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RESEARCH ON OPTIMIZATION OF MULTIMODAL HUB-AND-SPOKE TRANSPORT NETWORK UNDER UNCERTAIN DEMAND

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Abstract:

In the cargo transportation system, the hub-and-spoke transport network can make full use of the scale effect between logistics hubs and reduce logistics costs. Joint transportation of multiple modes of transportation can give full play to the advantages of different modes of transportation, which not only reduces logistics costs but also improves transportation efficiency. Therefore, this paper combines the advantages of multimodal transportation and hub-and-spoke network, and establishes an optimization model of multimodal hub-and-spoke transport network under demand uncertainty. The model takes into account hub capacity constraints and customer satisfaction with respect to transportation time, and to facilitate the model solution, we utilize the fuzzy expected value method and the fuzzy chance constraints based on credibility to clarify the uncertain variables in the model. We use mixed coding to describe the selection of hubs, assignment of nodes, and choice of transportation modes in this study and use the NSGA-II algorithm with local reinforcement to solve the problem. Finally, numerical experiments are designed to verify the validity of the model and algorithm through sensitivity analysis of relevant parameters, determine the reasonable number of hubs and confidence level, and obtain the influence of the change of hub capacity limit and the ratio of single and double hub transit on the research objectives. The results show that: the NSGA-II algorithm with local reinforcement can significantly improve the convergence speed of the algorithm; There is benefit inversion between economic cost and time cost, and the pursuit of economic cost minimization and time cost minimization, respectively, will lead to different choices of the number of hubs; Increasing the ratio of goods transfer between hubs is beneficial for fully utilizing the scale effect between hubs, achieving the goal of reducing economic costs, but at the same time, it will increase time costs.

Keywords: *highway railway intermodal transportation, bi-objective programming, hub-and-spoke network, routing and network design, fuzzy planning, non-dominated sorting genetic algorithm-II*

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1. Introduction

The concept of hub-and-spoke networks was first introduced in the 1970s, when scholars noticed the advantages of hub-and-spoke networks in reducing the direct connection of lines, and since then a lot of research on hub-and-spoke networks has been conducted. O'Kelly (1986;1987) proposed a quadratic Integer programming model to better solve the hub median problem, and gave two simple heuristic methods to solve it. Campbell (1994) first proposed the mathematical model of hub center problem, which is a quadratic Integer programming model. The research includes hub center problem and hub coverage problem. Kapov et al. (1996) studied the capacity constrained multi allocation and single allocation P-Hub median problems, and performed strict linear relaxation on the model formulas. However, it is difficult to study hub-and-spoke networks alone to exploit their advantages, and with the development of society, research on multimodal transport continues to grow in fervor (Leleń & Wasiak, 2019; Han et al., 2023). Arnold et al. (2004) combined multiple transportation modes in axial networks to establish a 0-1 programming model and solved it using heuristic methods. Costa et al. (2008) investigate and classify the network hub location models, and model the dual-objective single-assignment hub location problem according to the latest trends in hub construction. Sheu, Meng and Wang (2011) studied the multimodal hub-and-spoke network model with equilibrium constraints considering the existence of different stakeholders in the actual multimodal transport network. Lin (2012) proposed a new logistics hierarchical network planning model using the hierarchical clustering analysis method, which simultaneously considered the minimization of network costs, the maximization of benefits in the operation process, and customer satisfaction. Zhalechian et al. (2017) proposed a new multi-objective model that simultaneously considers economic, response and social aspects, and the waiting time for cargo at the hub is calculated using M/M/c queuing theory. With the increasing importance of airline economics, Chou (1990) developed a hierarchical hub location model for an hub-and-spoke network, using airlines as the object of study, which has the advantage that the number of hubs does not need to be specified externally, but is derived by internal calculation. Sun et al. (2017) conducted a review study of air transportation and high-speed rail. In addition, Anoop and Panicker (2022) have done a study on combined road and rail transport. Regarding the determination of the number of hubs, Almur and Kara (2008) proposed two methods to determine the upper limit of the number of hubs and solved them by a hybrid heuristic algorithm. Shang et al. (2021) designed a hierarchical multimodal hub-and-spoke network with multilevel hubs. Xu et al. (2021) conducted a study on optimizing the hub-and-spoke logistics network considering traffic congestion. Korani and Eydi (2021) developed a two-tier planning model that minimizing the cost of establishing a hub network in the first layer and reducing the loss due to service disruptions in the second layer. However, many studies of the hub location problem are too idealistic and do not consider some of the constraints that exist in practice. Therefore, Ma et al. (2020) added time constraints to the China Railway Express hierarchical multimodal hub siting problem to study the location of hubs and the hinterland corresponding to the hubs for different number of hubs. Demir and Kiraz et al. (2022) considered hub capacity constraints to establish a multi-objective multi-allocation hub siting problem.

Hub construction belongs to advanced planning, so there is a lot of uncertainty in the transportation network. Yang (2009) considered the variability of air cargo volume with seasons and developed a stochastic programming model with two stages, where the first stage decision is not affected by randomness and the second stage decision is affected by randomness. Sim et al. (2009) proposed the P-hub center problem with chance constraint for travel time variability treated by random travel time with independent normal distribution. Yang et al. (2013) proposed a new risk-averse P-Hub center problem considering travel time uncertainty, fuzzy travel time by trapezoidal and normal distribution. Ghodratnama (2015) integrated cost, time and CO_2 to model the single-assignment hub problem with capacity constraints and used robust optimization to handle the uncertain parameters in the model. Mohammadi (2016) developed a bi-objective mixed integer nonlinear programming model by considering time, cost and uncertainty in hub operations, and modeled the uncertainty in the network using a fuzzy queuing approach. Yang et al. (2016) considered the transport time and travel time uncertainties in multimodal hub-and-spoke networks and design a hybrid approach combining fuzzy simulation techniques and simulated annealing algorithms for solving them. Zhang et al. (2019) transformed the water-rail intermodal network problem under uncertainty into a deterministic equivalent multi-objective model and then into a single-objective model for solution using the ε-constraint method. Sun (2019) studied a multi-objective model for multimodal transportation of hazardous materials, where uncertain variables are treated by fuzzy theory. Shang et al. (2020) considered the uncertainty of travel time and hub construction cost, developed a stochastic programming model to express this problem, and designed the modal algorithm to solve the model.

The existing literature on multimodal hub-and-spoke networks has shortcomings, mainly including:

1. Only road transport can be used between hubs.
2. Most studies of uncertain variables in the hub-and-spoke network are based on temporal uncertainty and ignore demand uncertainty.
3. Most studies seek to minimize economic costs, ignoring customer satisfaction with the quality of logistics services.
4. Some of the studies are over-idealized and do not consider whether there is congestion at the hubs and whether the choice of the final schemes will result in high carbon emissions, which is not conducive to the green and sustainable operation of hub-and-spoke intermodal networks.
5. The traditional NSGA-II algorithm suffers from defects such as premature convergence in solving the dual-objective hub location problem.

With regard to the above research deficiencies, this paper makes the following improvements：

1. In addition to railway transport, road transport can also be selected between the hub pair, and the choice of transport mode can also be different when the transport direction is different.
2. In this paper, demand is used as an uncertain variable to make the study more realistic.
3. In order to improve the quality of logistics services, we add customer satisfaction constraints for transportation time in the model, which can effectively reduce the loss of customer resources.
4. In order to build an environmentally friendly multimodal hub-and-spoke transport network, we introduce carbon emissions as part of the economic cost in the objective function. To avoid prolonged congestion at the hubs, this paper sets capacity limits for the hubs.
5. In this paper, local reinforcement operation is added to NSGA-II to avoid the algorithm from falling into local optimum and accelerate the convergence of the algorithm.

Next the article will be studied in the following five parts, the first part focuses on the article's methodology for dealing with uncertain requirements; the second part performs the problem description and model construction; the third part performs the algorithm design; the fourth part is the numerical experiments; and the last part is the conclusion.

