

# Establishing a Network Planning Model of Urban-Rural Logistics Based on Hub-and-Spoke Network

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**Abstract:** The demand of urban-rural logistics (URL) has scattered characteristics, which result in difficulty in applying the existing network planning model of URL. A network planning model of URL was established to create a planning scheme that can meet scattered logistics demands. This model is combined with the hub-and-spoke network modeling method, including the hybrid hub-and-spoke network, single-assignment, and hub node quantity constraints. For this model, the minimum total cost was taken as the objective function, whereas the hub node location, assignment relationship, and direct path planning were taken as decision variables. Moreover, the model was solved using the tabu search algorithm. Finally, the model was applied to the network planning example of URL in Nanjing-Zhenjiang-Yangzhou, China. Results indicate that the optimal hub location and quantity, the optimal distribution path, and the most reasonable straight-through route can be determined by the hub-and-spoke network planning model of URL. In addition, the URL network shows the form of two-level hybrid hub-and-spoke with multi hubs and single distribution, in which the scattered demands can be concentrated on a few hub nodes and axes. Findings indicate that the network planning problem of URL under scattered demands can be effectively solved by the new model.

**Keywords:** hub-and-spoke network; network planning model; tabu search algorithm; urban-rural logistics network

## 1 INTRODUCTION

The logistics network is the basis of the circulation of goods and is highly valued by operators [1]. However, the biggest problem in urban-rural logistics (URL) is its low unit demand, which makes the planning of the logistics network difficult. In contrast to the shortage of total logistics demand, low unit demand means that the demand is too scattered [2]. In other words, the small-scale, small-batch, and fragmented characteristics of demand require the node location and route setting of the URL network to centralize logistics demands and then maximize the input-output benefit [3]. In reality, URL networks built in condition of ignoring this requirement often have low node utilization rate, transport load deficit, and empty load problems, which bring huge losses and resource waste to operators. For example, the 402 logistics outlets opened by yuan tong express in China's Guangxi Province are all operating at a loss. The European Commission suggests that the empty loading rate of Europe's road traffic is 20% and can cost 50 million euros per year. Therefore, urban and rural circulation enterprises should pay attention to the analysis of freight demands [4], and use it as decision information to arrange network nodes and lines under the condition of demand dispersion, so that the network flow can be concentrated and transported on a small number of channels, thereby minimizing logistics costs. This process minimizes the logistics cost. URL has three existing network planning models, namely, conceptual [5], evaluation [6], and mathematical planning [7]. The conceptual network planning model of URL is a theoretical network concept based on literature analysis and investigation. It can provide a macro solution to demand dispersion, but it cannot determine the specific number, location, and connection of nodes. Hence, this model is difficult to implement. However, the network planning scheme of URL can be obtained from the evaluation planning model by consulting experts and constructing the evaluation index system of node site selection and route connection. Although the impact of logistics demands is considered, the evaluation planning model is too subjective

and prone to decision-making errors. Relatively speaking, the mathematical planning model for the network design of URL has the highest reliability and scientific degree. However, only the maximum demand limitation is considered in the common mathematical planning model, and the scattered logistics demands cannot be gathered. Hence, it has a small scope of application and is only suitable for highly urbanized areas. On the contrary, the combination of network flows can be achieved by the hub-and-spoke network, which has obvious scale, agglomeration, and spatial benefits [8]. Therefore, a network planning model of URL is established from the perspective of the hub-and-spoke network to provide a feasible, scientific, and economic node location and route layout scheme.

## 2 STATE OF THE ART

The network planning problem of URL has three core issues, namely, the location of logistics nodes planning, the quantity of logistics nodes, and logistics route planning. In this regard, some scholars presented the planning ideas and conceptual models of URL networks from a macro perspective. Tao, Pan, and Chu [5] proposed that logistics centers and service points should be selected according to the distribution of demand points by analyzing the status quo of URL network construction in China. Pan, Tao, and Chu [9] advocated the establishment of a three-tier URL network based on complex network theory. Among them, the idea of "determine the network structure according to the flow of goods" was conformed to the URL network planning needs of agglomeration and decentralization. However, such models cannot provide specific planning solutions, and the practical guidance was weak. An evaluation site selection model was then established by scholar Yang [6] based on the mutation theory, and the location of logistics nodes was determined according to the expert scoring results of different site selection schemes. The logistics demand was taken as the evaluation index of site selection in this model so that the URL network was established based on demand concentration. The

