Research on location-routing problem of highway and high-speed railway multimodal transportation considering timeliness demand

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Abstract—Nowadays, highway and high-speed railway multimodal transportation can meet the customer demand for timely services, which is also the focus of logistics enterprises. Reasonable logistics nodes layout and routing optimization can help logistics organizations save costs and time. Therefore, this paper mainly discusses the location-routing problem of highway and high-speed railway multimodal transportation. Considering the time-sensitive nature of customer demand, the logistics services are divided into three types: arrival on the same day, arrival on the next morning and arrival on the next day, thereupon the penalty cost function for customer timeliness demand is designed, and then the Multi-Dot Location-Routing Problem with Time Window (MDLRPTW) model based on timeliness demand is constructed. Meanwhile, this model simultaneously determined quantities and locations of distribution centers, transportation modes and routes from logistics centers to distribution centers, quantities and locations of transportation mode conversion facilities and routes of products from the distribution centers to customer nodes. An integer linear programming is presented for the problem, and a genetic algorithm with a new chromosome structure proposed to solve the problem. Proposed chromosome structure consists of two different parts for multimodal transportation and location-routing parts of the model. Finally, simulation results show: the proposed method can provide reasonable suggestions for logistics enterprises to reduce the cost and improve service efficiency, furthermore, it also provides a theoretical reference for the practice of multimodal transportation location-route problem.

Keywords—Location-routing problem; Multimodal transportation; Timeliness requirements; Genetic algorithm

I. INTRODUCTION

Multimodal transportation of highway and high-speed railway refers to the "one ticket, door to door" transport of goods by road and high-speed rail. Among them, the speed of the high-speed railway trunk line can reach 350 km/h and the load can reach 120 tons, which has a certain scale benefit from the unit transport cost of goods. Under the impact of COVID-19, on January 26, 2020, through the unified deployment of the Material Department of China Railway Zhengzhou Bureau Group and other relevant ministries and commissions, multiple batches of emergency medical supplies were transported to Wuhan by G545 train, and the end was connected by road, successfully delivering these supplies to hospitals in the epidemic area at the first time. In addition, carrying out the combined transport business of highways and railways can not only improve the logistics efficiency in the emergency, but also effectively use the idle transport capacity at ordinary times and increase the operating income of high-speed railway lines. In general, there are the following characteristics of multimodal transportation of highway and high-speed railway.

(1) It overcomes the isolation of traditional highway and high-speed rail freight, strengthens the connection between different modes of transportation, and is conducive to improving the logistics service level.

(2) The unified deployment of the two modes of transportation can effectively utilize the resources such as facilities and equipment in the transportation network, effectively speed up the turnover of goods and reduce the detention time.

(3) From the perspective of environmental protection, highway and rail intermodal transport can help reduce the pressure of road transport, alleviate urban traffic congestion and reduce air pollution.

II. LITERATURE REVIEW

In terms of highway and high-speed rail intermodal transportation, Xie, Lu, Wang, and Quadrifoglio[1] introduced a location and route selection problem for dangerous materials on a multimodal transportation network. Also they used risk parameters in the problem because of dangerous materials. Pazour Jennifer A[2] thought that foreign high-speed railway lines have the potential to carry out freight business, and established a network model with capacity constraints on the basis of ensuring the timeliness of transportation. Winebrake JJ[3] considered that energy and environmental parameters will have an impact on the total cost, and establishes a multi-objective mathematical model that comprehensively considers the factors such as time window, vehicle transportation distance and environmental pollution. Jeong[4] analyzed the facility hubs and transportation routes in high-speed rail freight lines, and built an integer programming

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model with the lowest operating cost and the lowest transportation time. Hajibabai and Ouyang[5] presented a location and routing problem for biofuel transformation facilities.

As for location-routing problem research, it is defined by Nagy and Salhi[6] as: "location planning with tour planning aspects taken into account", emphasizing that Location-Routing should be an integrated solution. Martin[7] studied the LRP model with capacity constraints and solved the model using neural network algorithm. Macedo[8] and others combined the variable neighborhood search algorithm with the large neighborhood search (LNS) algorithm proposed by Hemmelmayr[9] to solve the periodic location-path optimization problem.

Research on the LRPTW problem, Zarandi et al[10]proposed LRPTW under uncertainty. They represented demands and travel times as fuzzy variables, with a fuzzy chance constrained programming (CCP) model designed using credibility theory. Gharavani and Setak[11] described a LRPTW onto which a semi-soft time window was imposed where delays in service delivery resulted in penalties (cost).Gündüz[12] addressed single-stage LRP with time windows and proposed a Tabu search heuristic to efficiently solve largescale instances. Mirzaei, Krishnan, and Yildrim[13] explained a development of the LRPTW where energy minimization was considered: energy-efficient LRPTW. Govindan, Jafarian, Khodaverdi, and Devika[14] introduced a two-echelon LRPTW for sustainable supply chain network design and optimizing economic and environmental objectives in a perishable food supply chain network.