2. Fuzzy theory

2.1. Fuzzy expectation value method

Using the fuzzy expected value method to convert a fuzzy target into a clear target, the objective function is to maximize or minimize the expected value of the fuzzy objective function. According to Liu's (2002) research on fuzzy theory, it can be concluded that the expected value of trapezoidal fuzzy variable $\tilde{b} = (b_1, b_2, b_3, b_4)$ is calculated as shown in equation (1), b_1 and b_4 represents the most optimistic and pessimistic values of the variable, respectively, $[b_2, b_3]$ is the interval where the variable is most likely to occur.

$$\mathrm{EV}[\tilde{b}] = \sum_{L=1}^{4} \frac{b_L}{4} \tag{1}$$

2.2. Fuzzy Chance Constraints Based on Fuzzy Credibility

According to the study by Zheng Y et al. (2006), the credibility measure of the fuzzy chance constraint is self-dual, which can guarantee that the fuzzy event must fail when the credibility is 0 and must hold when the credibility is 1, so this paper uses the fuzzy credibility measure to establish the fuzzy chance constraint. According to the literature of Zarandi et al. (2011), when given a definite number a and a trapezoidal fuzzy number, equation (2) provides a clear expression, which can obtain the credibility of trapezoidal fuzzy numbers greater than the definite number, and also the credibility of trapezoidal fuzzy numbers less than the definite number.

$$\mathrm{Cr}\{a \geq \tilde{b}\} = \begin{cases} 1, & a \geq b_4 \\ \frac{b_4 - 2b_3 + a}{2(b_4 - b_3)}, & b_3 \leq a \leq b_4 \\ 0.5, & b_2 \leq a \leq b_3 \\ \frac{a - b_1}{2(b_2 - b_1)}, & b_1 \leq a \leq b_2 \\ 0, & \text{other} \end{cases} \quad (2)$$

When it is specified that the confidence level must be greater than θ, i.e. $\mathrm{Cr}\{a \geq \tilde{b}\} \geq \theta$, constraint (2) can be converted to constraint (3), thus the fuzzy constraint is transformed into a clear constraint.

$$\begin{cases} 2\theta(b_2 - b_1) \leq a - b_1, 0 \leq \theta \leq 0.5 \\ (2\theta - 1)(b_4 - b_3) \leq a - b_3, 0.5 < \theta \leq 1.0 \end{cases} \quad (3)$$

2.3. Fuzzy variable representation

Fuzzy time window: the customer accepts the arrival time of goods into different time periods, as shown in Figure1, e_1, e_2, e_3, e_4 representing the earliest time the customer can tolerate the arrival of goods, the earliest time the customer most expects the arrival of goods, the latest time the customer most expects the arrival of goods, and the latest time the customer can tolerate the arrival of goods, respectively. The arrival time of goods in the range of $[e_2, e_3]$, customer satisfaction is 1, the time window is the most desired time window; goods arrival time in the range of $[e_1, e_2]$,, customer satisfaction gradually increases; goods arrival time in the range of $[e_3, e_4]$, customer satisfaction gradually decreases; other cases customer satisfaction is 0. Satisfaction calculation of membership function based on time window, as shown in formula (4).

$$\mu(T_{ij}) = \begin{cases} 0, & \text{other} \\ \frac{T_{ij} - e_1}{e_2 - e_1}, & T_{ij} \in [e_1, e_2] \\ 1, & T_{ij} \in [e_2, e_3] \\ \frac{e_4 - T_{ij}}{e_4 - e_3}, & T_{ij} \in [e_3, e_4] \end{cases} \quad (4)$$

Customer satisfaction: This article refers to customer satisfaction with transportation time. Lower satisfaction will lead to the loss of customers, and it is necessary to set the minimum customer satisfaction λ, and the transportation time window [Inf, Sup] is calculated by (4). Inf is the minimum allowable time cost at the lowest level of satisfaction, and Sup is the maximum allowable time cost at the lowest level of satisfaction. The calculation formula (5) is as follows:

$$\begin{cases} \mathrm{Inf} = e_2 \cdot \lambda + e_1 \cdot (1 - \lambda) \\ \mathrm{Sup} = e_3 \cdot \lambda + e_4 \cdot (1 - \lambda) \end{cases} \quad (5)$$

Fuzzy freight demand: $\tilde{f}_{ij} = (f_{ij}^1, f_{ij}^2, f_{ij}^3, f_{ij}^4)$, $\tilde{f}_{ij}$ is the fuzzy freight volume from region *i* to region *j*, f_{ij}^1 is the most pessimistic estimate of demand, f_{ij}^4 is the most optimistic estimate of demand, these two cases occur very rarely, $[f_{ij}^2, f_{ij}^3]$ is the most likely interval of demand.

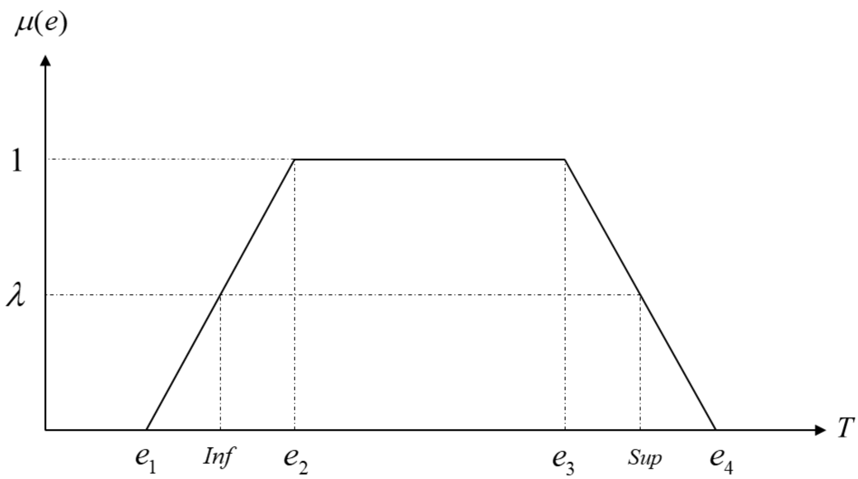

Fig. 1. Customer satisfaction function diagram

3. Model building

3.1. Problem Description

The transportation network consists of several nodes, and cargo transportation exists between each node. The planning department needs to select some nodes from these nodes as cargo collection and transit hubs to make full use of the scale effect of the freight system. The rapidly changing environment makes it difficult for decision makers to determine the specific demand and cargo delivery time in advance, and this paper can solve this difficulty well by representing the fuzzy demand and time window through trapezoidal fuzzy numbers. At the same time, it is necessary to consider the satisfaction of transportation time between different nodes comprehensively to avoid the phenomenon of long transportation time and low customer satisfaction between some nodes due to the pursuit of minimizing the total target.

In this section, the total economic cost and cargo delivery time cost are in conflict, and the gain of one of the objectives may lead to the loss of the other, so it is necessary to weigh the two objectives. A higher number of cargo transits will result in higher transit costs and transit time, and this paper specifies that cargo should be transited at most twice, with cargo transiting through one hub as a single-hub transit and through two hubs as a dual-hub transit. The operation process of the hub is shown in Figure 2: road transport is used for the cargo collection process from the node to the hub, and both road and rail transport can be used for the inter-hub pair transport.

3.2. Assumptions

The modeling should follow several assumptions to make it rigorous:

1. Any two nodes in the network are connected to each other.
2. At most one hub can be built at a node, and the cost and capacity of building a hub are unified, and only the highway railway intermodal transport hub is considered.
3. The transportation of goods between nodes can be transferred through up to two hub.
4. The collection and bulk cargo from ordinary nodes to hub nodes and from hub nodes to ordinary nodes are transported by road.

3.3. Description of symbols and variables

The decision variables and parameter description are shown in Table 1 and Table 2.