advantages and disadvantages of the planning scheme depended on the experience of experts, and the reliability was insufficient. However, other scholars used the operational research method to establish the mathematical planning model of the URL network. Lu [7] established the mixed integer programming model to study the design of the urban-rural chain operation distribution network. According to her, the network was composed of urban-rural chain supermarkets, distribution centers, and other nodes and connection lines existed between the distribution center and each supply and demand node. The node distribution, processing capacity, and other information were also known. Therefore, the network planning decision was determined as the optimal quantity and location of the distribution center. Accordingly, in the mixed integer programming model, the decision content was represented with 0-1 variables. The objective function representing the total cost of the network as well as the constraint conditions representing the capacity balance, maximum demand, or processing capacity limit were abstracted. The feasibility and scientificity of the model were verified by an example. However, the model only considered the processing capacity of nodes and routes to meet the maximum demand, and they did not consider the insufficient demand. For example, the model assumed that the distribution center was directly connected to each supermarket chain, but it was built on the premise that the logistics demand was sufficient. Otherwise, resources were wasted. The unit demand of URL is small and not enough to support the fully connected network structure. However, this modeling approach was continued by all the existing mathematical planning models of the URL network, resulting in weak practical application. Researchers, such as Peng et al. [10-12] added variables to the model to set up a direct route between the supply and demand nodes of URL. Despite meeting the logistics timeliness requirement of fresh agricultural products, the demands were made dispersed, and the planning effect was not good.

In contrast to previous research, the current study constructs a hub-and-spoke network planning model of URL. The hub-and-spoke network is a network structure that connects most nodes in the network with one or several central hub nodes, which interact with each other to deliver logistics and people flow economically and efficiently. It also gathers logistics demands [13]. The research of hub-and-spoke network model focuses on the selection of nonhub node assignment [14], the cost discount rate setting between hub nodes [15], the connection constraint between nonhub nodes [16], and the multilevel [17]. At present, the hub-and-spoke network model has been described integrally [18], and it has begun to expand into new research directions in combination with applications in different fields. For example, a hybrid hub-and-spoke postal logistics network was studied by LEE, and Moon [19]. The hub-and-spoke route network in the competitive market was studied by Yang, and Huang [20], and the secondary diffusion of Marine species introduced in Indonesia using hub-and-spoke networks was studied by Azmi, Hewitt, and Campbell [21]. However, applying the design of the hub-and-spoke network to the network planning field of URL is a relatively new idea. In particular, the URL network is a complex system with various carrying fluids, vast coverage, and numerous

routes and nodes [22]. Its planning and design should extend the traditional hub-and-spoke logistics network planning model. As such, the modeling method of the hub-and-spoke network is referenced in this study. Goods between any origin-destination (OD) points must be transferred through hub nodes by the hub-and-spoke network and single distribution constraints. The scale benefit of goods flow agglomeration on the hub routes is represented by the cost discount coefficient. On this basis, the homogeneity hypothesis of commodities is changed in this study. Moreover, the urban and rural link factor and direct linking variables between nonhub city nodes are introduced, and the node construction, environmental, and cargo loss costs are added as objective functions. Finally, the tabu search (TS) algorithm is designed to obtain the network planning scheme of URL that matches scattered logistics demands.

The remainder of this study is organized as follows. Section 3 establishes the hub-and-spoke network planning model of URL and proposes the TS algorithm to solve this model. Section 4 applies the model to the network planning example of URL in Nanjing-Zhenjiang-Yangzhou (NZY), China, to verify the feasibility and effectiveness of the hub-and-spoke network planning model of URL. Section 5 gives the conclusions of this study.

### 3 METHODOLOGY

#### 3.1 The Traditional Hub-and-Spoke Network Planning Model

The traditional hub-and-spoke network model was first developed by O'Kelly, and Bryan [23, 24]. Its common basic assumptions include the following. The number of network demand points is given (the OD points the network needs to serve are known). The flow on the OD pairs, which are composed of nodes, is given. The discount rate (or segmentation discount function) of unit transport cost and transport cost between hub nodes are given in advance. Connections between nodes do not have capacity limit. The model can be expressed as follows:

$$\text{Min}Z = \sum_i \sum_j w_{ij} \left( \sum_k Z_{ik} C_{ik} + \sum_m Z_{jm} C_{jm} + \alpha \sum_k \sum_m Z_{ik} Z_{jm} C_{km} \right) \quad (1)$$

S.t.

$$(n - p + 1)Z_{kk} - \sum_i Z_{ik} \geq 0 \quad (2)$$

$$\sum_k Z_{ik} = 1 \quad (3)$$

$$\sum_k Z_{kk} = p \quad (4)$$

$$Z_{ik} \in \{0, 1\} \quad \forall i, k \quad (5)$$

where  $p$  is the number of hubs in the network;  $i, j$  are the nodes in the network,  $i, j \in \{1, 2, \dots, n\}$ ;  $w_{ij}$  is the traffic between nodes  $i, j$ ;  $C_{ik}$  is the unit transport cost parameter between nodes  $i, k$ ;  $Z_{ik}$  is the nonhub node allocated variable; if the node  $i$  is allocated to the hub node  $k$ , then  $Z_{ik} = 1$ . Otherwise,  $Z_{ik} = 0$ .