Through literature analysis, it can be seen that there is little research on road and high-speed railway intermodal transportation, and currently there is no literature considering the classification of goods in LRPTW research. Considering the time-sensitive nature of customer demand, the logistics services are divided into three types: arrival on the same day, arrival on the next morning and arrival on the next day, thereupon the penalty cost function for customer timeliness demand is designed, and then the Multi-Dot Location-Routing Problem with Time Window (MDLRPTW) model based on timeliness demand is constructed. The proposed method can provide reasonable suggestions for logistics enterprises to reduce the cost and improve service efficiency.

III. THE PENALTY COST OF TIME FUNCTION DESIGNED FOR CUSTOMER TIMELINESS REQUIREMENTS

Set different ideal service time windows and acceptable service time windows for the above three types of timeliness goods according to the expectation and tolerance of different customer groups for logistics services. Take the current day, next morning and next day delivery products of China Railway Express as an example, when the delivery time of goods is advanced, delayed or exceeds the customer's tolerance time window, there will be corresponding time penalty costs. However, if it is delivered in advance, it will disrupt the customer's plan, which is universal and has nothing to do with the type of goods.

In this section, the penalty cost of time function designed for customer timeliness requirements is as follows:

$$\varphi_i\left(T_{ip}\right)=\begin{cases} f_1\left(Et_{ip}-T_{ip}\right), T_{ip}<Et_{ip} \\ 0, Et_{ip}<T_{ip}<Lt_{ip} \\ f_2^p\left(T_{ip}-Lt_{ip}\right), Lt_{ip}<T_{ip}<LLt_{ip} \\ f_2^p\left(LLt_{ip}-Lt_{ip}\right) \\ +f_3^p\left(T_{ip}-LLt_{ip}\right), T_{ip}>LLt_{ip} \end{cases} \tag{1}$$

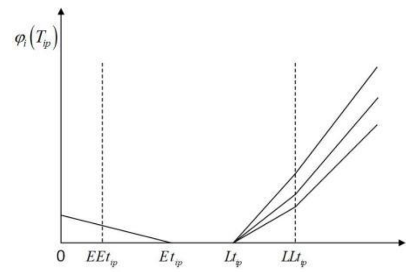

Fig. 1 Penalty cost of time function

In the formula, f_1 represents the penalty cost of time coefficient when the products are delivered to all customers in advance; f_2^p represents the penalty cost of time coefficient when the vehicle delays arriving at the customer point with the required goods category within the acceptable time window; f_3^p represents the penalty cost of time coefficient of del

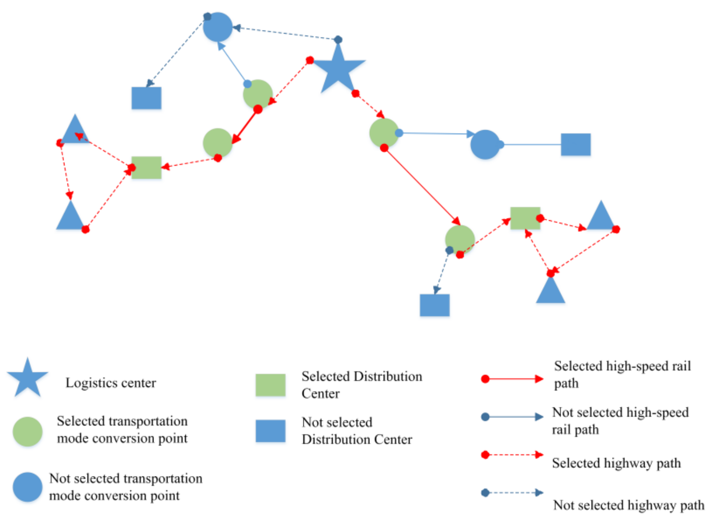

Fig. 2 Schematic diagram of LRP in multimodal transportation of highway and railway based on customers' timeliness requirement

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ayed delivery of goods to the customer when the vehicle exc eeds the acceptable time window。

IV. PROBLEM DESCRIPTION AND MATHEMATICAL FORMULATION

The problem can be described as: in the commodity supply and demand system of two different cities, there is one logistics center, several potential distribution centers and several customer nodes. Now a batch of goods is transported from the logistics center node to each customer node to meet the personalized needs of different customers.

In general, the model built in this summary mainly solves the following four problems: (1) Determine the number and location of distribution centers. (2) Determine the transportation mode and route from the logistics center to the distribution center. (3) Determine the number and location of transportation mode conversion points. (4) Determine the route of goods from the distribution center to each customer node.