3.4. Objective function and constraints

3.4.1. Objective function

Minimize total economic cost: Total cost includes transportation cost, hub transfer cost, hub construction cost and environmental cost. The environmental cost mainly refers to the carbon emission cost generated during the transportation and transit of goods. Total cost calculation is shown in (6).

$$\begin{aligned} min\, z_1 &= \sum_{\mathrm{i,j,k,m}\in N} \sum_{s\in S} \tilde{f}_{ij} X^s_{ikmj} (C^1_{ik} + \alpha_s C^s_{km} + C^1_{mj} \\ &+ C_k + C_m \times \mathrm{sign}|m-k|) + \sum_{k\in N} F_k\, y_k \\ &+ \rho \sum_{i,j,k,m\in N} \sum_{s\in S} \tilde{f}_{ij} X^s_{ikmj}\, (h_1(d^1_{ik} + d^1_{mj}) \\ &+ h_s d^s_{km} + h'_k + h'_m \times \mathrm{sign}|m-k|) \end{aligned} \tag{6}$$

Minimize total cargo delivery time: total delivery time includes total transportation time and total transit time at the hub. See (7) for calculation of total cargo delivery time.

$$min\, z_2 = \sum_{i,j,k,m\in N} \sum_{s\in S} (t^1_{ik} + t^1_{mj} + t^s_{km} + t_k + t_m \times \mathrm{sign}|\mathrm{m}-k|) \tilde{f}_{ij} X^s_{ikmj} \tag{7}$$

Since the demand is a fuzzy variable, both objective functions contain fuzzy variables.

3.4.2. Constraint condition

The following constraints are established according to the above.

$$\sum_{k\in N} y_k = P \tag{8}$$

$$X^s_{ikmj} \le y_k, \forall i,k,m,j \in N, s \in S \tag{9}$$

$$X^s_{ikmj} \le y_m, \forall i,k,m,j \in N, s \in S \tag{10}$$

$$\sum_{i\in N} \sum_{m\in N} \sum_{j\in N} \sum_{s\in S} \tilde{f}_{ij} X^s_{ikmj} \le U_k, \forall k \in N \tag{11}$$

$$\sum_{i\in N} \sum_{k\in N} \sum_{j\in N} \sum_{s\in S} \tilde{f}_{ij} X^s_{ikmj} \le U_m, \forall m \in N \tag{12}$$

$$\sum_{k\in N}\sum_{m\in N}\sum_{s\in S} X_{ikmj}^{s} = 1, \forall i,j \in N \quad (13)$$

$$T_{ij} = t_{ik}^{1} + t_{km}^{s} + t_{mj}^{1} + t_k + t_m \times \text{sign}|m-k| \quad (14)$$

$$\text{Inf} \le T_{ij} \le \text{Sup} \quad (15)$$

$$X_{ikmj}^{s}, y_k, y_m \in \{0,1\}, \forall i,j,k,m \in N, s \in S \quad (16)$$

The quantity requirements for building hubs are shown in (8). (9) and (10) indicate that goods can only be transferred through hubs. Hub capacity constraints in (11) and (12). Equation (13) indicates that only one transportation path can be selected between nodes (i,j). Delivery time calculation for each piece of cargo between nodes (i,j) in (14). Upper and lower bound constraints for cargo delivery time between nodes (i,j) in (15). Decision variables in (16). The demand is a fuzzy variable, so constraints (11) and (12) are fuzzy constraints.

3.5. Handling of fuzzy objectives and fuzzy constraints

The objective functions (6) and (7) in the above model are fuzzy objectives. Using the fuzzy expectation value method (1), the fuzzy objective function is converted into a clear objective function as shown in (17) and (18):

$$\begin{aligned} min\, z_1 = &\sum_{i,j,k,m\in N}\sum_{s\in S}\sum_{L=1}^{4}\frac{f_{ij}^{L}}{4}X_{ikmj}^{s}(C_{ik}^{1} + \alpha_s C_{km}^{s} + C_{mj}^{1} + C_k + C_m \times sign|m-k|) + \sum_{k\in N} F_k\, y_k \\ &+\rho \sum_{i,j,k,m\in N}\sum_{s\in S}\sum_{L=1}^{4}\frac{f_{ij}^{L}}{4}X_{ikmj}^{s}\,(h_1(d_{ik}^{1} + d_{mj}^{1}) + h_s d_{km}^{s} + h_k' + h_m' \times \text{sign}|m-k|) \end{aligned} \quad (17)$$

$$min\, z_2 = \sum_{i,j,k,m\in N}\sum_{s\in S}(t_{ik}^{1} + t_{km}^{s} + t_{mj}^{1} + t_k + t_m \times \text{sign}|m-k|)\sum_{L=1}^{4}\frac{f_{ij}^{L}}{4}X_{ikmj}^{s} \quad (18)$$

The constraints (11) and (12) are fuzzy constraints, and transforming (11) and (12) into constraints (19) and (20) by considering fuzzy credibility:

$$\text{Cr}\{\sum_{i\in N}\sum_{m\in N}\sum_{j\in N}\sum_{s\in S}\tilde{f}_{ij}X_{ikmj}^{s} \le U_k, \forall k \in N\} \ge \theta \quad (19)$$

$$\text{Cr}\{\sum_{i\in N}\sum_{k\in N}\sum_{j\in N}\sum_{s\in S}\tilde{f}_{ij}X_{ikmj}^{s} \le U_m, \forall m \in N\} \ge \theta \quad (20)$$

Clearly express (19) and (20) using fuzzy chance constraints based on fuzzy credibility, as shown in (21) and (22):

$$\begin{cases} 2\theta\left(\sum_{i\in N}\sum_{m\in N}\sum_{j\in N}\sum_{s\in S} f_{ij}^{2}X_{ikmj}^{s} - \sum_{i\in N}\sum_{m\in N}\sum_{j\in N}\sum_{s\in S} f_{ij}^{1}X_{ikmj}^{s}\right) \le \\ \qquad U_k - \sum_{i\in N}\sum_{m\in N}\sum_{j\in N}\sum_{s\in S} f_{ij}^{1}X_{ikmj}^{s}, 0 \le \theta \le 0.5, \forall k \in N \\ (2\theta - 1)\left(\sum_{i\in N}\sum_{m\in N}\sum_{j\in N}\sum_{s\in S} f_{ij}^{4}X_{ikmj}^{s} - \sum_{i\in N}\sum_{m\in N}\sum_{j\in N}\sum_{s\in S} f_{ij}^{3}X_{ikmj}^{s}\right) \le \\ \qquad U_k - \sum_{i\in N}\sum_{m\in N}\sum_{j\in N}\sum_{s\in S} f_{ij}^{3}X_{ikmj}^{s}, 0.5 < \theta \le 1.0, \forall k \in N \end{cases} \quad (21)$$

$$\begin{cases} 2\theta(\sum_{i\in N}\sum_{k\in N}\sum_{j\in N}\sum_{s\in S} f_{ij}^{2}X_{ikmj}^{s} - \sum_{i\in N}\sum_{k\in N}\sum_{j\in N}\sum_{s\in S} f_{ij}^{1}X_{ikmj}^{s}) \le \\ \qquad U_m - \sum_{i\in N}\sum_{k\in N}\sum_{j\in N}\sum_{s\in S} f_{ij}^{1}X_{ikmj}^{s}, 0 \le \theta \le 0.5, \forall m \in N \\ (2\theta - 1)(\sum_{i\in N}\sum_{k\in N}\sum_{j\in N}\sum_{s\in S} f_{ij}^{4}X_{ikmj}^{s} - \sum_{i\in N}\sum_{k\in N}\sum_{j\in N}\sum_{s\in S} f_{ij}^{3}X_{ikmj}^{s}) \le \\ \qquad U_m - \sum_{i\in N}\sum_{k\in N}\sum_{j\in N}\sum_{s\in S} f_{ij}^{3}X_{ikmj}^{s}, 0.5 < \theta \le 1.0, \forall m \in N \end{cases} \quad (22)$$

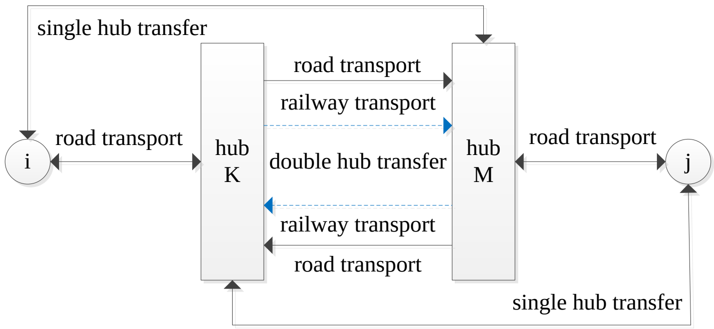

Fig. 2. Multimodal hub-and-spoke transport network route allocation method.

