Bi-level Optimal Scheduling of Emergency Materials Considering Multimodal Transport

Zhiwei Zhang, Changfeng Zhu, Kangru Liu and Qingrong Wang

Abstract—**In order to ensure that emergency materials can be transported to the material demand points in the shortest time within the golden rescue time after emergencies, and to ensure the fairness of material distribution, a bi-level optimal scheduling model of emergency materials considering multimodal transport is constructed in this paper. The upper model takes the shortest transportation time as the objective function by considering multimodal transport. The lower model takes the minimum variance of emergency material distribution at each material demand point as the objective function by considering the fairness of emergency material distribution. The improved genetic algorithm is used to solve the bi-level optimal model. Compared with the classical genetic algorithm, the improved genetic algorithm is found to be effective. Finally, a case study is conducted to verify the rationality of the model. The results show that the emergency materials can be transported to the material demand points in the shortest possible time according to the requirements of decision-makers through this model. Besides, the fairness of emergency material distribution can be guaranteed and can provide further emergency decision-making reference for decision-makers.**

Index Terms—**bi-level programming; emergency materials; multimodal transport; triangular fuzzy number;**

I. Introduction

Recently, frequent emergencies have caused great losses to people's lives and property. Therefore, the government departments must take emergency measures to minimize the adverse impact of the emergency on the society. However, emergency material scheduling is inseparable from the emergency measures taken by government departments after emergencies. If the scheduling scheme of emergency material is unreasonable, the rescue effect will be reduced, and even greater disasters will be caused. Therefore, a reasonable scheduling scheme of emergency material should be formulated to reduce the losses caused by emergencies.

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Domestic and foreign researchers have conducted several studies on the emergency material scheduling problem. Most scholars mainly construct single-objective and multi-objective programming model to solve emergency material scheduling problem. A few scholars construct bi-level programming model to solve emergency material scheduling problem.

In terms of single-objective programming, an optimization model of emergency route is built in [1][2][3][4]. Aiming at the multi-stage emergency material scheduling problem, [5] takes the shortest transportation time as the objective function to construct mixed-integer programming model. [6] designs a particle swarm optimization algorithm based on single-objective model to solve the materials distribution problem. Aiming at the emergency material scheduling problem after earthquake, an optimization model of emergency material scheduling is constructed by considering timeliness in [7]. However, the disadvantage is that these studies only consider one mode of transportation and cannot guarantee emergency materials are transported within an acceptable time. Therefore, the emergency material scheduling problem considering multimodal transport has attracted scholars' attention. [8][9][10]11] take the shortest transportation time as the objective function to construct path optimization model of emergency materials by considering multimodal transport. Although timeliness is crucial factor in emergency material scheduling, it can not comprehensively describe the emergency material scheduling problem without considering other influencing factors. In view of the above shortcomings, some scholars have studied the multi-objective programming model of emergency material scheduling.

In terms of multi-objective programming, [12] designs a heuristic algorithm based on multi-objective optimization model to solve the problem of emergency material scheduling. Aiming at the emergency material scheduling problem after emergencies, a multi-objective optimization model is constructed by considering the timeliness, costs and path environment in [13][14]15]. Considering the psychological perception of the victims, a multi-objective optimization model of emergency material scheduling is constructed by considering timeliness and satisfaction in [16][17]18]. In terms of multimodal transport of emergency materials, [19][20][21] design an intelligent bionic algorithm that is based on multi-objective optimization model of emergency material scheduling by considering multimodal transport. The disadvantage is that the above scholars don’t not consider the fairness of emergency materials scheduling. However, some scholars have studied it, a multi-objective optimization model of emergency material scheduling is constructed by considering fairness of emergency material distribution in [22][23][24][25]. Considering the complex characteristics of road network after emergencies, [26][27] established a multi-objective optimization model of emergency materials scheduling based on robust theory. However, these studies did not consider the uncertainty of material demand at the disaster site. It is worth mentioning that [28] used trapezoidal fuzzy number simulation method to study the uncertainty of emergency materials demand. Considering the demand uncertainty of emergency materials, a multi-objective programming model is constructed to study the emergency material scheduling problem in [29]. Aiming at the emergency material scheduling problem after emergencies, the existing studies have considered several goals, such as timeliness, costs and fairness, but have not considered the master-slave game relationship among them, which is often considered when making a decision of emergency material scheduling. Therefore, some scholars have studied the bi-level programming model of emergency material scheduling.

Regarding bi-level programming model, [30] constructs a bi-level programming model of emergency material scheduling with disaster-stricken countries as the leader and international emergency organizations as the followers, and designs a fuzzy optimization algorithm to solve the model. Besides, a improved intelligent bionic algorithm is designed in [31][32] to solve bi-level optimization model of emergency material scheduling. Considering people's limited rational behavior, [33] constructs a bi-level programming model by introducing prospect theory and non-cooperative game theory. A bi-level integer programming model is constructed by considering uncertainty of demand and hierarchical decision-making complexity in [34]. Considering the complexity of road network after emergencies, a bi-level programming model of emergency material scheduling is constructed by considering the reparability of road network in [35][36]. Considering the uncertainty of emergency information, [37] constructs a bi-level mixed-integer grey nonlinear programming model by considering uncertainty of materials demand and transport time.

As a matter of fact, the emergency material scheduling problem should focus on timeliness after emergencies. Only by transporting emergency materials timely and accurately to the material demand points can we minimize the loss caused by emergencies. In addition, the fairness of emergency material distribution should be attached more importance. If the distribution of emergency material is not reasonable, it will lead to a surplus of emergency materials in some material demand points, while materials will still not be satisfied in other material demand points. This will increase the severity of the disaster. However, most existing studies have only considered timeliness when studying the emergency material scheduling problem, but the fairness of emergency material distribution is ignored. Moreover, they have only considered one transport mode, the multimodal transport of emergency materials is ignored, and they have only considered demand of material while ignoring the uncertainty of materials demand. Besides, most studies ignore the impact of secondary disasters on the transportation time of emergency materials

In view of this, this paper mainly makes the following contributions based on the existing research: (1) A bi-level optimization model of emergency materials scheduling is constructed by considering multimodal transport. The upper model takes the shortest transportation time of emergency materials as the objective function; the lower model takes the maximum fairness of emergency materials distribution as the objective function. For example, multi-modal transport is not considered in the bi-level optimization model of emergency materials scheduling in [33][34][35], so it can not guarantee that emergency materials can be transported to the material demand point in the shortest time. (2) In the emergency rescue multimodal transport network, the accessibility of each road section and the influence of secondary disasters are considered, and the road section transportation time is modified to make the model more accurately reflect the timeliness of the emergency rescue process. Conversely, the transportation time of road section is not be modified in [11][12][13], but viewed the road section transportation time under normal conditions as a reference. (3) The triangular fuzzy number is introduced to quantify the demand of emergency materials in the disaster points. For example, the demand uncertainty of emergency materials is not considered in [28][29][30], so the model could not accurately reflect fairness of emergency material distribution when materials are in short supply. (4) The improved genetic algorithm is used to solve the bi-level optimization model of emergency materials scheduling considering multimodal transportation, and the results are analyzed from different perspectives to verify the effectiveness of the model and algorithm.

