time and unit cost of dispatching at the affected point is not definite and fuzzy, and the information of the affected point can be expressed by using triangular fuzzy number. In this paper, triangular fuzzy numbers are introduced to portray the fuzzy demand for materials and the fuzzy time required for dispatching materials at the disaster-stricken point, and the demand at the disaster-stricken point Hj can be expressed as, where is the triangular fuzzy number, hj3 is the optimistic value of the fuzzy number, hj2 is the most probable value of the fuzzy number, and hj1 is the pessimistic value of the fuzzy number. The scheduling unit time required for the out rescue point Pi to reach the affected point Hj is denoted as, where is the triangular fuzzy number, tij3 is the optimistic value of the fuzzy number, tij2 is the most probable value of the fuzzy number, and tij1 is the pessimistic value of the fuzzy number. The triangular fuzzy number is converted into clear value and defuzzification is done using weight summing method with the formula:

$$\mathrm{E}(\tilde{h}_j) = \omega_1 \mathrm{h}_{\mathrm{j}1} + \omega_2 \mathrm{h}_{\mathrm{j}2} + \omega_3 \mathrm{h}_{\mathrm{j}3} \tag{3}$$

$$\mathrm{E}(\tilde{t}_{ij}) = \omega_1 t_{ij1} + \omega_2 t_{ij2} + \omega_3 t_{ij3} \tag{4}$$

$$\omega_1 + \omega_2 + \omega_3 = 1 \tag{5}$$

The formula ω1, ω2, ω3, respectively, for the pessimistic value, the most likely value, the optimistic value of the weight of the three, of which the most likely value is the most important, given ω2 weight ratio should be the largest, while the pessimistic value and optimistic value is the boundary constraint value, the two weights can not be set too optimistic and pessimistic, or it may lead to too large a discrepancy with the actual situation. Taken together, the three values are set as follows: ω1=ω3=0.25, ω2=0.5.

Based on the known triangular fuzzy numbers of demand and time, the minimum cost and the shortest dispatch time of emergency material dispatch are taken as the objectives of this paper, and a scheme to optimise material dispatch is developed.

Modelling uncertain multi-objective emergency material dispatch:

$$\min \sum_{j=1}^{b} \sum_{i=1}^{a} \tilde{t}_{ij} x(Z_n)_{ij} \tag{6}$$

$$\min \sum_{j=1}^{b} \sum_{i=1}^{a} c_{ij} x(Z_n)_{ij} \tag{7}$$

$$s.t. \sum_{i=1}^{a} \mathrm{p}(Z_n)_i = \sum_{j=1}^{b} \tilde{h}(Z_n)_j \tag{8}$$

$$\sum_{i=1}^{a} x(Z_n)_{ij} = \tilde{h}(Z_n)_j \tag{9}$$

$$\sum_{j}^{b} x(Z_n)_{ij} \leq \mathrm{M}(Z_n)_i \tag{10}$$

$$\sum_{j=1}^{b} x(Z_n)_{ij} = \mathrm{p}(Z_n)_i \tag{11}$$

$$x_{ij} \geqslant 0 \tag{12}$$

In the above formula, equation (6) indicates that the dispatch time of emergency supplies in the objective function is the shortest; equation (7) indicates that the dispatch cost of emergency supplies in the objective function is the lowest; equation (8) indicates that the total supply of emergency supplies to material Zn is equal to the total demand for emergency supplies; equation (9) indicates that the quantity of emergency supplies supplied to material Zn by the outgoing point of rescue is equal to the demand for emergency supplies of the corresponding disaster-stricken point; (10) indicates that the actual storage capacity of the rescue point is greater than or equal to the sum of the demand of each affected point for material Zn at the rescue point; Equation (11) indicates that the quantity of emergency materials dispatched to the affected point from material Zn at the rescue point is equal to the actual quantity of emergency materials dispatched at the rescue point; and Equation (12) indicates that the quantity of emergency materials dispatched from rescue point Pi to the affected point Hj can not be negative.