Table 1. Decision variables

Decision variables	Description
X_{ikmj}^{s}	If goods between (i, j) pass through hub pair (k, m) and the s-th mode of transportation is used between the hubs, $X_{ikmj}^{s} = 1$. Otherwise, $X_{ikmj}^{s} = 0$
y_k	If node k is a hub, y_k takes 1, otherwise it takes 0

Table 2. Parameter description

Parameter	Description
N	City Node Collection
P	Number of Hub Construction
S	The set of transportation modes, $S = \{1，2\}$, 1 means road transportation, 2 means rail transportation
i, j, k, m	Node index, i, j represents normal nodes, k ,m represents hub nodes
$\tilde{f}_{ij}$	Fuzzy freight demand for nodes i to j, $\tilde{f}_{ij} = (f_{ij}^1, f_{ij}^2, f_{ij}^3, f_{ij}^4)$
C_{ij}^{s}	Unit transportation cost from node i to node j using transportation mode s
C_k	Hub k unit freight transfer cost
F_k	Fixed costs for constructing and operating the hub at node k, including leasing, sharing, and fund occupation
α_s	Discount factor for economy of scale using the s-th mode of transportation between hubs
h_s	Carbon emissions per unit of transport using the s-th mode of transport
h'_k	Hub k unit transit carbon emissions
sign $\lvert m - k\rvert$	Symbolic function, when $m = k$ taken as 0, when $m \neq k$ taken as 1
t_{ij}^{s}	Transportation time between nodes (i, j) using transportation mode s
T_{ij}	The sum of transportation time and transit time for each piece of goods between nodes i and j
ρ	Carbon tax value
U_k	Hub k capacity limit
θ	Confidence level of fuzzy constraints
[Inf, Sup]	Minimum and maximum values of allowable transit time to meet customer transit time satisfaction

4. Design of NSGA-II algorithm with local reinforcement

4.1. Chromosome encoding and initializing populations

To solve the model proposed in this paper, a combined coding scheme is used, as shown in Figure 3, and the proposed coding scheme consists of the following two parts.

The first part, consists of two arrays of length n. The first array is used to indicate whether the node is a hub, 1 means the node is a hub node, 0 means the node is a non-hub node, when the number of hubs is given, this array can be generated with the specified number of 1s generated from these nodes, the second

array represents the hubs connected to the node, if the *i*-th node is assigned to hub *k*, the *i*-th position of the second array is the value of *k*.
There are three types of recovery of the subsystem dismounted from the vehicle:

1. rebuilding to original operational properties (remanufacturing)- product recycling,
2. processing into raw materials or materials - material recycling,
3. thermal energy recovery - energy recovery.

The six distinguished forms of development differ from the point of view of their share in the balance of raw materials and energy of the vehicle system. The recycling demand for energy and possible additional raw materials should be included in the input streams of the P system. At the same time, recovered raw materials, materials and energy are the components of the system's output streams.
When considering the life cycle of a vehicle in a wider population of vehicles in the context of the long-term functioning of the automotive industry, two cycles will be noticed: product and energy-material (Figure 2).
The second part, consisting of a matrix of P rows and P columns, the value of P is the number of hubs, the matrix is used to indicate the mode of transportation between hubs, 0 represents the same hub does not occur transportation, 1 represents road transportation, 2 represents rail transportation, for example, the first row and second column value of 1, represents the first hub (node 2) to the second hub (node 5) transportation by using road transportation mode.

4.2. Genetic Process

4.2.1. Select

The genetic operator selection mechanism is used to select the better individual in the population for subsequent genetic operations. In this paper, we use binary tournament selection, which is performed by randomly selecting two individuals from the population for comparison, selecting the better individual, performing the same operation, and selecting the second better individual for subsequent crossover and mutation operations.

4.2.2. Crossover

The crossover operator is crucial for accelerating convergence. Here, the two-point crossover technique is used to perform crossover operations on the selected two operators. The encoding consists of two parts, so it is necessary to perform crossover operations on the two parts in Figure 3 respectively.
Part I: crossover operation of nodes. Step 1: Randomly generate two intersecting positions w,z $\in [1,n]$. Step 2: Performing a crossover operation on two parental chromosomes, exchanging gene fragments from the first and second arrays between w and z. This process involves a crossover operation on hub positions and node allocation, followed by a check on the number of hubs and node allocation. When the number of hubs after the crossover is less than the specified number, randomly select the non hub of the intersection segment to replace it with a hub, and vice versa, replace the hub with a non hub. When a non-hub node is not assigned to a hub, then you can assign that non-hub node to that hub node by selecting a hub node along with it.
Part II: Crossover operation of transport modes. Step 1: Randomly generate two intersecting positions $(i_1,j_1), i_1,j_1 \in [1,p]$ and $(i_2,j_2), i_2,j_2 \in [1,p]$. Step 2: Exchange the elements between the i_1 row, j_1 column, and i_2 row, j_2 column of two transportation method matrices.

4.2.3. Mutate

The mutation operator is to change one or more genes when the generated number is smaller than the predefined mutation probability, which can effectively avoid the solution from falling into local optimum, and the steps are as follows: Step 1: Two mutation positions are randomly generated, one is the hub position i and the other is the non-hub position *j*. Step 2: The hub position is changed from 0 to 1, and the non-hub position is changed from 1 to 0 to achieve the interchange of hub and non-hub, and the node assignment is mutated accordingly, and the node assignment value for *i* is all replaced by *j*.

4.3. Local reinforcement of the solution

Local reinforcement helps to improve the performance of solving complex problems. Compared with the traditional non-dominated ordering adding local reinforcement helps to enhance the search ability, reach the optimum faster, and can strengthen the structure of the solution to prevent the solution from falling into local optimum. In this paper, two types of strengthening are used, the first one is switching spokes, which refers to switching a demand node from connecting one hub to connecting another hub, and the second one is changing hubs, which refers to swapping a hub node with a non-hub node and assigning the node to the adjusted new hub. Check whether the solution formed by these two reinforcement operations is feasible, and if not, delete the solution and regenerate a new solution satisfying the conditions using the reinforcement approach, which are shown in Figure 4 and Figure 5.

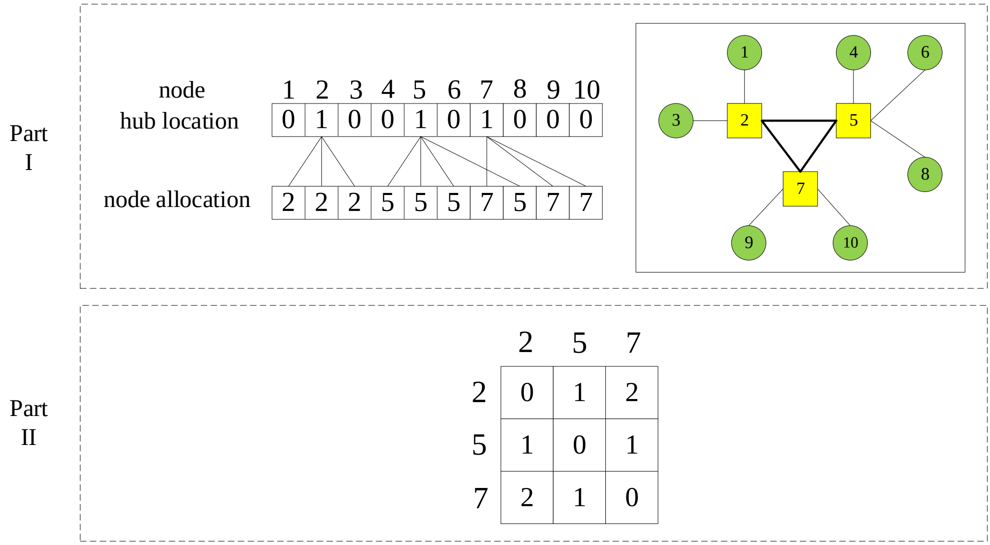

Fig. 3. Chromosome coding.