### 3.2 The Network Planning Problem of URL Based on Hub-and-Spoke Network

The URL network differs from the traditional hub-and-spoke network in many aspects. First, the fluids of the URL network include fresh agricultural products that are perishable and not suitable for multiple transshipments, and the transportation rate and carbon emission coefficient are higher than industrial products. Second, the direction of goods flow in the URL network is twofold, which leads to multiple flows on the logistics route. Third, the nodes in the URL network have subordinate and radiative relationships, and the logistics scales are quite different. Hence, they should be mixed for node location.

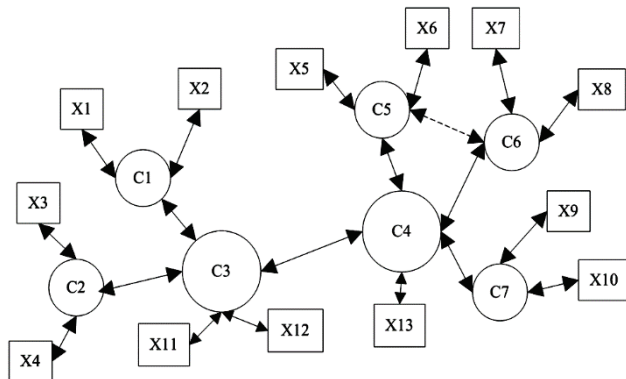


Figure 1 The structure of the two-level hybrid hub-and-spoke network with multi hubs and single distribution

For this reason, in this study, the structure of the URL network is defined as a two-level hybrid hub-and-spoke network with multi hubs and single distribution. As shown in Fig. 1,  $x_1, \dots, x_{13}$  and  $c_1, \dots, c_7$  are urban and rural nodes, respectively, and  $c_3, c_4$  are hub nodes. The rest are nonhub nodes. Each nonhub node is only assigned to one hub node. Most nonhub nodes are not connected, and only a direct route exists between  $c_5$  and  $c_6$ . In such a network, goods between urban and rural areas can first be distributed through the corresponding urban nodes. They are then transferred to the destination urban nodes through direct routes or via single or multiple hub urban nodes. Therefore, this network cannot only retain the advantages of hub-and-spoke network aggregation but also enjoy the advantages of short time and low loss of direct transport. Hence, it is the best choice for the network planning of URL. To match the shape of this network, urban and rural connection factors and the direct connection variable of nonhub urban nodes are introduced into the traditional hub-and-spoke network model. The homogeneity assumption of commodities is then changed to distinguish the transportation rate and carbon emission coefficient of fresh and industrial products. Finally, logistics cost is an important factor to measure the performance of enterprise logistics [25], so the node's location of URL is designed with the minimum sum of transportation, node construction, environmental, and cargo damage costs. Besides, the damage cost of fresh agricultural products is added as the objective function.

In conclusion, the network programming problem of URL based on the hub-and-spoke network can be summarized as follows. In a series of urban and rural nodes with known locations and demands, several urban nodes

are selected as hub nodes. Connected hub nodes are assigned to the remaining nonhub urban nodes, and the nonhub urban nodes for establishing a straight-through path are chosen. The premise of decision-making is as follows. The logistics demand of rural nodes is distributed through subordinate urban nodes. Each path has multiple goods flows, and the scale effect of traffic agglomeration is quantified by the transport discount coefficient. Decision-making aims to realize the lowest total node construction, transportation, cargo damage, and environmental costs. The constraint condition of decision-making is that the flow between urban nodes must pass through the hub node. However, nonhub urban nodes with the large flow can pass through directly, and nonhub urban nodes can only be assigned to one hub urban node.

### 3.3 Establishing a Network Planning Model of URL Based on Hub-and-Spoke Network

#### 3.3.1 Model Assumptions

- (1) Assume that the logistics demands between nodes are known and can be met.
- (2) Each node is a logistics demand point and a logistics supply point, and the location is known. Moreover, several nodes are selected from the urban nodes to construct hub nodes.
- (3) Fixed connections exist between urban and rural nodes, that is, rural goods can only flow to the urban node of their upper level.
- (4) The commodities flowing in the network are divided into industrial and fresh agricultural products. Fresh agricultural products are transported via cold chain, and losses are generated in the loading, unloading, and handling links of hub nodes.