3 CASE STUDIES

3.1 Case Introduction

In August 2023, heavy rainfall process occurred in most areas of Hebei Province of China under the joint influence of cold and warm air and Typhoon Dusu Rui, resulting in sudden flooding. In this paper, four more seriously affected areas in Hebei Province, Zhuozhou, Gaobeidian, Dingxing and Laishui, are selected as the typical affected areas, and the four areas are denoted by H1, H2, H3 and H4, respectively; and water, food and medicine, which have the greatest demand at the time of the disaster, are selected as the emergency supplies in this case, and they are denoted by Z1, Z2 and Z3, respectively, in which the table 1 denotes the quantity and type of the emergency supplies required for the various affected points.4 Affected Points There are mainly 2 out relief points P1 Hebei Province Emergency Management Department and P2 Hebei Province Red Cross Society, whose quantities of stored relief materials are shown in Table 2. The data in the following table was obtained from the official websites of Hebei Provincial Emergency Management Department, Hebei Red Cross and other related departments, and the data has been slightly processed, but the impact on the final results is minimal, and its authenticity is still guaranteed.

Table 1. Quantity and type of emergency supplies required at each affected site

Disaster area	Z_1/Piece	Z_2/Case	Z_3/Piece
H_1	7159	5616	10613
H_2	2861	2196	8163
H_3	1567	951	6617
H_4	1945	1349	7156

Table 2. Quantity and type of emergency supplies stored at each extraction point

Rescue point	Z_1/Piece	Z_2/Case	Z_3/Piece
P_1	9013	11267	22534
P_2	8830	11542	24038

According to the distance from the rescued point to the affected point, the unit cost and unit time of the emergency supplies in the mobilisation process can be found out, due to the complexity of the rescue process, in which many factors are uncertain, so it is assumed that only the fuel consumption of the vehicle transport process, road tolls and the cost of labour are taken into account, as can be shown in Table 3 below.

Table 3. Unit cost and time for dispatch of material from the point of dispatch to the point of impact

Rescue point	Disaster area	Cost /¥			time/min		
		Z_1	Z_2	Z_3	Z_1	Z_2	Z_3
P_1	H_1	100	100	100	1.68	1.68	1.68
	H_2	75	75	75	1.5	1.5	1.5
	H_3	82	82	82	1.4	1.4	1.4
	H_4	80	80	80	1.38	1.38	1.38
P_2	H_1	88	88	88	1.6	1.6	1.6
	H_2	83	83	83	1.47	1.47	1.47
	H_3	69	69	69	1.3	1.3	1.3
	H_4	86	86	86	1.56	1.56	1.56

3.2 Modelling Applications

Since the demand for each first aid material at each affected site is uncertain, the amount of emergency material required at the affected site is expressed as a triangular fuzzy number.The triangular fuzzy numbers of Z1 are respectively: $\tilde{h}_1 = [6600，7200，8000]$ ， $\tilde{h}_2 = [2700，2900，3000]$ ， $\tilde{h}_3 = [1500，1600，1800]$， $\tilde{h}_4 = [1800，2000，2100]$。

Now to make the optimal solution that minimises transport costs, de-fuzzification has to be done: $\mathrm{E}(\tilde{h}_1) = 7250$， $\mathrm{E}(\tilde{h}_2) = 2875$， $\mathrm{E}(\tilde{h}_3) = 1625$， $\mathrm{E}(\tilde{h}_4) = 1975$。

Since the time to mobilise the material from the rescue point to the disaster point is uncertain, the time to mobilise the material from the rescue point to the disaster point is expressed by the triangular fuzzy number, because the three kinds of material mobilisation takes the same time, the triangular fuzzy number of the three is also the same, as follows in table 4 now the optimal scheme to make the transport so the least time, de-fuzzification to get table 5.