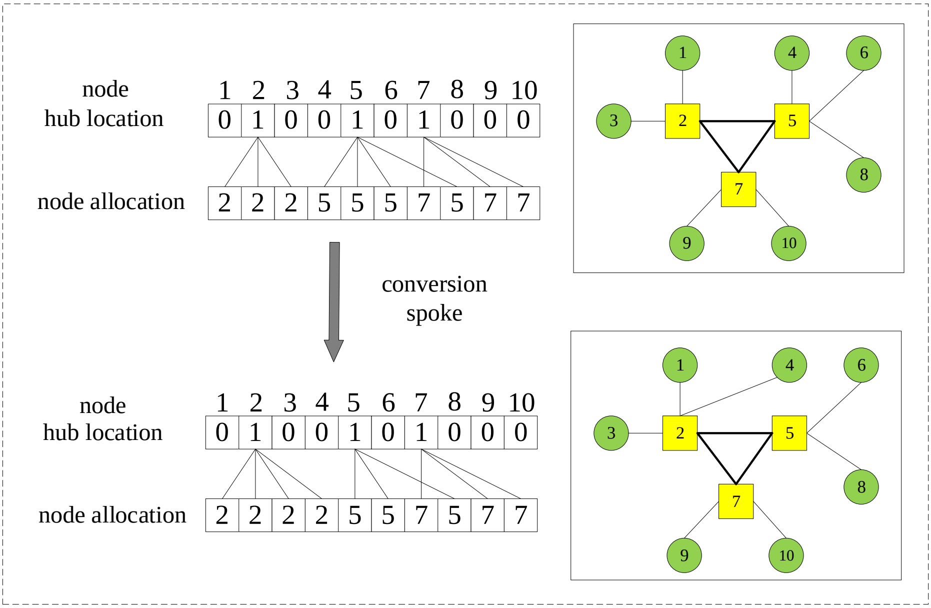

Fig. 4. Conversion Spokes

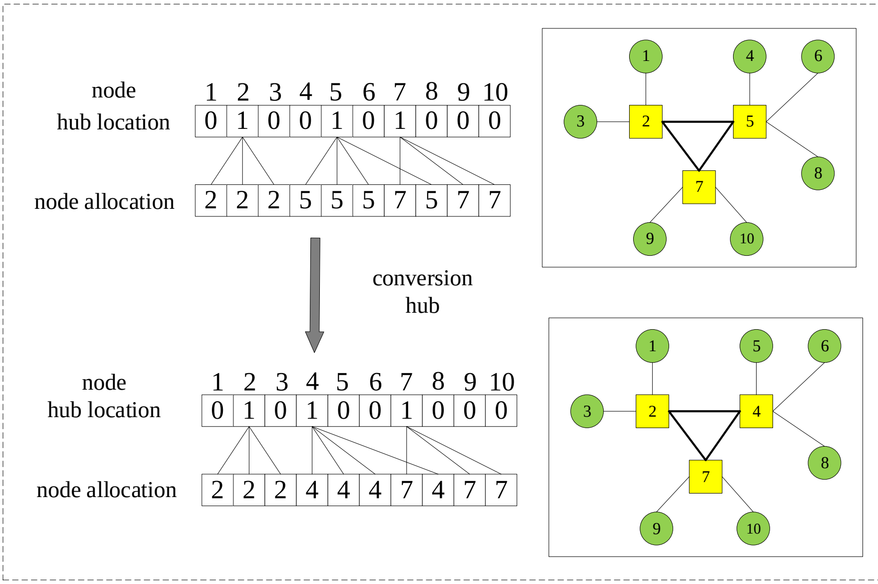

Fig. 5. Conversion Hub

5. Numerical experiments

5.1. Network-related data

This article studies the optimization problem of hub and spoke multimodal transportation networks. Taking into account the freight volume in some regions of China, an case is set up with 13 network nodes. The data in the China Logistics Network are shown in Table 3 to Table 9.

Ordinary nodes to the hub node collection of goods using road transport, hub nodes between the mode of transport can choose one of the road and railroad, different from previous studies, the same hub pair (i,j) in this paper, i to$j$and$j$to i transport mode can be different. The model includes some parameters: P,θ and U_k, represent the number of hubs, confidence level, and hub capacity limitations, respectively. By adjusting the values of these parameters, the influence of parameter value changes on the Pareto curve is analyzed, and then the optimal number of hubs, reasonable confidence level and hub capacity limit are determined. The final results are displayed, and the factors that affect the location of the hub and the impact of single and double hub transfer ratio on the scheme selection are analyzed.

Transportation costs are based on the volume of freight, transport distance and the selected mode of transport to determine the unit transport costs. Road transport costs and rail transport costs between node i and node j are calculated in (23) and (24), respectively. Due to the lack of railway connections between some nodes or the lack of railway distance data, this article uniformly adopts road transportation distance for railways and highways. d_{ij} represents the transportation distance between node i and node j, and the transportation distance data is shown in Table 4. According the papers of Alumur et al. (2012) and Shang et al. (2021), this treatment method is feasible.

$$C_{ij}^1 = 0.35 \times d_{ij} \tag{23}$$

$$C_{ij}^2 = (0.033 + 0.039) \times d_{ij} + 7.9 \tag{24}$$

Among them, 0.033 is the construction fund for railroad whole car transportation, 0.039 is the operating base price for cargo transportation, and 7.9 is the sending-to base price for cargo transportation, unit: CNY/t.

Using (21) and（22）can determine the optimal hub capacity limit, to facilitate sensitivity analysis, here to determine the hub capacity limit of 30,000, cargo transportation process need to consider economic cost, for time sensitive goods at the same time need to consider the time of transportation, the article studies the cost and time of the dual objective problem, here set the cost of economies of scale discount factor $\alpha_1 = 0{,}8$, $\alpha_2 = 1$. The time window is [0,15,48,60], customer satisfaction for time $\lambda = 0{,}6$, uncertainty constraint reliability $\theta = 0{,}8$. When conducting sensitivity analysis on a certain parameter, the value of that parameter can be changed.

Table 3. Network node city and number

No	1	2	3	4	5
name	Xi'an	Linfen	Jiexiu	Yulin	Yuanping
No	6	7	8	9	10
name	Datong	Lianyungang	Baoding	Fuping	Jinzhong
No	11	12	13		
name	Shijiazhuang	Changzhi	Handan		

Table 4. Transportation distance between city nodes (km)

City	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	405	540	695	775	1006	1152	1196	860	617	791	559	706
2	405	0	135	650	398	629	734	609	498	257	439	500	670
3	540	135	0	315	263	494	618	491	372	126	321	224	368
4	595	650	315	0	500	482	890	738	612	361	607	656	772
5	775	398	263	500	0	231	444	317	195	142	355	404	500
6	1006	629	494	482	231	0	374	514	408	299	645	620	810
7	1152	734	618	890	444	374	0	131	274	497	283	617	450
8	1196	609	491	738	317	514	131	0	126	338	131	481	300
9	860	498	372	612	195	408	274	126	0	257	121	460	295
10	617	257	126	361	142	299	497	338	257	0	203	200	362
11	791	439	321	607	355	645	283	131	121	203	0	338	165
12	559	500	224	656	404	620	617	481	460	200	338	0	384
13	706	670	368	772	500	810	450	300	295	362	165	384	0

Table 5. Blurred freight volume f_{ij}^{1} between city nodes (million tons)

City	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	322	0	312	0	0	0	0	0	0	0	0	610	512
3	310	310	0	0	0	0	0	0	0	293	0	0	0
4	200	192	315	0	589	0	880	320	172	684	738	470	172
5	124	121	190	0	0	0	1248	0	0	420	688	390	186
6	110	84	74	0	1060	0	3050	80	80	132	160	124	52
7	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	802	0	0
9	0	0	0	0	0	0	0	300	0	0	410	0	0
10	228	228	398	0	0	0	0	0	0	0	0	3540	1374
11	0	0	0	0	0	0	3710	0	0	0	0	0	5820
12	0	0	0	0	0	0	0	0	0	0	0	0	2630
13	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6. Blurred freight volume f_{ij}^2 between city nodes (million tons)