#### 3.3.2 Symbol Description

- (1) Subscript set
  - $i$  or  $j$  is a nonhub urban node; and  $n$  is the number of urban nodes.
  - $k$  or  $m$  is an urban node that is open to the hub; and  $p$  is the number of urban hub nodes.
  - $h$  or  $g$  is a rural node; and  $l$  is the number of rural nodes.
  - $a$  stands for industrial products, and  $b$  stands for fresh agricultural products.
- (2) Decision variables
  - $x_{ik}$  or  $x_{jm}$  is the variable assigned to nodes of nonhub cities;  $x_{ik} = 1$  or  $x_{jm} = 1$  represents that the nonhub urban node  $i$  or  $j$  is assigned to the hub urban node  $k$  or  $m$ ; otherwise,  $x_{ik} = 0, x_{jm} = 0$ .
  - $\delta_{ij}$  is the direct connection variable of nonhub urban nodes;  $\delta_{ij} = 1$  indicates that the nonhub urban node  $i$  is directly connected with the nonhub urban node  $j$ ; otherwise,  $\delta_{ij} = 0$ .
  - $Y_k$  is the judgment variable of hub urban nodes;  $Y_k = 1$  indicates that node is opened as the hub urban node; otherwise,  $Y_k = 0$ .
- (3) Parameters
  - As shown in Fig. 2,  $q_{ij}$  is the transport volume from urban node  $i$  to urban node  $j$ .  $q_{hi}$  is the transport volume from rural node  $h$  to its urban node  $i$ .  $q_{hj}$  is the transport volume from rural node  $h$  to the other urban node  $j$ , which should be transferred to urban node  $j$  through urban node  $i$ .  $q_{ig}$  is

the transport volume from the other urban node  $i$  to the rural node  $g$ , and this part of the transport volume should also be transferred to urban node  $j$  via node  $g$ . Therefore, in the rural-level logistics network, the traffic volume on route  $h \rightarrow i$  is  $q_{hi} + q_{hj}$ . In the urban-level logistics network, the traffic volume on route  $i \rightarrow j$  is  $q_{ij} + q_{ij} + q_{ig}$ , similar to the opposite direction.

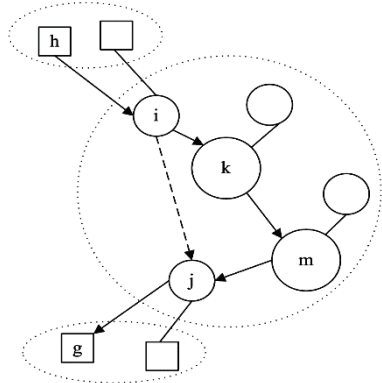


Figure 2 The schematic diagram of network symbols of URL

$\gamma$  is the urban-rural connection factor;  $\gamma_{hi} = 1$  means the rural node  $i$  is connected to urban node, that is, node  $h$  is subordinate to node  $i$ ;  $\gamma_{hi} = 0$  represents that rural node  $h$  is not connected with urban node  $i$ , that is, the node  $h$  is not associated with node  $i$ , and  $\gamma_{hi} = \gamma_{ih}$ .

$d_{ij}$  is the transport distance between urban nodes  $i$  and  $j$ ,  $d_{ij} = d_{ji}$ .

$c_a$  is the unit transport cost of industrial products, that is, the transport cost per unit weight of goods per unit distance;  $c_b$  is the unit transport cost of fresh agricultural products,  $c_b \geq c_a$  (fresh agricultural products generally require cold chain transport, and the unit transport cost is higher than that of industrial products).

$\alpha$  is the discount coefficient of unit transport cost between the nodes of hub cities,  $0 \leq \alpha \leq 1$ .

$\beta$  is the discount coefficient of unit transport cost between the nodes of nonhub cities,  $0 \leq \beta \leq 1$ . When the nonhub urban nodes are directly connected, the number of goods transported can reach a certain scale. Moreover, the transport cost of this part of the traffic should enjoy scale effect discount.

$s$  is the unit production cost of fresh agricultural products.

$w$  is the unit construction cost of hub nodes.

$\varphi$  is the carbon tax rate, that is, the tax rate levied on unit carbon emissions in the transportation process.

$f_a$  is the carbon emission coefficient of the transportation of industrial products, that is, the carbon emission of the per unit transportation distance of per unit weight goods.  $f_b$  is the carbon emission coefficient of the transportation of fresh agricultural products,  $f_b \geq f_a$ .