The reminder of this paper is summarized as follows: Section II presents the problem description, and a bi-level optimization model of emergency materials scheduling is constructed. Section III designs an improved genetic algorithm to solve the emergency materials scheduling problem. Section IV verifies the rationality of the model through a case study, and the influence of parameter on the results is also analyzed in this section. Section V concludes the paper, and gives future research directions.

II. MODEL CONSTRUCTION

A. Problem Description

Suppose there is an emergency in some place, there are p material supply points. The set of material supply points $O=\{O_i | i=1,2,...,p\}$, and there are q material demand points, the set of material demand points $D=\{D_i| i=1,2,...q\}$. the multimodal transport networks $G=(N,E)$, as shown in Fig.1. $M=\{a, h, r\}$ is the set of transport modes, $B=\{1,2,3,...b\}$ is the set of emergency material class. Where N is the node set of multimodal transport network, E is the set of edges in the networks, a represents aviation transportation, h represents highway transportation, r represents railway transportation, i and j represent network nodes, $i,j\in N$, t_{ij}^{m} is the transport time from node i to j by transport mode m. d_{ij}^{m} is the transport distance from node i to j by transport mode m; $t_{j}^{m,n}$ is the transfer time from transport mode m to n at node j. x_{ij}^{m} is the 0-1 variable, the transportation route is selected by transport mode m from node i to j is equal to 1, otherwise equal to 0. $y_{j}^{m,n}$ is the 0-1 variable, the transport mode is changed from m

to n is equal to 1 at node j, otherwise equal to 0. S^m is the maximum transportation distance of the emergency materials by transport mode m. $c_{(i,j)}^b$ represents the quantity of class b materials transported from material supply points i to material demand points j. σ is the penalty coefficient of secondary disasters in the emergency rescue process, $\sigma \in (0,1)$. $\theta_{(i,j)}$ is the 0-1 variable, transporting material from material supply points i to material demand points j is equal to 1, otherwise equal 0. C_d^b represents the fuzzy demand for class b materials at material demand points d. w_d^b represents the amount that supplies class b materials at the material demand points d. $g_{(o)}^b$ is the amount of class b material in material supply points o. $\varepsilon_{i,j}^m$ is the accessible coefficient of road section (i, j) through the transportation mode m after emergencies, $0 \le \varepsilon_{i,j}^m \le 1$. v^m is the speed of transport mode m.

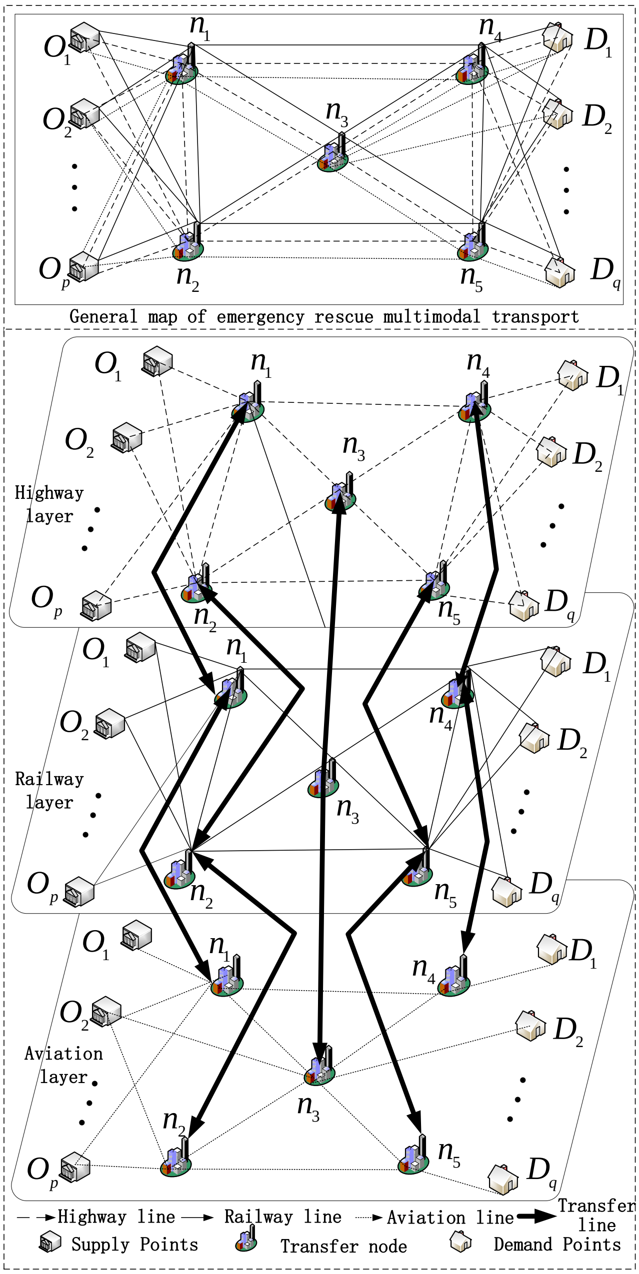

Fig.1. Layered network diagram of multimodal transport

In order to alleviate the disaster and reduce the loss, it is necessary to transport emergency materials to the material demand points in time. The emergency materials scheduling problem is divided into bi-level. From the perspective of government, the upper layer selects the shortest path to deliver emergency materials to the material demand points and completes the transportation task of emergency materials. From the perspective of victims, the lower layer distributes emergency materials to material demand points and completes the task of emergency materials distribution.

Obviously, this is a bi-level emergency material scheduling problem, and it is suitable to adopt the bi-level programming method to solve this problem. The upper level decision-maker is in the dominant position, the goal is to reasonably program the multi-modal transport path, and transport the emergency materials to the material demand points. The lower level decision-maker is in the following position, but it also has some degree of freedom. The goal is to reasonably distribute emergency materials according to the transportation path of emergency materials selected by the upper level, and ensure the maximum fairness of the emergency material distribution.

According to the characteristics of the problem, the following assumptions are put forward:

(1) The mode of transport can be changed only once at the nodes of the multimodal transport network, and only one transport model can be selected for each road section.

(2) Emergency materials are in short supply.

(3) Limited emergency vehicles.

The transfer of transportation modes is shown in Figure. 2.

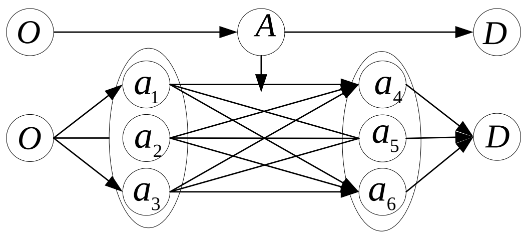

Fig.2. Multimodal transport node transformation diagram

As can be seen from Fig. 2, there are three kinds of transport modes when emergency materials arrives to node A, so node A is split into three new nodes a_1, a_2 and a_3, which represent ending point of highway, railway and aviation transportation from O-A respectively. When need to transfer transport mode at node A, there are three kinds of transport modes from node A starting, and then A is split into three new nodes a_4, a_5 and a_6, which represent starting point of highway, railway and aviation transportation from A-D respectively.