Table 4. Triangular fuzzy numbers for material mobilisation times at each disaster site

i，j	1，1	1，2	1，3	1，4
$\tilde{t}_{ij}$	1.6，1.68，1.7	1.4，1.5，1.55	1.32，1.4，1.65	1.3，1.38，1.5
i，j	2，1	2，2	2，3	2，4
$\tilde{t}_{ij}$	1.4，1.6，1.8	1.3，1.47，1.6	1.25，1.3，1.5	1.5，1.56，1.7

Table 5. Expectation of material mobilisation time by disaster site

i，j	1，1	1，2	1，3	1，4
$\tilde{t}_{ij}$	1.67	1.49	1.44	1.39
i，j	2，1	2，2	2，3	2，4
$\tilde{t}_{ij}$	1.6	1.46	1.34	1.58

According to the model established in 2.2, this paper solves the uncertain multi-objective model based on a fuzzy algorithm with objective assignment of two-dimensional Euclidean distances, C(x) denotes a function of cost, and T(x) denotes a function of time, and based on the data mentioned above a multi-objective model can be constructed with Z1 aiming at the shortest time and the lowest cost:

minC(x)=100x11+75x12+82x13+80x14+88x21+83x22+69x23+86x24

minT(x)=1.67x11+1.49x12+1.44x13+1.39x14+1.6x21+1.46x22+1.34x23+1.58x24

s.t.

$x_{11}+x_{12}+x_{13}+x_{14}\leqslant 9013$； $x_{21}+x_{22}+x_{23}+x_{24}\leqslant 8830$

$x_{11}+x_{21}=7250$； $x_{12}+x_{22}=2875$； $x_{13}+x_{23}=1625$； $x_{14}+x_{24}=1975$； $x_{ij}\geqslant 0$；

The upper and lower bounds of the above functions were calculated using the LINGO software:

sup{C(x)}=1266725； inf{C(x)}=1124290；

sup{T(x)}= 21769.64； inf{T(x)}= 20809.65；

This leads to the two satisfaction functions, respectively:

$$\mu_1=\frac{1266725-\mathrm{C(x)}}{142435},\quad \mu_2=\frac{21769.64-\mathrm{T(x)}}{959.99} \tag{13}$$

Checking many sources it is concluded that experts give the weight ratio of time and cost as ω3: ω4=0.8:0.2, which can be obtained by transforming the multi-objective model of Z1 into a single-objective model:

$\max f(x)=\omega_{32}\mu_{12}+1-\omega_{32}(1-\mu_1)^2+\omega_{42}\mu_{22}+1-(1-\mu_2)^2$

s.t.

$x_{11}+x_{12}+x_{13}+x_{14}\leq 9013$; $x_{21}+x_{22}+x_{23}+x_{24}\leq 8830$;

$x_{11}+x_{21}=7250$; $x_{12}+x_{22}=2875$; $x_{13}+x_{23}=1625$; $x_{14}+x_{24}=1975$; $x_{ij}\geq 0$;

The scheduling results for Z1 using LINGO software are as follows:

$x_{11}=0$, $x_{12}=1295$, $x_{13}=1975$, $x_{14}=1945$, $x_{21}=7250$, $x_{22}=1580$, $x_{23}=1567$, $x_{24}=0$.

According to this method, the uncertain multi-objective model is established for Z2 and Z3 respectively, and then LINGO software is used to find out the scheduling results of Z2 and Z3 as follows:

The scheduling result for Z2 is:

$x_{11}=5537$, $x_{12}=2175$, $x_{13}=975$, $x_{14}=1350$, $x_{21}=0$, $x_{22}=0$, $x_{23}=0$, $x_{24}=0$.

The scheduling result for Z_3 is:

$x_{11}=0$, $x_{12}=0$, $x_{13}=3325$, $x1_4=1837$, $x_{21}=10550$, $x_{22}=8125$, $x_{23}=0$, $x_{24}=5363$.

Based on the data derived above, it can be seen that when the objective is to have the least dispatch cost and the shortest dispatch time, the material dispatch programme can be derived as shown in table 6.