A. The Assumptions

In order to highlight the important factor of timeliness requirements of different customers, the following assumptions are proposed for the model: (1) The geographical location of the distribution center and all customer nodes is known, and the cost of goods from any transfer point to the distribution center is included in the use cost of the distribution center; (2) The customer demand and the capacity of the distribution center are limited by the capacity of the transport vehicles. The vehicles start from the logistics center node at 0 o'clock and always keep a constant speed. (3) Once the vehicle enters the transportation mode conversion point, the transportation mode will be changed. The starting point and destination of any vehicle providing service must be in the same distribution center, and the vehicle activation cost will be included in the transportation cost, and will not be calculated separately; (4) Only one mode of transportation can be selected for one kind of goods. The difference in freight rates due to the type of goods is mainly the whole process of transportation and the time and cost of sorting, loading, unloading and handling in the distribution center; (5) In the path from the logistics center to the customer, there are at most two transportation mode conversion points between each line, and only high-speed rail transportation is used between each transportation mode conversion point.

B. The notations

(1) Sets

O : Location of logistics center ; M : Modes of transportation, $M \in$ {H (Highway), R (High-speed railway)}; V : Set of group of transportation mode conversion nodes. (Highway and high-speed railway are used in the route from the logistics center to the distribution center); E_{mp} : Set of products (P) adopts different transportation routes, and there is a connection between points of transportation mode (M). (From logistics center to distribution center); J : Potential distribution center nodes; I : Customer nodes; R : Set of logistics center nodes, facility conversion nodes and potential distribution center nodes. $R=\{V \cup O \cup J\}$; $G=I \cup J$: Set of potential distribution centers and customer nodes ; $N=R \cup I$: Set of logistics centers, transportation mode conversion nodes, potential distribution centers and customer nodes; K : Set of all vehicles used to deliver products from the distribution center to customers; P : Set of the type of products。

(2) Parameters

d_{ij} : Distance between nodes i and j , $i,j \in G$; D_{ab} : Distance between nodes a and b , $a,b \in R$; q_i^p : Raised demand by customer i ; Q_k : Capacity of vehicle k ; τ_k : The transportation time per unit distance of vehicle k from the distribution center to the customer node; τ_{m} : Transportation time per unit distance of transportation mode m ; C_{kp} : The transportation cost per unit distance from the distribution center to the customer point for products p and vehicle k ; C_{mp} : For products p , the transportation cost per unit distance of transportation mode m is adopted; F_j : Use cost of distribution center j , $j \in J$; η_{jp} : Time for products p to sort unit products in the distribution center at node j , $j \in J$; σ_{jp} : For products p , the cost of sorting unit products in the distribution center at node j , $j \in J$; θ : Number of customer nodes; δ_{V} : The handling cost of unit product when the mode of transportation is changed; ε_{V} : Loading and unloading time of unit product when the mode of transportation is changed ; n : Number of potential distribution centers ; St_r : Time to provide service for customer point r ; t_{ip} : The time when products p arrive at customer node i from the distribution center; t_{jp} : The time when products p arrive at the distribution center from the logistics center; T_{ip} : The time when products p arrive at customer point i from the logistics center; φ_i : Penalty cost function; $\left[Et_{ip}, Lt_{ip}\right]$: The best service time window of customer node i for products p ; $\left[EEt_{ip}, LLt_{ip}\right]$: Acceptable time window of customer node i for products p ;

(3) Decision variables

$z_j=1$, If a distribution center is established at node j , $j \in J$, Else $z_j=0$; $\gamma_{jp}=1$, If the distribution center of products p is established at node j , $j \in J$, $p \in P$; Else $\gamma_{jp}=0$; $u_{ijp}=1$, If products p of customer point i are assigned to distribution center j , $i,j \in G$ $p \in P$; Else $u_{ijp}=0$; $y_{vp}=1$, If the mode of transportation of products p is changed at v ; $v \in V$, $p \in P$, Else $y_{vp}=0$; $x_{ij}^{kp}=1$, If the vehicle k transport products p from node i to node j ; $i,j \in G$, $p \in P$, Else $x_{ij}^{kp}=0$; w_{ab}^{jmp} : The quantity of products p during transportation, based on transportation mode m , from node a to b , $a,b \in V \cup J$; β_{ab}^{jmp} : This path exists for products p , which is based on transportation mode m , from node a to node b , $a,b \in V \cup J$.

C. Explanation of Objective Function Calculation

(1) Cost components

The objective function: $\operatorname{Min} Z=C+\sum_{p}^{P} \sum_{i=1}^{N} \varphi_i\left(T_{ip}\right)$

The total cost in the objective function is mainly composed by penalty cost of time and other cost:

$$
\begin{aligned}
C = &\sum_{i}^{G}\sum_{j}^{G}\sum_{k}^{K}\sum_{p}^{P} C_k d_{ij} x_{ijkp} + \sum_{j}^{J} F_j Z_j \\
&+\sum_{(a,b)}^{E_{mp}}\sum_{m}^{M}\sum_{j}^{J}\sum_{p}^{P} D_{ab} C_m w_{ab}^{jmp} \\
&+\sum_{v}^{V}\sum_{p}^{P}\sum_{(a,b)}^{E_{mp}} w_{ab}^{jmp}\delta_v y_{vp} + \sum_{m}^{M}\sum_{j}^{J}\sum_{p}^{P}\sum_{(a,b)}^{E_{mp}} w_{ab}^{jmp}\sigma_{jp} z_j
\end{aligned} \tag{2}
$$

The first part of the above formula represents the transportation cost of products p from the distribution center to the customer point; The second part represents the fixed cost of establishing or leasing a distribution center; The third part represents the transportation cost of products p from the logistics center to the distribution center; The fourth part shows the handling cost of products p when the mode of transportation is changed; The fifth part shows the cost of products p when sorting, loading, unloading and handling in the distribution center.