B. Upper Model of Path Selection

In this paper, the road section accessible coefficient $\varepsilon_{i,j}^m$ is introduced to modify the road section transportation time after emergencies, as shown in Figure. 3. Therefore, in the multimodal transport of emergency materials, the transportation time by transport model m at road section (i,j) is expressed by following:

$$t_{ij}^m = \frac{t_{ij}'^m}{1-\sqrt{1-\varepsilon_{ij}^m}} \quad (1)$$

Where, $t_{ij}'^{m}$ is the transportation time from node i to j by transport mode m under normal circumstances. The calculation formula is expressed by following:

$$t_{ij}'^{m} = \frac{d_{ij}^{m}}{v^{m}} \tag{2}$$

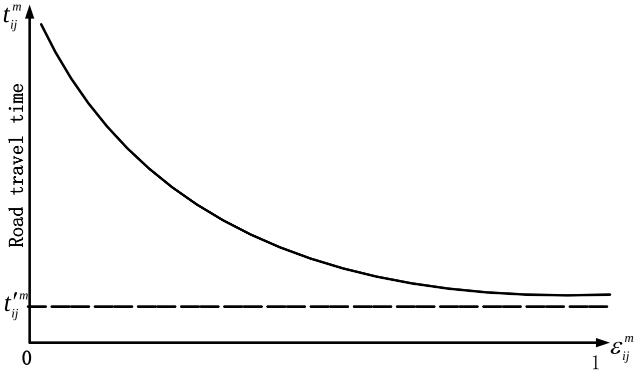

Fig.3. Relation between road section transportation time and ε_{ij}^{m}

Build the 0-1 variables.

$$\theta_{(i,j)} = \frac{\sum_{a\in A} c^{b}_{(i,j)}}{\min\left\{\sum_{a\in A} c^{b}_{(i,j)}, \lambda\right\}} \qquad i \in O, j \in D \tag{3}$$

Where λ is the equilibrium constant, Takes 5000 t.

B.1 Upper Objective Function

The upper model is minimizing transportation time of emergency materials, so upper objective function can be expressed as:

$$\begin{aligned} \min\ f_1 = (1+\sigma)\cdot(&\sum_{m\in M}\sum_{i\in N}\sum_{j\in N} t_{ij}^{m}\cdot x_{ij}^{m}\theta_{(i,j)}^{m} \\ &+\sum_{m\in M}\sum_{n\in M}\sum_{j\in N} t_{j}^{m,n}\cdot y_{j}^{m,n} \end{aligned} \tag{4}$$

The objective function (4) represents the shortest transportation time of emergency materials, where the first part is the road transportation time; the second part is the transfer time of transport mode.

B.2 Upper Constraints

$$\sum_{m\in M} x_{ij}^{m} = 1, \forall i, j \in N \tag{5}$$

$$\sum_{i\in N, i\notin D}\sum_{m\in M} x_{ij}^{m} = 1, \forall j \in D \tag{6}$$

$$\sum_{m\in M}\sum_{j=s, j\neq i} x_{ij}^{m} - \sum_{m\in M}\sum_{j=d, j\neq i} x_{ji}^{m} = \begin{cases} 1 & \forall i = O \\ 0 & \forall i \in N, i \notin \Omega \\ \text{-1} & \forall i = D \end{cases} \tag{7}$$

$$x_{ij}^{m} + x_{jk}^{n} \geq 2y_{j}^{m,n} \tag{8}$$

$$\sum_{m\in M}\sum_{n\in M} y_{j}^{m,n} \leq 1, \forall j \in N \tag{9}$$

$$\sum_{i\in N}\sum_{j\in N} d_{ij}\cdot x_{ij}^{m} \leq S^{m} \tag{10}$$

$$\sum_{m\in M}\sum_{i\in O} x_{ij}^{m} \geq 1 \qquad j \in D \tag{11}$$

$$\sum_{m\in M}\sum_{j\notin O} x_{ij}^{m} \geq 1, i \in O \tag{12}$$

$$x_{ij}^{m} \in \{0,1\}, \forall m \in M; \forall i, j \in N \tag{13}$$

$$y_{j}^{m,n} \in \{0,1\}, \forall m, n \in M; \forall j \in N \tag{14}$$

Constraint (5) is only one transport mode can be selected in two adjacent nodes. Constraint (6) ensures emergency materials can be transported through one path from the material supply points to the material demand points. Constraint (7) indicates the flow balance of multimodal transport network. Constraint (8) means that transport vehicles arrives j by transport mode m and leaves j through transport mode n, when the transport mode is changed from m to n at node j. Constraint (9) means that transport mode can only change once at the node. The constraint (10) represents the maximum limit of transport vehicles. Constraint (11) ensures that rescue is carried out at material demand points. Constraint (12) ensures that material supply points participate in the rescue. Constraint (13) and (14) are 0 -1 variables.

C. Lower Model of Emergency Materials Distribution

C.1 Triangular Fuzzy Number

The material demand is fuzzy in material demand points after emergencies. So this paper introduces the triangular fuzzy number to quantify the material demand, which is expressed by triangular fuzzy number $C_d^b = (C_d^{b,l}, C_d^{b,m}, \ C_d^{b,u})$, $0 \leq C_d^{b,l} \leq C_d^{b,m} \leq C_d^{b,u}$. $C_d^{b,m}$ is called the principal value of triangular fuzzy numbers C_d^b, where $C_d^{b,l}$ and $C_d^{b,u}$ are called the lower and upper bounds of C_d^b respectively. Its membership function is shown in formula (15):

$$C_d^b) = \begin{cases} 0 & , \quad C_d^b < C_d^{b,l} \\ (C_d^b - C_d^{b,l})/(C_d^{b,m} - C_d^{b,l}) & , C_d^{b,l} \leq C_d^b \leq C_d^{b,m} \\ (C_d^{b,m} - C_d^b)/(C_d^{b,u} - C_d^{b,m}) & , C_d^{b,m} \leq C_d^b \leq C_d^{b,u} \\ 0 & , \quad C_d^b > C_d^{b,u} \end{cases} \tag{15}$$

Membership function graph of triangular fuzzy number is shown in Fig. 4.

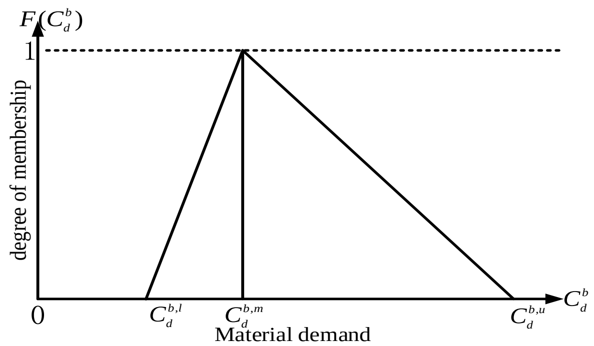

Fig.4. Membership function graph of triangular fuzzy number

$E(C_d^b)$ is the fuzzy average of the triangular fuzzy number C_d^b, The balance between decision-maker's risk preference and the possibility degree of attribute value is considered comprehensively, the average weight method is adopted to calculate the fuzzy average value, namely:

$$E(C_d^b) = \omega_1 \cdot C_d^{b,l} + \omega_2 \cdot C_d^{b,m} + \omega_3 \cdot C_d^{b,u} \tag{16}$$

Where: ω_1, ω_2, and ω_3 respectively represents the weight of decision-maker to fuzzy lower bound, principal value and upper bound. The principal value of triangular fuzzy numbers is usually the most important attributes, so higher weight should be given. While lower and upper bounds are marginal constraints, they are given a weight that is not too pessimistic and not too optimistic. Based on this, $\omega_1=\omega_3=1/6$, $\omega_2=4/6$.