City	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	368	0	334	0	0	0	0	0	0	0	0	634	538
3	341	364	0	0	0	0	0	0	0	306	0	0	0
4	218	200	335	0	628	0	920	344	186	722	802	484	184
5	136	132	200	0	0	0	1314	0	0	434	712	414	200
6	144	90	90	0	1290	0	3700	94	94	146	184	140	66
7	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	876	0	0
9	0	0	0	0	0	0	0	360	0	0	460	0	0
10	294	294	430	0	0	0	0	0	0	0	0	3650	1500
11	0	0	0	0	0	0	3873	0	0	0	0	0	6140
12	0	0	0	0	0	0	0	0	0	0	0	0	2738
13	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 7. Blurred freight volume f_{ij}^3 between city nodes (million tons)

City	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	423	0	366	0	0	0	0	0	0	0	0	678	570
3	354	390	0	0	0	0	0	0	0	322	0	0	0
4	234	215	354	0	666	0	980	372	200	774	874	494	198
5	148	142	218	0	0	0	1482	0	0	450	752	432	216
6	160	100	106	0	1355	0	3900	104	104	156	194	148	74
7	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	918	0	0
9	0	0	0	0	0	0	0	400	0	0	480	0	0
10	314	314	448	0	0	0	0	0	0	0	0	3700	1596
11	0	0	0	0	0	0	3950	0	0	0	0	0	6380
12	0	0	0	0	0	0	0	0	0	0	0	0	2856
13	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8. Blurred freight volume f_{ij}^4 between city nodes (million tons)

City	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	465	0	388	0	0	0	0	0	0	0	0	710	606
3	376	422	0	0	0	0	0	0	0	335	0	0	0
4	255	230	370	0	715	0	1026	406	210	808	958	508	210
5	164	152	236	0	0	0	1665	0	0	464	794	454	229
6	192	107	118	0	1430	0	4550	128	128	170	208	162	88
7	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	962	0	0
9	0	0	0	0	0	0	0	464	0	0	516	0	0
10	368	368	490	0	0	0	0	0	0	0	0	3870	1700
11	0	0	0	0	0	0	4262	0	0	0	0	0	6694
12	0	0	0	0	0	0	0	0	0	0	0	0	3164
13	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 9. Other data

Carbon emissions from road transport units （t/t·km）	Carbon emissions from railway transport units （t/t·km）	Carbon emissions from unit cargo transfer （t/t）	Carbon tax value （CNY/t）	Hub construction costs (Billion CNY）	Hub Capacity Limit （million t）	Unit transit costs at the hub （CNY）	Cargo hub dwell time （h）
0.000796	0.000028	0.0156	10	4	30000	25	15

5.2. Sensitivity analysis on the number of hubs built

The number of hub construction is set in advance by decision-makers when planning their route, and the choice of hub number has a significant impact on cost and time. In this study, in order to select a reasonable number of hubs, it is necessary to analyze the sensitivity of Pareto boundaries to cost and time. We select a representative number of hubs through a large number of experiments, and the corresponding Pareto curves are shown in Figure 6.

From Figure 6, it can be seen that the leftmost point is on the Pareto curve with P=5. If cost is considered separately, the minimum total cost solution can be obtained when the number of hubs is 5. The lowest point is on the Pareto curve with P=3, and the minimum total time solution can be obtained when the number of hubs is 3. When considering cost and time comprehensively, the optimal Pareto curve corresponds to P=3. Comparing most of the points on the curves in Figure 6, it was found that the Pareto boundary moved upwards right, and The degree to which the image moves up is greater than the degree to which it moves right, the sensitivity of time cost to the number of hubs is higher than that of economic cost to the number of hubs. When the number of hubs is different, compare the changes in the minimum economic cost and minimum time cost on different pareto curves. It is concluded that the number of hubs is within a certain range and when economic cost is considered alone, it decreases as the number of hubs increases. If it is beyond this range the economic cost increases instead; Although the construction of hubs can improve the efficiency of logistics, the number of hubs should not be too many, and too many hubs will increase the total time cost of goods transportation. In this paper, Time is more sensitive to the number of hubs than cost, the main reason for this phenomenon is that the economic cost of building hubs is a smaller proportion of the total economic cost due to the larger freight volume, and as the number of hubs increases, the larger freight volume leads to a significant increase in transit and transportation time, so the sensitivity of the number of hubs to economic cost is weaker than the cost of time.

Through experimental verification, the ordinary NSGA-II algorithm requires approximately 42 iterations, while the NSGA-II algorithm with local reinforcement requires approximately 30 iterations. The NSGA-II algorithm with local reinforcement has 28.6% fewer iterations than the ordinary NSGA-II algorithm. Local reinforcement greatly improves the convergence speed of the algorithm.

5.3. Sensitivity analysis on confidence level

The confidence level of the fuzzy chance constraint is set according to the subjective preference of the decision maker, and a low confidence level affects the reliability of the fuzzy constraint, and when the confidence level exceeds a certain value, the reliability of the fuzzy constraint does not improve significantly with the increase of the confidence level. In this study, the sensitivity of the value of confidence level to time and cost is analyzed separately, and the sensitivity of cost and time to the confidence level when the confidence level is set to 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1 is shown in Figure7.

From Figure 7, we can see that the confidence level is not sensitive to time until 0.8, and the confidence level is not sensitive to cost until 0.9, and the time cost appears a small increase when the confidence level is 0.8-0.9, and the confidence level to grow from 0.9 to 1 at the cost of larger economic and time cost, here the confidence level of 0.8 or 0.9 can be used as a reference for the decision maker's confidence level setting. The confidence level can be considered to be 0.9 in case of sufficient time for goods delivery. If the confidence level is set to 1, the fuzzy constraint is completely reliable and can help the decision maker to find a more economical transportation solution than the deterministic model of demand.

To verify the economic cost and time cost sensitivity to the confidence level in the above study and to test whether the model and algorithm are reasonable, this paper takes 0.8, 0.9 and 1.0 for the confidence level respectively and plots the Pareto frontier as in Figure 8.