(2) Transportation time

The transportation time of products p from the logistics center to the distribution center is:

$$
time_1 = \sum_{(a,b)}^{E_{mp}}\sum_{m}^{M}\sum_{j}^{J}\sum_{p}^{P} D_{ab}\tau_m \beta_{ab}^{jmp} \tag{3}
$$

When the transportation mode is changed, the loading and unloading time of products p at the transfer station is:

$$
time_2 = \sum_{(a,b)}^{E_{mp}}\sum_{v}^{V}\sum_{p}^{P} \varepsilon_v y_{vp} w_{ab}^{jmp} \tag{4}
$$

The time for loading, unloading, handling and sorting of products p in the distribution center is:

$$
time_3 = \sum_{(a,b)}^{E_{mp}}\sum_{j}^{J}\sum_{p}^{P} \eta_{jp}\gamma_{jp} w_{ab}^{jmp} \tag{5}
$$

Therefore, the time of products p from the logistics center to the distribution center is:

$$
\begin{aligned}
t_{jp} &= time_1 + time_2 + time_3 \\
&= \sum_{(a,b)}^{E_{mp}}\sum_{j}^{J}\sum_{p}^{P} \eta_{jp}\gamma_{jp} w_{ab}^{jmp} + \sum_{(a,b)}^{E_{mp}}\sum_{m}^{M}\sum_{j}^{J}\sum_{p}^{P} D_{ab}\tau_m \beta_{ab}^{jmp} \\
&+ \sum_{(a,b)}^{E_{mp}}\sum_{v}^{V}\sum_{p}^{P} \varepsilon_v y_{vp} w_{ab}^{jmp}
\end{aligned} \tag{6}
$$

The time when products p are transported from the distribution center to customer node i is:

$$
t_{ip} = \sum_{k}^{K}\sum_{i}^{I} x_{ir}^{pk}(\mathrm{t}_{rp} + \tau_k d_{ir} + St_r), \forall p \in P, r \in I \tag{7}
$$

The time when products p are transported from the logistics center to the customer point i is:

$$
T_{ip} = t_{ip} + t_{jp} \tag{8}
$$

Refer to the following figure for specific time description:

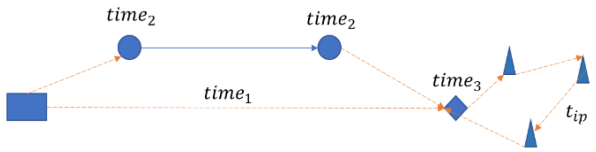

Fig. 3 Time description of the whole logistics process

D. The problem formulation

$$
\text{Min } Z = C + \sum_{p}^{P}\sum_{i=1}^{N} \varphi_i\left(T_{ip}\right) \tag{9}
$$

S.T.

$$
\sum_{(a,b)}^{E_{mp}}\sum_{m}^{M}\sum_{j}^{J} w_{ab}^{jmp} - \sum_{(b,c)}^{E_{mp}}\sum_{m}^{M}\sum_{j}^{J} w_{bc}^{jmp} = 0, \forall b \in V, \forall p \in P \tag{10}
$$

$$
\sum_{(a,b)}^{E_{mp}}\sum_{j}^{J} w_{ab}^{jmp} - \sum_{(b,c)}^{E_{mp}}\sum_{j}^{J} w_{bc}^{jmp} \le \mathrm{B} y_{bp}, \forall b \in V, m \in M, p \in P \tag{11}
$$

$$
\sum_{m}^{M}\sum_{(a,j)}^{E_{mp}} w_{aj}^{jmp} - \sum_{i}^{I} q_i^p u_{ijp} = 0 \quad \forall j \in J, a \in R, p \in P \tag{12}
$$

$$
\sum_{i}^{G} u_{ijp} = 1 \quad \forall j \in J, p \in P \tag{13}
$$

$$
w_{ab}^{jmp} \le \mathrm{B}\gamma_{jp} \quad \forall m \in M, (a,b) \in E_{mp}, j \in J, p \in P \tag{14}
$$

$$
\sum_{j}^{G}\sum_{k}^{K} x_{ij}^{kp} = 1 \quad \forall i \in I, p \in P \tag{15}
$$