The satisfaction degree of material demand points d to class b materials can be expressed as:

$$\eta_d^b = \frac{\sum_{o\in O} c_{(o,d)}^b \cdot \theta_{(o,d)}}{E(C_d^b)}, \quad d \in D \tag{17}$$

The average satisfaction degree of class b materials at all material demand points can be expressed as:

$$\bar{\eta}^b = \frac{\sum_{d\in D} \eta_d^b}{q} \tag{18}$$

C.2 Lower Objective Function

The lower model is maximum fairness of emergency material distribution, which is minimizing the variance of emergency materials distribution at all material demand points. So lower objective function can be expressed as:

$$\min f_2 = \sum_{b\in B} \frac{\sum_{d\in D}(\eta_d^b - \bar{\eta}^b)^2}{q-1} \tag{19}$$

C.3 Lower Constraints

$$w_d^b = \sum_{o\in O} c_{(o,d)}^b \tag{20}$$

$$\sum_{o\in O} \theta_{(o,d)} \geq 1, d \in D \tag{21}$$

$$\sum_{o\in O} \theta_{(o,d)} \cdot c_{(o,d)}^a \leq C_d^a, \quad d \in D \tag{22}$$

$$c_{(o,d)}^b \leq \theta_{(o,d)} g_o^b, \quad o \in O, d \in D \tag{23}$$

Constraint (20) indicates that the quantity of class b materials supplied at material demand points d is the sum of all material supply points. Constraint (21) ensures that each material demand point has at least one material supply points to provide rescue. Constraint (22) indicates that emergency materials are in short supply. Constraint (23) is reaction function of upper and lower-level connection, for any class b materials, the total amount supplied by supply points o to all demand points d does not exceed its storage capacity.

III. Algorithm Design

A. Improved Genetic Algorithm

Bi-level programming is a kind of NP-Hard problem, which requires high differentiability and convexity of solution set, so it is difficult to find the exact solution. Combined with the characteristics of the model, the upper model is 0-1 integer variable, because the node through the shortest path cannot be known in advance, the path has a variable length, so the coding method of variable length path is adopted. In view of the multi-modal transport network nodes have characteristics of multimodal transport, Chromosomes are encoded sectionally. The lower level is real number variable, so the improved genetic algorithm of real number coding is adopted.

Chromosome coding is determined according to the characteristics of the upper model. The coding example is shown in Figure 5. The chromosome represents a path of transporting emergency materials from material supply point O to material demand point D_5.

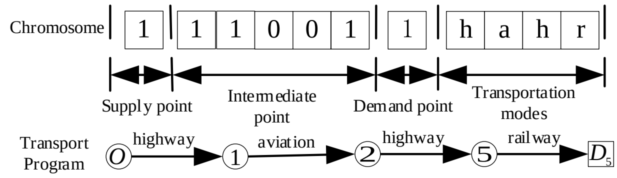

Fig.5. Chromosome coding pattern

In the lower model, real-value encoding operations are used in this paper. Chromosome $X=[x_i^b \mid i=1,2,...n]$, where n is the number of material demand points, and x_i^b represents the quantity of class b materials to be distributed to material demand point i. The value range of x_i^b is determined jointly by the $C_d^{b,l}$, $C_d^{b,u}$ and $C_d^{b,m}$ of the material demand points. The improvement of genetic algorithm is mainly reflected in the intersection and variation.

(1) Crossover: $X=[x_i^b \mid i=1,2,...n]$ is coded with real values in this section. In order to protect some information of the paternal chromosomes, analog binary crossover[38] is used in this paper, namely:

$$X_1^b = 0.5\cdot[(1-\tau)\cdot X_{1'}^b + (1+\tau)\cdot X_{2'}^b] \tag{24}$$

$$X_2^b = 0.5\cdot[(1+\tau)\cdot X_{1'}^b + (1-\tau)\cdot X_{2'}^b] \tag{25}$$

Where, X_1^b and X_2^b represent new individuals after crossing, $X_{1'}^b$ and $X_{2'}^b$ represent random individuals selected by roulette wheel method, and τ is shown in formula (26):

$$\tau = \begin{cases} [2\cdot\alpha]^{\frac{1}{\gamma+1}} & 0 \leq \alpha < 0.5 \\ [2\cdot(1-\alpha)]^{\frac{-1}{\gamma+1}} & 0.5 \leq \alpha < 1 \end{cases} \tag{26}$$

Where, α is random number between 0 and 1, and γ is the distribution index, in this paper, $\gamma=5$.

The specific process of crossover is shown in Figure. 6. All the gene sites will be crossed and the corresponding crossed genes will be combined to obtain the new two chromosomes after crossing.

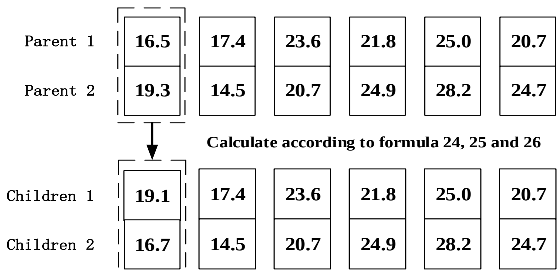

Fig.6. Schematic diagram of crossover operation

(2) Mutation: In order to avoid falling into local optimization, real value variation is selected, as shown in formula (27) to (28):

$$X_i^b = X_{i'}^b + \eta\kappa \tag{27}$$

$$\kappa = \begin{cases} (2\cdot\beta)^{\frac{1}{\lambda+1}} & 0 \leq \beta < 0.5 \\ 1-[2\cdot(1-\beta)]^{\frac{1}{\lambda+1}} & 0.5 \leq \beta < 1 \end{cases} \tag{28}$$

Where, η is the step size, it is set according to the size of the problem, $\beta \in (0,1)$ is the random number, λ represents the distribution index, and $\lambda=5$ in this section.

The specific process of variation is shown in Figure. 7. All gene sites are mutated. New chromosomes can be obtained by combining the mutated corresponding genes.

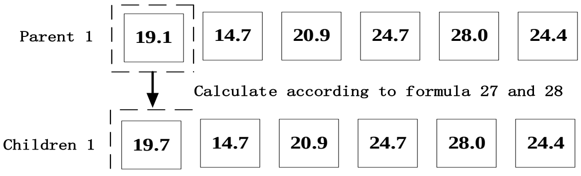

Fig.7. Schematic diagram of variation operation

B. Algorithm Steps

The algorithm flow is shown in Figure.8.

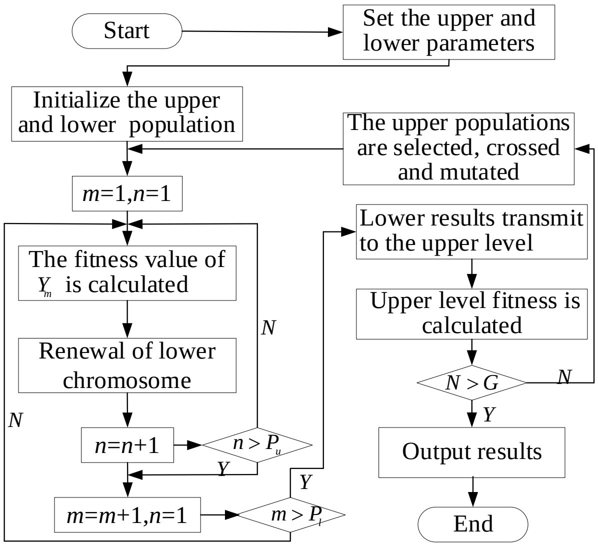

Fig.8. Algorithm flow

Step1: Parameters of upper and lower level genetic algorithm are set. The upper fitness evaluation function F_1 is determined as shown in formula (29):

$$F_1 = f_1 \tag{29}$$

Step2: The upper feasible solution X_k is initialized, the materials are distributed according to the fuzzy demand of emergency materials and the result of upper route selection.