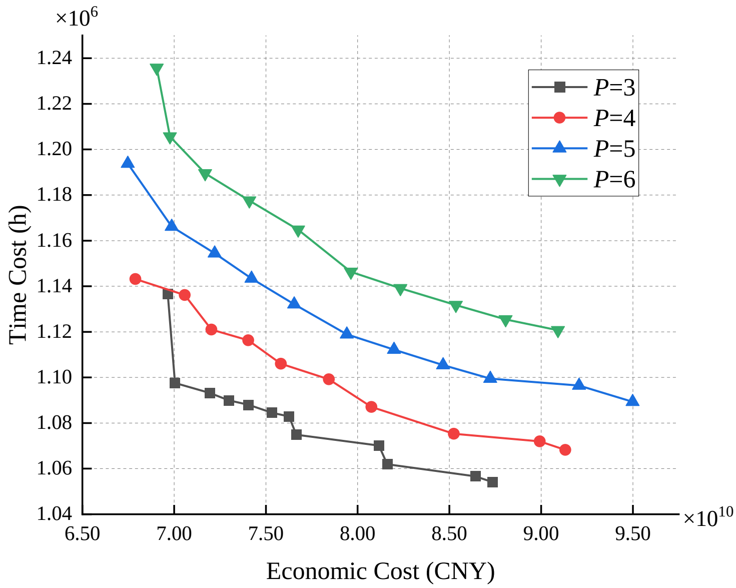

Fig. 6. The sensitivity of Pareto border to the number of hubs

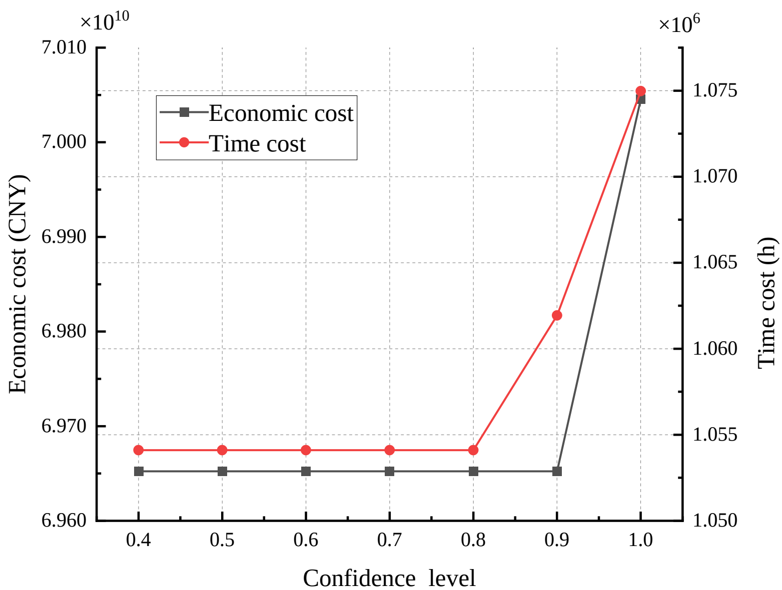

Fig. 7. Cost and time sensitivity to confidence level

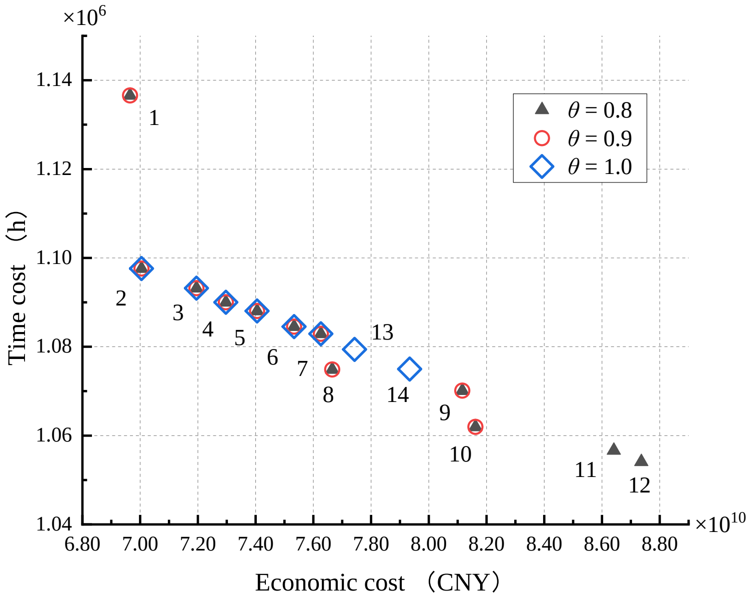

Fig. 8. Sensitivity of Pareto Boundaries to Confidence Level

As can be seen from Figure 8, the confidence level increases from 0.8 to 0.9, and the Pareto boundary eliminates scenario 11 and scenario 12 with the smallest time cost, which is in line with the research conclusion in Figure 7: The confidence level is sensitive to time and not sensitive to cost when the confidence level increases from 0.8 to 0.9. When the confidence level rises from 0.9 to 1.0, the Pareto boundary eliminates option 1 with the smallest economic cost and options 8, 9 and 10 with small time cost, which is in line with the conclusion of Figure 7: The confidence level has high sensitivity to both economic and time costs when the confidence level rises from 0.9 to 1.0.
The calculation results of the 12 schemes corresponding to the confidence level $\theta = 0.8$ are shown in Table 10, which includes the location and node allocation of hubs, the selection of transportation methods, and the corresponding time cost and economic cost for each scheme.

5.4. Sensitivity analysis on hub capacity

Hub capacity is a hard constraint that affects the choice of multimodal transport solutions. Hub capacity limits are determined by decision makers during pre-planning, and it should be noted that the following sensitivity analysis is a study conducted at a confidence level of 0.8, and the corresponding Pareto boundaries are shown in Figure 9 when hub capacity is set to 30000, 40000 and 50000, respectively.
As can be seen in Figure 9, the upper left side of the Pareto frontier remains stable, i.e., when the hub capacity limits, the choice of options prefers low economic cost and high time cost. As the hub capacity rises from 30000 to 40000 and 50000, the capacity limitation weakens, the options available increase, providing more choices for decision makers, and the Pareto frontier extends to the lower right, as the hub capacity increases, the additional options are more inclined to high economic cost and low time cost, without producing options corresponding to lower economic cost. In this study, it can be seen that when the hub capacity exceeds 30000, the hub capacity limit is more sensitive to time, while it is not sensitive to economic cost. If decision-makers tend to have low time costs, the hub capacity limit can be set relatively large, and there is a conflict between the time cost and economic cost goals. If goods have strict time requirements, decision-makers will inevitably lead to higher economic costs when choosing a lower time cost.

Table 10. Running results

No	Hub location and node allocation	Transportation method selection	Economic cost (× 10^{10} CNY)	Time cost (× 10^{6} h)
1	[[0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 0, 0] [10,10,10,10,10,10, 7,11,11,10,11,10,11]]	[0,2,1;2,0,2;2,2,0]	6.965229	1136568
2	[[0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 0, 0] [10,10,10,10,10, 7, 7,11,11,10,11,10,11]]	[0,2,2;2,0,2;2,2,0]	7.004561	1097598
3	[[0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 0, 0] [10,10,10,10,10, 7, 7,11,11,10,11,10,11]]	[0,1,2;2,0,2;2,1,0]	7.195402	1093189
4	[[0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 0, 0] [10,10,10,10,10, 7, 7,11,11,10,11,10,11]]	[0,2,1;2,0,1;2,2,0]	7.297266	1089993
5	[[0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 0, 0] [10,10,10,10,10, 7, 7,11,11,10,11,10,11]]	[0,1,2;2,0,2;1,2,0]	7.405229	1088032
6	[[0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1, 0, 0] [10,10,10,10,10, 7, 7,11,11,10,11,10,11]]	[0,2,1;1,0,1;2,2,0]	7.533459	1084536
7	[[0, 0, 0, 0, 0, 0, 0, 1, 0, 1, 1, 0, 0] [10,10,10,10,10,10,11, 8,11,10,11,10,11]]	[0,1,2;2,0,2;2,1,0]	7.626239	1082891
8	[[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0] [10,10,10,10,10,10,11,11, 9,10,11,10,11]]	[0,2,1;1,0,2;1,1,0]	7.665529	1074884
9	[[0, 0, 0, 0, 0, 0, 0, 1, 0, 1, 1, 0, 0] [10,10,10,10,10,10,11, 8,11,10,11,10,11]]	[0,1,2;2,0,1;2,2,0]	8.116150	1070099
10	[[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0] [10,10,10,10,10,10,11,11, 9,10,11,10,11]]	[0,1,1;1,0,1;1,1,0]	8.161486	1061934
11	[[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0] [10,10,10,10,10,11,11,11, 9,10,11,10,11]]	[0,1,2;2,0,1;2,2,0]	8.641111	1056662
12	[[0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0] [10,10,10,10,10,11,11,11, 9,10,11,10,11]]	[0,1,1;1,0,1;1,1,0]	8.736473	1054103

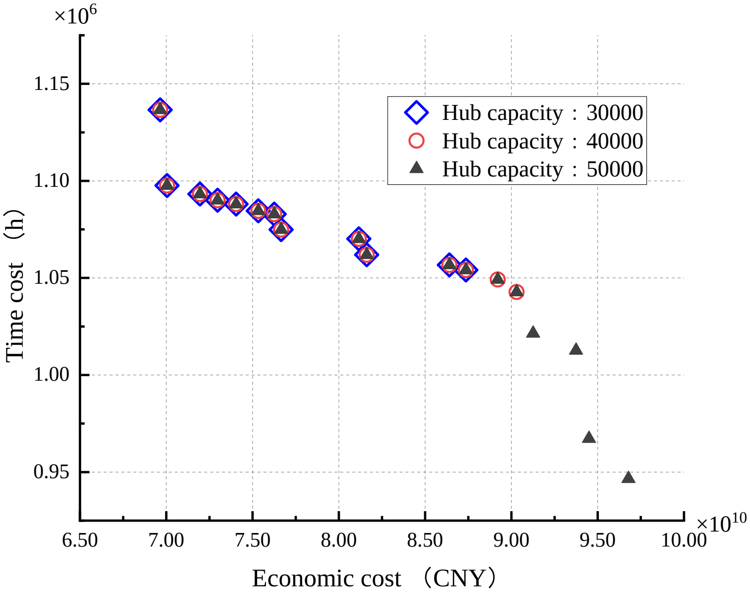

Fig. 9. Sensitivity of Pareto Boundaries to Hub Capacity

5.5. Sensitivity analysis on the Transfer ratio of single and double hub

There are two modes of transportation for goods, one is through single hub transportation, and the other is through double hub transportation. This paper defines the single and double hub transfer rate as the proportion of freight volume transferred through single and double hubs to the total freight volume. In order to study the impact of different transfer ratios of single and double hubs on scheme selection, this paper investigates the schemes with a confidence level of 0.8 in Figure 8, and draws a line chart diagram of transfer ratios of single and double hubs, as shown in Figure 10.