$$
\sum_{i}^{I} q_i^p \sum_{j}^{G} x_{ij}^{kp} \le Q_k \quad \forall k \in K, p \in P \tag{16}
$$

$$
\sum_{r}^{G} x_{ir}^{pk} - \sum_{r}^{G} x_{rj}^{pk} = 0 \quad \forall k \in K, i \in G, \mathrm{j} \in \mathrm{G}, p \in P \tag{17}
$$

$$
\sum_{i}^{I}\sum_{j}^{J} x_{ij}^{pk} \le 1 \quad \forall k \in K, p \in P \tag{18}
$$

$$
\sum_{k}^{K} x_{rj}^{pk} + \gamma_{jp} + \gamma_{rp} \le 2 \quad \forall r = 1,\ldots,n, r, j \in J, p \in P \tag{19}
$$

$$
-u_{ijp} + \sum_{r}^{G}\left(x_{ir}^{pk} + x_{rj}^{pk}\right) \le 1 \quad \forall i \in I, j \in J, k \in K, p \in P \tag{20}
$$

$$
\sum_{i}^{I}\sum_{k}^{K} x_{ij}^{pk} - \gamma_{jp} \ge 0 \quad \forall j \in J, p \in P \tag{21}
$$

$$
\sum_{i}^{I} x_{ij}^{pk} - \gamma_{jp} \le 0 \quad \forall j \in J, k \in K, p \in P \tag{22}
$$

$$
\sum_{i,j \in G}^{N} x_{ij}^{pk} \le |G| - 1, G \in \{1,2,...,N\}, \forall k \in K, p \in P \tag{23}
$$

$$
z_j, u_{ijp}, y_{vp}, u_{ijp}, \gamma_{jp}, \beta_{ab}^{jmp} \in \{0,1\}, \forall i \in I, j \in J, v \in V \tag{24}
$$

$$
x_{ij}^{pk} \in \{0,1\}, \forall i, j \in G, k \in K, p \in P \tag{25}
$$

$$
w_{ab}^{jmp} \ge 0 \quad \forall i \in I, k \in K, a, b \in V, j \in J, m \in M, p \in P \tag{26}
$$

$$
EEt_{ip} \le T_{ip} \le LLt_{ip} \quad \forall i \in N, p \in P \tag{27}
$$

$$
t_0 = 0 \tag{28}
$$

$$
\gamma_{jp} \le \sum_{j} z_j, \mathrm{p} \in \mathrm{P} \tag{29}
$$

$$
\beta_{ab}^{jmp} \le B w_{ab}^{jmp}, \forall m \in M, (a,b) \in E_{mp}, j \in J, p \in P \tag{30}
$$

Formula (9) is the total cost minimization function, mainly including penalty cost of time and other costs; Constraint set (10) means that the entry quantity of products at each node is equal to the outflow quantity, that is, it meets the principle of

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conservation of total quantity of products; Constraint set (11) means that once the vehicle enters the transportation mode conversion node, the transportation mode will be changed, which is limited to the interchange of highway and high-speed rail freight modes; Constraint set (12) means that the total amount of products arriving at the distribution center is equal to the total amount of customer demand allocated to the distribution center, ensuring that each customer's demand can be met; Constraint set (13) means that each customer is only assigned to one distribution center, that is, the distribution center service does not cross; B in Constraint set (14) is a constant large enough to ensure that no products can be allocated to the distribution center that has not been established；Constraint set (15) means to designate a vehicle to serve each customer's different needs p；Constraint set (16) means that the total customer demand does not exceed the vehicle load capacity；Constraint set (17) means that once the vehicle transporting product p enters a node, it will exit the node to ensure that the vehicle travels along the cycle path；Constraint set (18) means to ensure that each vehicle can only serve a distribution center at most and can only be sent from that distribution center；Constraint set (19) means to ensure that there is no connecting path between distribution centers and there is no flow of goods between distribution centers；Constraint set (20) means to ensure that the customer is assigned to the distribution center if and only if there is a path from the distribution center to the customer；Constraint set (21) and (22) means that vehicles can only be sent from established distribution centers；Constraint set (23) is an auxiliary variable Constraint set, which is used to eliminate sub-circuits；Constraint sets (24)-(26) define variables and determine the symbols of model variables；Constraint set (27) indicates that the customer can accept the time window Constraint set；Constraint set (28) means that the vehicle starts from the logistics center node at 0 o'clock; Constraint sets (29) and (30) represent the relationship between parameters.

V. ALGORITHM DESIGN

LRP (location path problem) is a combination of LAP (location problem) and VRP (path problem), and both LAP and VRP are NP-hard problems. Therefore, LRP also belongs to NP-hard problems. At present, the solution of NP-hard problems is mainly based on intelligent optimization algorithms[16][17]. Considering the characteristics of the model built in this paper and the large amount of simulation data, the coding method of traditional genetic algorithms has been improved. The improved genetic algorithm is used for simulation.