Step3: The fitness evaluation function F_2 of the lower model is determined as shown in formula (30):

$$F_2 = f_2 \tag{30}$$

Step4: Let the number of upper iterations k=0, for each solution x in the upper feasible solution set X_k, the optimal solution set Y_k of the lower level is solved according to the iterative rules of the lower level genetic algorithm.

Step5: returning each solution y in Y_k back to F_1, so as to obtain the fitness function value corresponding to the upper solution X_k.

Step6: The roulette wheel method is used to select the offspring satisfying the upper feasible solution X_k to accomplish crossover mutation operation. and then the new offspring are brought into the lower level to solve the lower level optimal solution set Y_k, and return to the F_1 to obtain the corresponding fitness function value, then X_k is updated according to the principle of survival of the fittest, and $k = k+1$ was set at the same time.

Step7: Judge whether upper $K>G$, the algorithm terminates, otherwise, repeat Step 6.

IV. CASE STUDY

A. Case Background

Suppose a major emergency occurred in an area, the transportation network diagram is shown in Figure.9, material demand points are D in the affected area, numbered as q=6, the government sets up a material supply point O. The intermediate node n between the material supply points and the material demand points is numbered 1 to 5. In order not to lose generality, it is assumed that the transfer time between different transport models is shown in Table I, the distance of nodes is shown in Table II. The fuzzy demands for emergency materials are shown in Table III. $\varepsilon_{i,j}^{m} = 0.9$, σ=0.1.

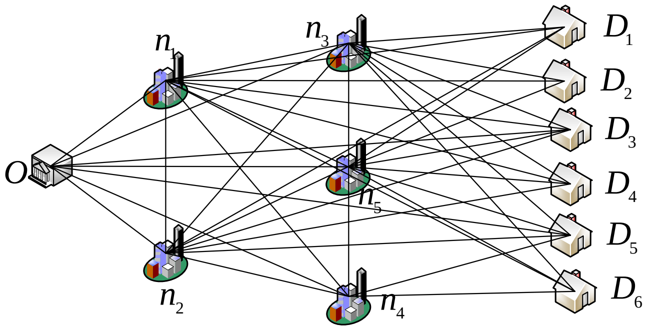

Fig.9. Transportation network diagram

TABLE I
TRANSIT TIME OF DIFFERENT TRANSPORT MODES (UNIT: H)

transport mode	highway	railway	aviation
highway	0	1	1.3
railway	1	0	1.5
aviation	1.3	1.5	0

TABLE II
MINIMUM TRANSPORT DISTANCE OF EMERGENCY MATERIALS BETWEEN TRANSPORT NETWORK NODES (UNIT: KM)

origination	destination										
	O	n_1	n_2	n_3	n_4	n_5	D_1	D_2	D_3	D_4	D_5	D_6
O	0	50	62	69	74	80	1000	1000	1000	1000	1000	1000
n_1	50	0	57	63	67	75	95	900	900	900	900	900
n_2	62	57	0	57	61	73	91	700	700	700	700	700
n_3	69	63	57	0	54	68	86	150	151	190	153	180
n_4	74	67	61	54	0	59	74	90	150	167	171	178
n_5	80	75	73	68	59	0	70	77	75	74	57	89

TABLE III
FUZZY DEMAND FOR EMERGENCY MATERIALS (UNIT: T)

Material Class	1						2						3					
demand point	D_1	D_2	D_3	D_4	D_5	D_6	D_1	D_2	D_3	D_4	D_5	D_6	D_1	D_2	D_3	D_4	D_5	D_6
Upper bound	45	48	40	39	56	47	75	78	70	69	86	77	65	68	60	59	76	67
Lower bound	5	8	10	7	21	9	25	23	19	17	26	22	15	13	9	7	16	13
Class Material	4						5						6					
demand point	D_1	D_2	D_3	D_4	D_5	D_6	D_1	D_2	D_3	D_4	D_5	D_6	D_1	D_2	D_3	D_4	D_5	D_6
Upper bound	95	98	90	89	99	97	85	88	80	79	96	87	55	58	50	49	66	57
Lower bound	20	18	14	12	21	18	35	38	29	27	36	32	30	33	24	22	31	27

B. Results Analysis

B.1 Algorithm Analysis

The upper population size is set as 40, crossover probability is set as 0.75, and mutation probability is set as 0.2. The lower population size is set as 40, crossover probability is set as 0.8, and mutation probability is set as 0.1. In this paper, the algorithm is implemented based on VisualStudio2017 development environment C++ programming language and MATLAB language. The algorithm iteration process is shown in Fig. 10 and 11.

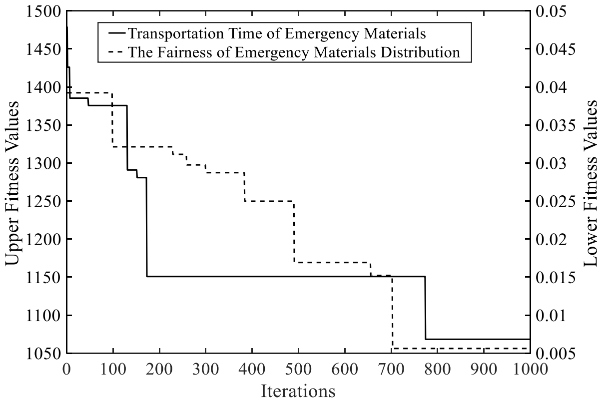

Fig.10. Genetic algorithm iteration

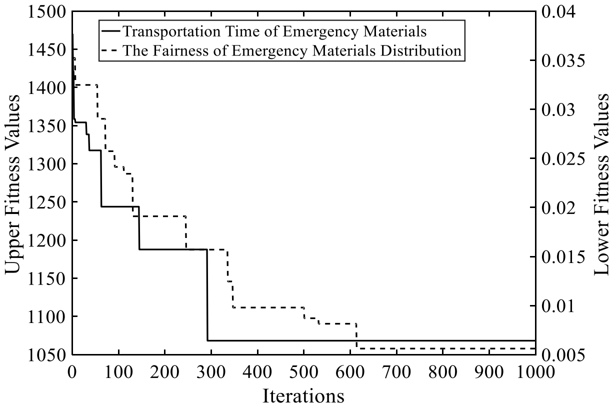

Fig.11. Improved genetic algorithm iteration

TABLE IV
RESULTS COMPARING OF DIFFERENT GENETIC ALGORITHM

	$f_1(x,y)$	$f_2(x,y)$	iterations
GA	1068.512	0.00562	750
I-GA	1068.512	0.00562	600

Notes: GA represents genetic algorithm, I-GA is improved genetic algorithm.