When the confidence level $\theta = 0{,}8$, 12 different schemes can be obtained In Figure 8, respectively. The time cost of these schemes gradually decreases, and the economic cost gradually increases. Looking at Figure 10, we can also see that the ratio of single-hub transfers gradually increases and the ratio of dual-hub transfers gradually decreases for these schemes. Based on the above phenomenon. we can get the conclusion: the transfer ratio of double hub has a scale effect, and as the transfer ratio of double hub transfers increases, the total economic cost will decrease. However, Double hub transit not only increases transit time, but also increases transportation time due to the increase in transportation distance.

Observing Figure 8, we can find that Option 2 has little change in economic cost compared with Option 1, but saves a great deal of time cost, and Option 2 has little change in time cost compared with Option 3, but saves a great deal of economic cost. The results of Schemes 2 are therefore displayed in Figure 11.

Analysis of Figure 11, nodes 7, 10 and 11 selected as hub nodes, other nodes for ordinary nodes, nodes 10 and 11 in the center of the network can be used as a hub node, node 7 is Lianyungang, not in the center of the network, but the amount of freight to Lianyungang is large, while Lianyungang has a large number of goods need to be exported to the outside world, so it is not difficult to understand Lianyungang can be used as a hub node. In summary, the hub is generally selected in the network of some central location or freight volume of the larger areas. In this paper, both railroad and road transport can be used between hubs, and the choice of transport mode can be different while the transport direction is different. The study found that most of the solutions, inter-hub transportation is more in favor of railroad transportation, in addition, if the same goods are transported, there are goods transported in both directions between two regions, lack of integration of resources, resulting in the waste of economic and time costs, subsequent research is necessary to integrate resources for the same type of goods.

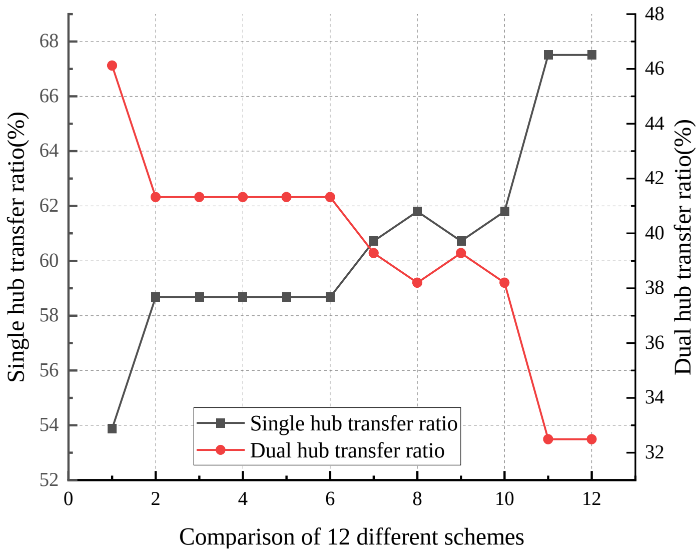

Fig. 10. Sensitivity of different schemes to single and double hub transit

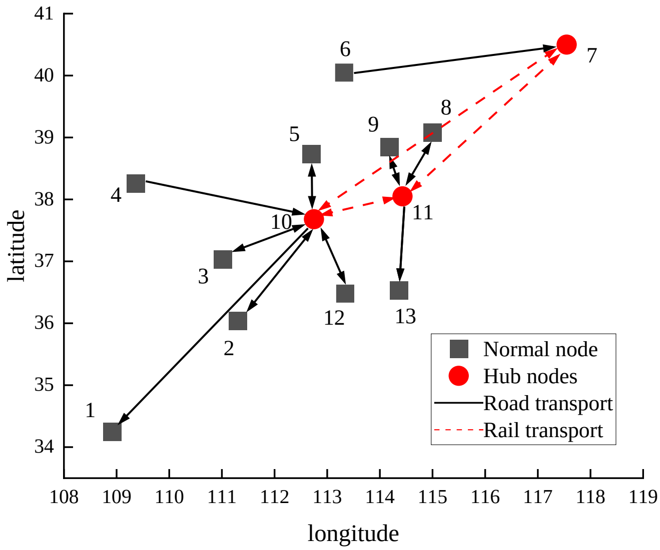

Fig. 11. Scheme 2 inter-node transportation network diagram

6. Conclusions

With the rapid development of the logistics industry, logistics costs are increasing rapidly, and customers are demanding more and more with the quality of logistics services. In order to reduce the logistics cost and improve the transportation efficiency, we have studied the multimodal hub-and-spoke transport network, and the main contributions are as follows:

1. We have developed a bi-objective integer planning model with the objective of minimizing the economic and time costs. This model is constrained by the satisfaction of customers with transportation time between different O-D pairs, ensuring the service quality of the logistics network. We incorporate the conversion of carbon emissions into economic costs into our objective function to create an environmentally friendly and sustainable logistics network. We also consider that transportation directions between hubs are different, and different transportation methods can be chosen between hubs. (There is little research on this issue).
2. On the problem of solving the multimodal hub-and-spoke transport network, we customized the NSGA-II algorithm with hybrid coding. To solve the problems of slow convergence speed and easy falling into local optima in the traditional NSGA-II algorithm, we added local reinforcement to the algorithm. This method effectively improves the convergence speed of the algorithm and avoids the algorithm falling into local optima as much as possible.
3. Taking the Chinese network as the case study, some interesting conclusions can be obtained, which can provide decision support for decision makers. The number of hubs is a crucial factor affecting economic and time costs. Hub usually needs to be built in the middle of the network or at some edge locations with high freight volume. Properly increasing the frequency of goods transfer is beneficial for fully utilizing the scale effect between hubs and achieving the goal of reducing economic costs, however, for goods that are more sensitive to time, it may lead to excessively high time costs.

There are some limitations to the research in this paper, mainly in the following areas:

1. In our study, the goods were transferred at most twice, without comparing the situation where the goods were transferred more than twice, this may also result in the loss of some of the higher quality solutions. Due to the lack of data corresponding to the railway transportation distance between some nodes, the railway transportation distance in this paper is uniformly

replaced by the highway transportation distance. Although this method is feasible in theoretical research of this problem, more accurate data is needed to solve practical problems.

2. Hub congestion can incur additional economic and time costs. Although there are hub capacity limitations in the study, it is also worth considering whether there is congestion in the hub under these capacity limitations. In addition, the freight volume during different time periods may vary, and the paper did not analyze it.

To address the shortcomings of the research in this paper, future research can be conducted in the following areas:

1. Future research can consider whether goods can be transferred through three or four hubs, and compare this method with layered multimodal transportation to analyze which method is more cost-effective and time saving.
2. Further research is needed on hub capacity constraints and to analyze the congestion present in them;
3. Future research can consider dividing the entire year into periods with high freight volume and periods with low freight volume, making decisions on plans separately, comparing the whole year as a whole and dividing it into different stages, and analyzing which situation is more cost-effective in terms of economic and time costs.

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