Step 1: Chromosome coding. The first part uses matrix coding to represent the path of goods from the logistics center to the distribution center; The second part uses row vector coding to indicate the route of products from the distribution center to each customer node.

(1) Path code from logistics center to distribution center

The number of rows in the matrix is equal to the number of distribution centers. The number of columns represents the transformation nodes and transportation modes that pass through the path. Each row represents the path from the logistics center to the corresponding distribution center. The first element in the matrix represents the type of upstream transport mode conversion node. The number that can be selected is (0，1，2，…，n_{up}), and n_{up} represents the number of upstream transport mode conversion node. When the first element is greater than zero, it means that the upstream transport mode conversion node corresponding to the number is selected; When the element is equal to zero, it means that the upstream transport mode conversion point is not selected. Taking the first row of data as an example, it means that the logistics center uses highway transportation to reach the upstream transportation mode conversion node 1, then uses high-speed rail transportation to reach the downstream conversion node 2, and finally uses highway transportation to reach the distribution center 1, as shown in figure 4:

$$\begin{bmatrix} 1 & 2 & 1 \\ 3 & 1 & 0 \\ 0 & 4 & 1 \\ 3 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Fig. 4 Path coding method from logistics center to distribution center

(1) Path code from distribution center to customer

A row vector is used to represent the path from the distribution center to the customer. Take an example of five distribution centers and eight customer sizes, as shown in figure 5:

3 6 4 12 11 2 9 5 8 10 7 1

Fig. 5 Path coding method from distribution center to customer

The numbers 1 to 8 represent eight different customers, and the numbers 9, 10, 11 and 12 represent four different distribution centers. The whole vector is divided into five parts, and each part corresponds to one distribution center. Take figure 6 as an example to illustrate: the number in front of DCs 12 is {3, 6, 4}, which corresponds to the customers served by DCs 12, and the order of the number indicates the service order of customers, so the service route of DCs 12 is: DCs 12→ customer 3 → customer 6 → customer 4 → DCs 12. If the customer number in front of the DCs 11 is empty, it means that the DCs 11 does not serve customers, that is, t DCs 12 has not been established.

①	②	③	④	⑤
3 6 4	12	11 2	9 5 8	10 7 1

Fig. 6 Decomposition structure of route coding method from distribution center to customer

Step 2: Population initialization is generally produced randomly. The problem to be solved by the MDLRPTW model is to choose the optimal path of products with different timeliness from the logistics center to the customer node. Therefore, a chromosome should contain the matrix and vector combination of product quantity. The initialization generation of the matrix part in the chromosome should consider the path from the logistics center to each distribution center. For the first element of each row of the matrix, randomly select the number in (0, 1, 2, …, n_{up}), the second element randomly select the number in (0, 1, 2, …, n_{down}), the third element selects the number in (0, 1), and repeat the above steps until all elements in the matrix for each product are assigned.

For the vector part, a numerical order from 1 to n should be randomly generated, where n is equal to the sum of the number of distribution centers and customers minus 1. For

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each product, the number of customers who need it is different. Repeat the above steps until all elements in each product vector are assigned.

Step 3: Fitness function transformation. To minimize the value of the objective function in the model, the objective function of the minimum value can be converted into the fitness function of the maximum value.

$$f_z = \frac{1}{f_{\max} - f_{\min} + \delta}(f_{\max} - f + \delta) \qquad (31)$$

In the above formula, fz is the fitness function value after transformation, fmin is the minimum value in the same generation chromosome population, fmax is the maximum value in the same generation chromosome population, and f is the objective function value, δ belongs to interval (0, 1).

Step 4: Select operator. In order to improve the global convergence and avoid the loss of excellent genes, the roulette rule selection operator is adopted.

Step 5: The purpose of the crossover operator is to expand the characteristics of the population and generate new chromosomes. According to the coding method designed in step 1, it can be divided into matrix crossover operation and vector crossover operation.

(1) Matrix crossover

During matrix crossing, one of the two parent chromosomes can be randomly selected for exchange, and two new matrices can be produced as the composition of the offspring chromosomes, as shown in figure 7.

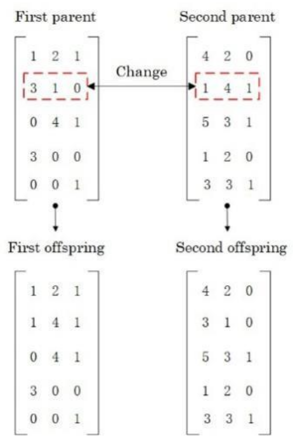

Fig. 7 Matrix crossing

(2) Vector crossing

For vector crossing, this algorithm uses partial mapping to carry out vector crossing.