Table 6. Emergency material mobilisation programme from relief point to disaster site

Rescue point	Disaster area	Z_1/Piece	Z_2/Case	Z_3/Piece
P_1	H_1	0	5537	0
	H_2	1295	2175	0
	H_3	1975	975	3325
	H_4	1945	1350	1837
P_2	H_1	7250	0	10550
	H_2	1580	0	8125
	H_3	1560	0	0
	H_4	0	0	5363

In practice, the dispatch of materials from the rescue point to the disaster point is not a one-time mobilisation, so it needs to be mobilised in phases, with reference to a number of sources, the experts give the importance ratio of these three kinds of materials as water: food: medicine = θ1: θ2: θ3 = 2: 2: 1, and then according to the formula (1) and the formula (2), it can be derived from Table 7.

Table 7. Phased programme for the movement of supplies from relief points to disaster sites

Rescue point	Disaster area	point	Z_1/Piece	Z_2/Case	Z_3/Piece
P_1	H_1	1	0	5537	0
	H_2	1	1295	1295	0
		2	0	880	0
	H_3	1	975	975	488
		2	1000	0	500
		3	0	0	2337
	H_4	1	1350	1350	675
		2	595	0	298
		3	0	0	864
P_2	H_1	1	7250	0	3625
		2	0	0	6925
	H_2	1	1580	0	790
		2	0	0	7335
	H_3	1	1560	0	0
	H_4	1	0	0	5363

According to the results in Table 7 above, the food in the affected points H1, H2, H3 and H4 are all mobilised by P1, indicating that the comprehensive cost of mobilising food to the affected points by P2 is greater than that of P1 under the premise of considering the lowest cost and the shortest time; whereas, the water and medicines in H1 are mobilised by P2; the medicines in H2 are mobilised by P2, and the medicines in H3 are all mobilised by P1; H2, The water in H3 is mobilised by P1 and P2 together, and the two cooperate with each other to achieve the lowest comprehensive cost; most of the drugs in H4 are mobilised by P2, and P1 plays a supporting role in it, and the water in H4 is mobilised by P1. Due to the different degree of demand for different kinds of materials in each affected point, the use of a phased approach to achieve the mobilisation of materials from the rescue point to the affected point can better reduce the ineffective waste of materials under emergency conditions, thus improving the utilisation rate of materials, and also more accurately deliver emergency materials to the affected points, so that the life safety and livelihood of the affected people can be effectively safeguarded in the first instance, and rescue work can be facilitated. Convenience. Through the model of the emergency supplies scheduling results and the actual needs of the disaster site emergency supplies comparison, found that the results of the model and the actual needs of the difference is very small, which shows that the feasibility of the model is high, if the reality of natural disasters can draw on this method of scheduling decision-making, to a certain extent, can help the rescue smoother.

4 SUMMARIES

This paper aims to solve the problem of how to dispatch emergency supplies quickly, accurately and efficiently after a natural disaster. It mainly applies an optimisation model for emergency material dispatching, which is based on multi-objective decision-making and fuzzy mathematical theory. By analysing the needs and characteristics of multiple affected sites in different natural disaster scenarios, the key problems and challenges of emergency material dispatching are clarified. Then, fuzzy mathematical theory is introduced to deal with the uncertainty information in emergency dispatching, and a multi-objective optimisation model with comprehensive consideration of dispatching cost and time is established. The fuzzy algorithm with two-dimensional Euclidean distance objective assignment is applied to transform the multi-objective model into a single-objective model in the process of solving, and then the LINGO software is applied to perform calculations to derive the results of the scheduling of the types and quantities of supplies from each outgoing point to different affected points, and the final results are obtained by the phased mobilisation through the degree of importance of each material.

Finally, through the analysis of the case of a major flood disaster in Hebei Province in August 2023, the results obtained from the thesis model are compared with the real data, which proves that the model and the method can not only effectively deal with the complexity and uncertainty of the actual disaster scenarios, but also provide decision makers with a scientific and reasonable material dispatching scheme to maximize the relief efficiency of the disaster-affected areas and the disaster-affected people's The model and method can not only effectively deal with the complexity and uncertainty of actual disaster scenarios, but also provide decision makers with scientific and reasonable material dispatching schemes to maximally guarantee the relief efficiency of disaster areas and the safety of affected people.

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