It can be seen from the iteration results in Table IV that there are $f_1 = 1068.512$ and $f_2 = 0.00562$, which shows that the algorithm is convergent. Moreover, the time complexity of the improved genetic algorithm is affected by the iterations number and the size of the solution set, the entire algorithm of the bi-level optimization model converges within 6 minutes. By comparing Table IV, it can be found that the improved genetic algorithm converges overall when the number of iterations reaches about 600 generations. While the unimproved genetic algorithm converges when the number of iterations is about 750 generations, this indicates that the improved algorithm is effective.

Because the convergence performance of genetic algorithm is mainly affected by algorithm parameters such as population size[39]. Therefore, this paper conducts 10 simulation experiments with different population sizes to analyze the effects of population size on the convergence performance of the bi-level optimal scheduling scheme of emergency materials. The simulation results are summarized in Table V.

TABLE V
CONVERGENCE PERFORMANCE OF THE IMPROVED GENETIC ALGORITHM UNDER DIFFERENT POPULATION SIZES

No.	Pop size -30		Pop size -40		Pop size - 50	
	iterate	T/min	iterate	T/min	iterate	T/min
1	760	8.43	627	12.62	491	19.32
2	787	6.68	594	12.15	517	19.15
3	765	9.98	627	13.07	484	18.63
4	845	7.88	587	10.68	450	17.32
5	836	6.72	625	10.42	519	19.42
6	810	6.08	567	10.18	474	19.45
7	828	6.73	570	11.98	528	16.68
8	759	7.10	629	13.37	508	19.35
9	801	6.90	587	12.57	512	16.57
10	835	6.15	646	11.98	514	17.28
Avg	803	7.27	606	11.90	500	18.32

Notes: Avg represents average of iteration.

By observing the speed of algorithm convergence and running time of program under different population sizes listed in Table V, it can be concluded that as the population size becomes larger, the algorithm has a faster convergence speed, but the program running time becomes more longer. The scheme of emergency materials scheduling must be made in a very short time after emergencies, the population size cannot be increased infinitely due to the limitation of the program running time. In other words, when the program running time can adapt to it, the size of the population can be increased to improve the convergence speed of the scheme.

B.2 Analysis of Path Selection Results

The results of upper path selection and transportation mode are shown in Table VI and VII. The transportation route and time is shown in Table VIII.

TABLE VI
RESULTS OF UPPER PATH SELECTION

material demand points	selection result of path node											
	O	n_1	n_2	n_3	n_4	n_5	D_1	D_2	D_3	D_4	D_5	D_6
D_1	1	1	1	1	0	0	1	0	0	0	0	0
D_2	1	0	0	0	0	1	0	1	0	0	0	0
D_3	1	0	0	0	1	0	0	0	1	0	0	0
D_4	1	0	0	0	0	1	0	0	0	1	0	0
D_5	1	0	1	1	0	0	0	0	0	0	1	0
D_6	1	0	0	0	0	1	0	0	0	0	0	1

Note: 0 means not passing through the node, and 1 means passing through the node, $n_i \in N$.

TABLE VII
CALCULATION RESULTS OF UPPER PATH TRANSPORTATION MODE

origination	destination											
	O	n_1	n_2	n_3	n_4	n_5	D_1	D_2	D_3	D_4	D_5	D_6
O	h	t	t	t	a	a	t	h	t	a	h	h
n_1	a	a	a	a	a	t	t	h	t	a	t	h
n_2	t	a	a	a	t	a	h	h	t	a	t	h
n_3	t	a	a	a	a	t	a	t	g	a	h	h
n_4	t	a	t	t	a	a	t	h	a	h	a	t
n_5	a	a	a	a	a	h	h	a	h	a	h	h

TABLE VIII
TRANSPORTATION PATH AND TIME OF EMERGENCY MATERIALS

material demand points	Optimal path	Transportation time/min
1	$O - railway - n_1 - aviation - n_2 - aviation - n_3 - aviation - D_1$	212.675
2	$O - aviation - n_5 - aviation - D_2$	74.849
3	$O - aviation - n_4 - aviation - D_3$	86.371
4	$O - aviation - n_5 - aviation - D_4$	67.147
5	$O - railway - n_2 - aviation - n_3 - highway - D_5$	427.826
6	$O - aviation - n_5 - highway - D_6$	199.644

The transportation path and the transport mode of emergency materials in each material demand point can be seen from Table VIII. It is not difficult to find that the aviation transportation mode plays a dominant role, followed by the railway and highway. Therefore, in order to transport emergency materials to material demand points during golden rescue time, decision-makers should pay attention to aviation transportation. At the same time, the material demand point 5 takes the longest transportation time, this is because the material demand points 5 is in high demand for emergency materials. Besides, its disaster degree is also the most serious among all the material demand points. Therefore, material demand points 5 should be taken seriously by decision-makers.

B.3 Analysis of Materials Distribution Results

The results of emergency material distribution are shown in Fig. 12, 13, 14and Table IX.

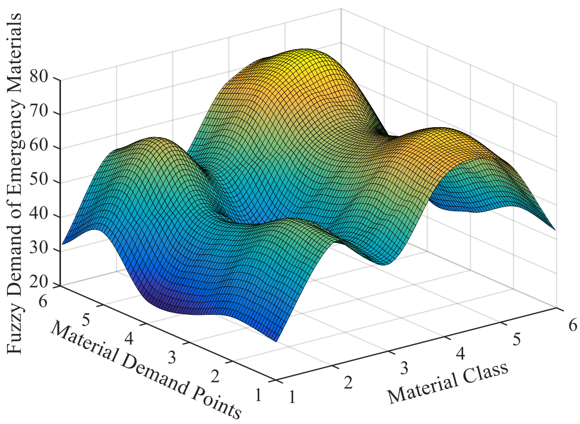

Fig.12. Fuzzy average demands of emergency materials

Figure.12 shows the fuzzy demand for various emergency materials at each material demand point. It can be found that the first material has the lowest demand, which is in the bottom of the surface. While the fifth class material has the largest demand, which is in the top of the surface. From the perspective of material demand points, it can be found that material demand point 4 has the lowest total material demand, which is in the bottom of the surface. While material demand point 5 has the largest total material demand, which is in the top of the surface.

TABLE IX
DISTRIBUTION RESULTS OF MATERIALS (UNIT: T)

MC	Materials Demand Points						Sum
	D_1	D_2	D_3	D_4	D_5	D_6	
1	25.0	28.0	25.0	23.0	38.5	23.0	162.5
2	25.7	24.6	23.0	21.5	26.4	23.6	144.7
3	15.7	14.6	13.0	11.5	16.4	14.2	85.3
4	28.2	26.5	19.4	19.6	27.3	27.2	148.1
5	35.7	38.7	39.0	31.5	36.4	33.6	214.8
6	42.5	42.0	37.0	35.5	48.5	42.0	247.5
Sum	172.8	174.3	156.3	142.5	193.5	163.6	1003

Note: MC means materials class

Table IX shows the distribution results of emergency materials. It can be found that emergency materials is provided at every material demand point, and all kinds of materials are distributed to materials demand points, this effectively avoids the lack of a certain class of emergency materials in one disaster stricken points while other disaster-stricken points are over-distributed the materials.