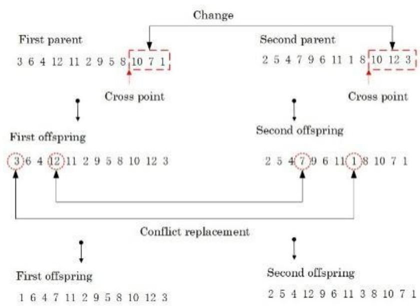

Fig. 8 Vector crossover

Step 6: Mutation operator. According to the different coding methods in step 1, matrix mutation and vector mutation are designed to generate new chromosomes, maintain population diversity, and increase the local search ability of the algorithm.

(1) Matrix mutation

First, the matrix part of a random product in the chromosome is selected for mutation, and then a row and column position is randomly produced. A number at this position is randomly generated according to the generation rules of the initial population, and a new matrix is produced as the composition of the offspring chromosome.

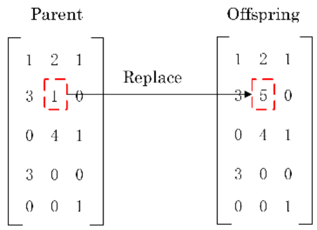

Fig. 9 Matrix variation

(2) Vector variation

For vector variation, firstly select some vectors of a random product in the chromosome for variation. There are three main ways of variation:

a) Two-point exchange mutation

Two elements in the vector are randomly selected and exchanged to generate the vector.

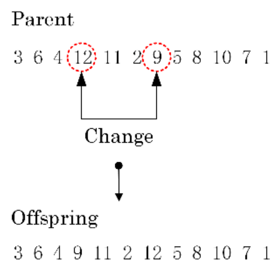

Fig. 10 Two node exchange mutation

b) Local exchange mutation

Two elements in the vector are randomly selected, and the segments before the first element (including the selected element) and after the second element (including the selected element) are exchanged to generate a new vector.

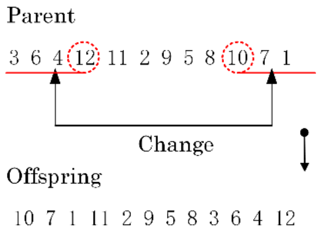

Fig. 11 Partial exchange variation

c) Local sequential variation

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Randomly select two elements in the vector, and arrange the elements between the two elements (including the selected two elements) in reverse order to generate a new vector.

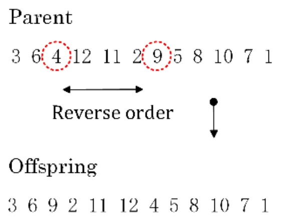

Fig. 12 Partial sequence variation

Step 7: Algorithm termination rules. Set a maximum number of iterations in advance, and stop the operation when the number of iterations reaches this value.

VI. Simulation

A. Data Description

An e-commerce platform A has a batch of three different types of express (arrival on the same day, arrival on the next morning and arrival on the next day) in Longquan Logistics Center, Chengdu, Sichuan Province, which needs to be delivered to 20 customer points (C1-C20) in Wuhan, Hubei Province. The company is considering cooperating with China Railway Shunfeng to complete the long-distance freight task. The purpose of this scheme is to select several distribution centers from the candidate distribution centers (D1-D6), and service all customer nodes by reasonably arranging the transportation path, so as to optimize the cost of the entire logistics network. The parameters are shown in the following table. (A1-A2 represent upstream traffic mode conversion node;B1-B2 represent Downstream traffic mode switching point). The other parameters are shown in the table below:

Table 1 Cost related parameters

	arrival on the same day	arrival on the next morning	arrival on the next day
Cost per kilometer per chest of product transported by high-speed rail（RMB/chest * km）	0.31	0.26	0.23
Cost per kilometer per chest of product transported by vehicle（RMB/chest * km）	0.28	0.24	0.18
Delivery cost per chest of product（RMB/chest * km）	0.5	0.48	0.45
Decide to choose a distribution center cost（RMB）	1000	1000	1000
Sorting cost per box of product（RMB/chest）	0.5	0.4	0.3
Cost per chest of product transportation mode conversion（RMB/chest）	0.08	0.08	0.08

Table 2 Transport time related parameters

	arrival on the same day	arrival on the next morning	arrival on the next day
Transportation time per kilometer of high-speed railway（hours/km)	0.004	0.004	0.004
Transportation time per kilometer of high way（hours/km)	0.03	0.03	0.03
Transportation time per kilometer of delivery（hours/km)	0.025	0.025	0.025
Time of product sorting（hours/chest）	0.01	0.02	0.028
Time of transportation mode conversion (hours/chest）	0.008	0.008	0.008
Time of customer service (hours/chest）	0.16	0.2	0.25

Table 3 The time window of Products

Best Time Window for arrival on the same day（hours）	8	18
Allowed time window for arrival on the same day（hours）	0	24
Best Time Window for arrival on the next morning（hours）	18	30
Allowed time window for arrival on the next morning（hours）	12	36
Best Time Window for arrival on the next day（hours）	24	36
Allowed time window for arrival on the next day（hours）	12	48

Table 4 Time penalty coefficient

	arrival on the same day	arrival on the next morning	arrival on the next day
Penalty coefficient for early delivery	2	2	2
Penalty coefficient for delayed delivery	50	40	30
Penalty coefficient for exceeding the time window range	600	500	400

B. Analysis of simulation results

This section uses an improved genetic algorithm to obtain the optimal objective function value of 296539.9 yuan（RMB））after operation on the Intel (R) Core (TM) i5-10210U CPU @ 1.6Hz 2.11 GHz) MATLAB R2014a system, with an average solution rate of 41.95 seconds per time. The D_1 and D_4 are selected, and the optimized transportation path is shown in Table5 below.

As can be seen from Table 5, in this example, from the logistics center to the customer point, the three modes of freight transportation are all combined transportation by highway and high-speed railway. If only highway transportation is used, the total cost of the transportation scheme is as high as 398669.06 yuan, and none of the three types of products can be reached within the optimal time window. Through comparative analysis, it is found that due to the relatively long distance from Chengdu to Wuhan and the prescribed time window restrictions for all three types of products, if the delivery is delayed, there will be a significant penalty cost of time， which will increase the total cost. However, high-speed railway has a significant advantage in transportation speed, which can greatly reduce the time cost. Therefore, the calculation result shows that the combined transportation of highway and high-speed railway is reasonable.

At the same time, input the location coordinates and demand conditions of each customer point in the Mapbox system to obtain the customer point demand thermal diagram in Figure 13. It can be seen that the customer locations are concentrated in the south of Jianghan District in Wuhan City and the east of Qiaokou District, and are distributed radially around the D1 and D4. The red coverage area in Figure 14 is a one-hour reach circle centered around the distribution center and, as shown in the figure, customer thermal points are included in the reach circle, indicating that trucks can provide logistics services directly from the distribution center to each customer point within one hour without considering traffic

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Table5 Optimized transportation route

product type	Logistics Centre	Upstream traffic mode conversion node	Downstream traffic mode switching point	Distribution Centre	Delivery path	Total cost (yuan)
Product 1 （arrival on the same day）	Longquan Logistics Center	A1	B2	D4	C8-C4-C10-C19-C14-C2-C17	296539.9
Product 2 （arrival on the next morning）	Longquan Logistics Center	A1	B3	D1	C13-C15-C9-C10-C5-C19-C20-C3	
Product 3 （arrival on the next day）	Longquan Logistics Center	A1	B2	D4	C6-C4-C7-C18-C10-C12-C1-C11-C16	

congestion, verifying the rationality of the selection of the number and location of distribution centers in the model output results.

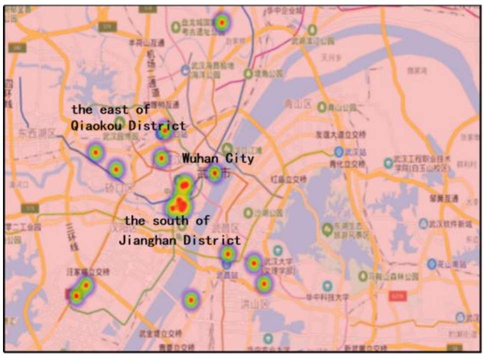

Fig. 13 Thermal diagram of customer demand

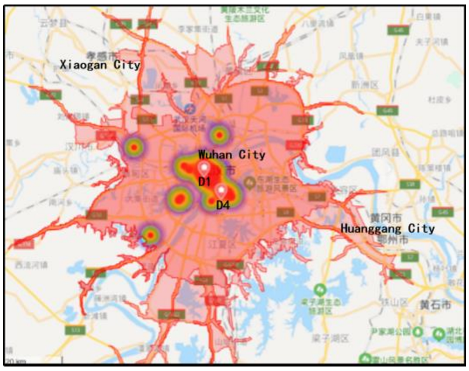

Fig. 14 Distribution center can reach the circle in one hour

VII. Conclusions

As a new branch of location problems, location-routing problem is still under development by various researchers.Present paper considered the time sensitivity of customer needs and divides logistics services into three types: same-day arrival, next-day morning arrival, and next-day arrival. A penalty cost function for customer timeliness needs is designed, and a multi-point location routing problem with time windows (MDLRPTW) model based on timeliness needs is constructed. Through case simulation, the specific locations of three transportation mode switching points and two distribution centers of Chengdu East railway station, Hankou railway station and Wuchang railway station were determined, and the trunk transportation modes and routes, and terminal distribution routes of the three kinds of timeliness goods were optimized. Compared with traditional highway transportation, it not only greatly reduced the transportation costs of enterprises, but also saved transportation time. In addition, this article improves the encoding method of genetic algorithm to address the complexity of the model and the large-scale processing of data. The results show that the algorithm can effectively solve large-scale problems in a reasonable time.

For future researches, first suggestion is to develop other solving algorithms including exact algorithms and comparing results. Other developments to LRP can be other suggestion for future research; mathematical model can be further developed considering uncertainties within data and dynamic programming issues, for example.

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