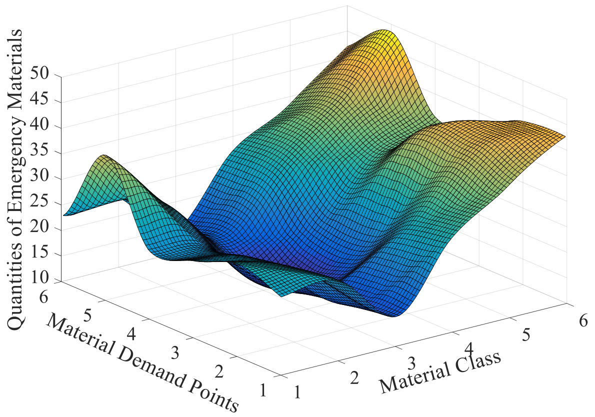

Fig.13. results analysis of emergency material distribution

In Figure.13, from the perspective of the materials demand, it can be found that the third class materials by distributed are the lowest and all of them are at the bottom. While the sixth class material by distributed is the largest and all of them are at the top. From the perspective of material demand points, it can be found that the quantity of material distribution in material demand points 4 is the lowest, which is in the bottom. While the quantity of material distribution in material demand points 6 is the largest, it is in the top of the surface. By comparing Figure.12 and 13, it can be found that the material demands of each material demand point is less than its average fuzzy demand, this is mainly because of the shortage of the emergency materials. So the emergency materials cannot fully meet the demands of the material demand points.

The satisfaction degree of emergency materials distribution can reflects the fairness of material distribution and the emergency situation of all kinds of materials at material demand points, which can provide decision-makers with reference in the next step of material preparation. Figure.14 shows the satisfaction degree of emergency materials distribution in three-dimensional space.

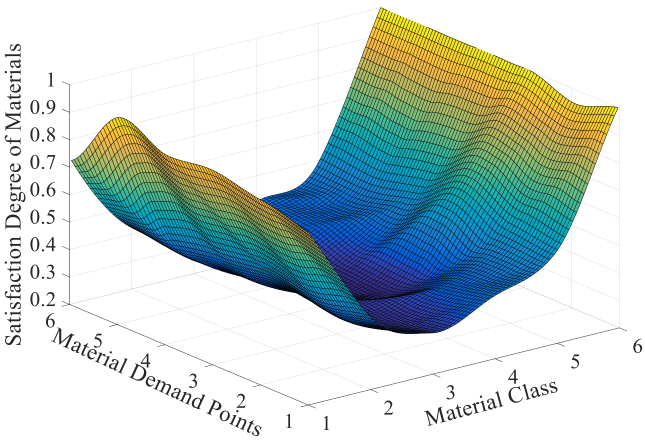

Fig.14. Satisfaction degree of emergency material distribution

As can be seen from Figure.14, the average satisfaction degree of material distribution for each material demand points is basically the same, with the average value ranging from 0.56 to 0.61, which indicates that the fairness of emergency material distribution is high. For each material demand points, the satisfaction degree of the first and sixth class materials is relatively high, but the satisfaction degree of other materials is not so high. The main reason is that the emergency materials are in short, and the material demand points can’t be satisfied on a large extent. Therefore, decision-makers should pay attention to the preparation of the second, third, fourth and fifth class materials to ensure the secondary emergency material scheduling can maximize the satisfaction degree.

B.4 Analysis of Crucial Parameters

In this paper, since the road section accessibility ($\varepsilon_{i,j}^{m}$) and the impact of secondary disasters (σ) are in an open environment and have a great impact on the transportation time of materials. Therefore, the sensitivity of them is further analyzed. The results are shown in Figures.15, 16 and 17.

As can be seen from the trend of Figure.15 and 16, secondary disasters and road section accessibility has a great impact on the transportation time of materials. The lower road accessibility and the impact of secondary disasters will lead to the longer transportation time of emergency materials.

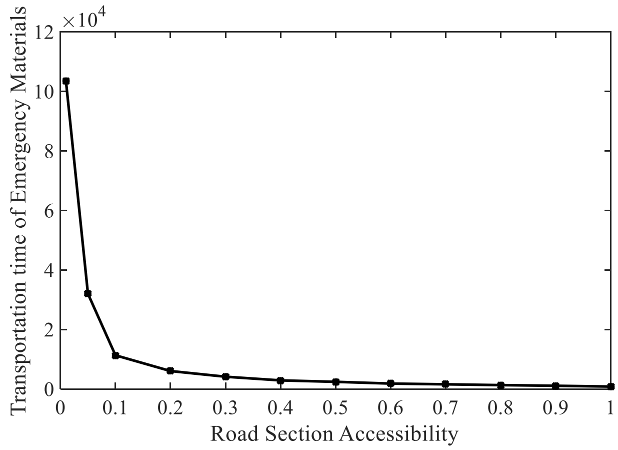

Fig.15. Influence of road section accessibility on transport time

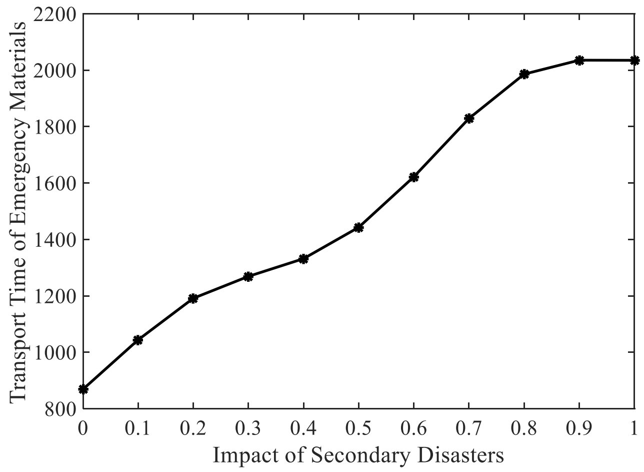

Fig.16. Influence of secondary disasters on transport time

As can be seen from the overall trend of Fig. 17, it is found that the influence of road section accessibility is far greater secondary disasters on the transportation time of emergency materials. Therefore, it may be difficult for emergency materials to be transported to the material demand points within the golden rescue time after emergencies. This will become the leading cause of emergency rescue failure. Therefore, the decision-makers should attach more importance on it.

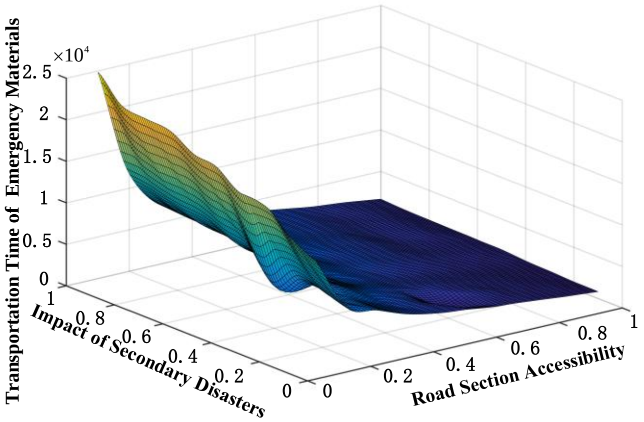

Fig.17. Comprehensive influence of road section accessibility and secondary disasters on transport time

B.6 Model simulation analysis under different perspectives

In order to verify the rationality of the model, the emergency material scheduling problem is considered from three different perspectives. The first is to consider the emergency material scheduling problem from the government's perspective, it is to minimize the transportation time of emergency materials without considering the subjective feelings of the victims. The second is to consider the emergency material scheduling problem from the perspective of victims; it is to maximize the satisfaction of victims with the fairness of material distribution. It can be found that the first two perspectives consider the emergency material scheduling problem from the perspective of different dominant players, while ignore the extreme situations that may occur in the case of a single perspective. The third is to consider the emergency material scheduling problem from the perspective of the government and the victims, which is defined as a bi-level optimal scheduling model. To avoid extreme situations from a single perspective, the two decision-makers (government and victims) are taken into account to determine the best solution in the proposed model. The simulation results of emergency material scheduling considering three different perspectives are shown in Table X. The objective functions of the upper and lower models are expressed by $f_1(x,y)$ and $f_2(x,y)$ respectively.

TABLE X
MODEL SIMULATION ANALYSIS UNDER DIFFERENT PERSPECTIVE

perspective	$f_1(x,y)$	$f_2(x,y)$
Government	819	0.01098
Victims	1837.520	0.00261
Bi-level	1068.512	0.00562

In Fig. 18, a graphical representation of the optimal point for the bi-level solution appears.

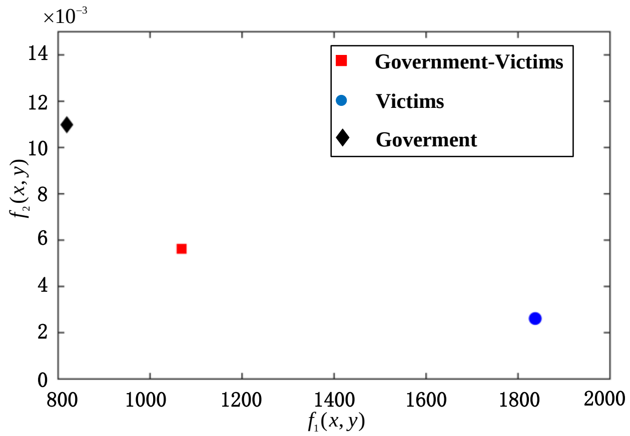

Fig. 18 Graphical illustration of the bi-level equilibrium

As can be seen from the simulation results in Table IX, $f_1^{goverment} < f_1^{bi-level} < f_1^{victims}$, $f_2^{goverment} < f_2^{bi-level} < f_2^{victims}$ .The results show that (1) under the government's perspective we can obtain the path scheme that is the shortest transportation time, but the variance of the material satisfaction degree is large at the material demand points. So the victims' satisfaction of the fairness is the lowest. This may lead to bad public opinion. (2) Under the victim's perspective we can improve the satisfaction of the fairness, but the transport time of the emergency materials is longer. This may make the emergency materials can't reach the material demand points within the golden rescue time. Obviously, both of these solutions are extreme situation, (3) from the perspective of the government and the victims, the solution obtained through the bi-level optimal model of emergency materials scheduling is obviously neutral. Therefore, it can provide the decision-maker with further reference on emergency material scheduling problem.

In order to verify the advantages of the bi-level optimal model of emergency materials scheduling in this paper, the growth rate formula of reference [39] is introduced to calculate the growth rate of two schemes relative to the optimal scheme. The calculation results are shown in Table XI、XII and Fig. 19. The growth rate formula is as follows:

$$\%increase = \frac{(current \quad value) - (best \quad value)}{(best \quad value)} \tag{31}$$

Figure 19 shows the comparative results of material transportation time at each material demand points. From the comparison results, we can see that the bi-level optimization model slightly increases the material transportation time compared with the single-objective model. This is mainly because the fairness of emergency materials distribution is not considered in the single-objective model.

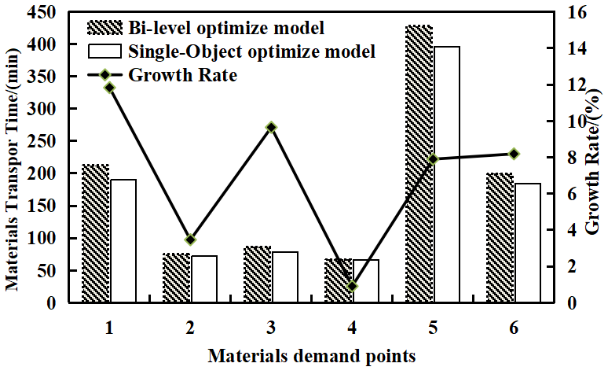

Fig. 19 Comparative analysis of the transport time in material demand points

On the one hand, the transportation time of emergency materials from the perspective of government is the smallest. The transport time of emergency materials from the perspective of government is compared with that from the other two perspectives. On the other hand, the variance of emergency materials distribution from the perspective of victims is the smallest. The variance of emergency supplies distribution from the perspective of victims is compared with that from the other two perspectives. The comparison results are shown in Table XI.

TABLE XI
The Increase Ration of Solutions under Different Perspectives to the Optimal Solution

	Increase in time (%)	Increase in variance (%)
government	——	320.69
Victims	124.36	——
Bi-level	30.47	115.33

TABLE XII
PERCENTAGE OF DECREASE PROVIDED BY THE BI-LEVEL MODEL

	Decrease in time (%)	Decrease in variance (%)
government	-23.35	95.37
Victims	71.97	-53.56
Bi-level	——	——

As shown in Table XII, when we comprehensively consider the bi-level optimal scheme of emergency materials scheduling from the perspective of the government and the victims, instead of choosing the optimal scheme from the single perspective of the victims, the emergency materials transportation time is reduced by 71.97%. Besides, when we comprehensively consider the bi-level optimal scheme of emergency material scheduling from the perspective of the government and the disaster victims instead of choosing the optimal scheme from the government's single perspective, the emergency material distribution variance at the material demand points is reduced by 95.37%. In both cases, the reduction is more significant than the expected increase shown in TableXI. The negative values respectively represent the increase in the total transportation time and distribution variance of emergency materials in Table XII.

V. CONCLUSION

This paper mainly studies the emergency material scheduling problem after emergencies. Aiming at the timeliness and fairness of emergency material scheduling, we constructs a bi-level optimization model of emergency materials scheduling considering multimodal transport.

Firstly, the simulation results show that the scheduling scheme of emergency material proposed in this paper considers both accessibility of road section and influence of secondary disaster, the transportation time of emergency materials is positively correlated with the accessibility of road sections, and negatively correlated with the impact of secondary disasters. Besides the scheme has satisfactory convergence performance, it can be applied to emergency material scheduling problems in different scales.

In addition, the comparative results of algorithms show that the improved genetic algorithm designed in this paper is feasible to solve the bi-level optimal problem of emergency material scheduling after emergencies. At the same time, it also proves the rationality of the model and algorithm designed in this paper.

Finally, the bi-level optimization model of emergency material scheduling is compared with the other two models considering extreme cases, the results are shown in Figure 18. The comparative results of model under different perspectives show the neutral solution obtained by the bi-level optimal model of emergency material scheduling effectively avoids extreme situations, it makes the scheme of emergency materials scheduling not only consider the transportation time of emergency materials, but also take into account the fairness of emergency materials distribution, and has great reference value for decision makers.

Future work will focus on considering the dynamic change of materials demand on the impact of emergency material scheduling scheme.

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