$\theta$  is the unit loss rate of fresh agricultural products, that is, the loss ratio of fresh agricultural products after loading, unloading, and handling at a single hub node,  $0 \leq \theta \leq 1$ .

### 3.3.3 The Network Planning Model of URL Based on Hub-and-Spoke Network

$$MinZ = Z_1 + Z_2 + Z_3 + Z_4 \tag{6}$$

$$Z_1 = Z_{11} + Z_{12} + Z_{13} + Z_{14} \tag{7}$$

$$Z_{11} = \sum_h^l \sum_i^n \sum_j^n \left\{ \begin{aligned} & [q_{hi}\gamma_{hi} + q_{hj}(1-\gamma_{hj})]c_b d_{hi} \\ & + [q_{ih}\gamma_{ih} + q_{jh}(1-\gamma_{jh})]c_a d_{ih} \end{aligned} \right\} \tag{8}$$

$$Z_{12} = \sum_i^n \sum_j^n \sum_h^l \sum_g^l [c_b q_{hj}(1-\gamma_{hj}) + c_a q_{ij} + c_a q_{ig}(1-\gamma_{ig})] \tag{9}$$

$$\left( \sum_k^p x_{ik} d_{ik} + \sum_m^p x_{jm} d_{jm} \right) (1-\delta_{ij})$$

$$Z_{13} = \alpha \sum_i^n \sum_j^n \sum_h^l \sum_g^l [c_b q_{hj}(1-\gamma_{hj}) + c_a q_{ij} + c_a q_{ig}(1-\gamma_{ig})] \tag{10}$$

$$\left( \sum_k^p \sum_m^p x_{ik} x_{jm} d_{km} \right) (1-\delta_{ij})$$

$$Z_{14} = \beta \sum_i^n \sum_j^n \sum_h^l \sum_g^l \left[ \begin{aligned} & c_b q_{hj}(1-\gamma_{hj}) + c_a q_{ij} \\ & + c_a q_{ig}(1-\gamma_{ig}) \end{aligned} \right] d_{ij} \delta_{ij} \tag{11}$$

$$Z_2 = w \sum_k^p Y_k \tag{12}$$

$$Z_3 = Z_{31} + Z_{32} + Z_{33} + Z_{34} \tag{13}$$

$$Z_{31} = \varphi \sum_h^l \sum_i^n \sum_j^n \left\{ \begin{aligned} & [q_{hi}\gamma_{hi} + q_{hj}(1-\gamma_{hj})]f_b d_{hi} \\ & + [q_{ih}\gamma_{ih} + q_{jh}(1-\gamma_{jh})]f_a d_{ih} \end{aligned} \right\} \tag{14}$$

$$Z_{32} = \varphi \sum_i^n \sum_j^n \sum_h^l \sum_g^l [f_b q_{hj}(1-\gamma_{hj}) + f_a q_{ij} + f_a q_{ig}(1-\gamma_{ig})] \tag{15}$$

$$\left( \sum_k^p x_{ik} d_{ik} + \sum_m^p x_{jm} d_{jm} \right) (1-\delta_{ij})$$

$$Z_{33} = \varphi \sum_i^n \sum_j^n \sum_h^l \sum_g^l [f_b q_{hj}(1-\gamma_{hj}) + f_a q_{ij} + f_a q_{ig}(1-\gamma_{ig})] \tag{16}$$

$$\left( \sum_k^p \sum_m^p x_{ik} x_{jm} d_{km} \right) (1-\delta_{ij})$$

$$Z_{34} = \varphi \sum_i^n \sum_j^n \sum_h^l \sum_g^l \left[ \begin{aligned} & f_b q_{hj}(1-\gamma_{hj}) + f_a q_{ij} \\ & + f_a q_{ig}(1-\gamma_{ig}) \end{aligned} \right] d_{ij} \delta_{ij} \tag{17}$$

$$Z_4 = s \theta \sum_i^n \sum_j^n \sum_k^p \sum_m^p \sum_h^l q_{hj}(1-\gamma_{hj})(1-\delta_{ij}) \tag{18}$$

$$(x_{ik} + x_{jm})$$

S.t.

$$\sum_k^p Y_k = p \tag{19}$$

$$\sum_k^p x_{ik} = 1, \forall i \in N \text{ or } \sum_m^p x_{jm} = 1, \forall j \in N \tag{20}$$

$$Y_k \geq x_{ik}, \forall k \in N, \forall i \in N \tag{21}$$

$$Y_k, x_{ij}, \delta_{ij} \in \{0, 1\}, \forall k \in N, \forall i \in N, \forall j \in N \tag{22}$$

First,  $Z_1$  in Eq. (6) is the transport cost. As shown in Eq. (7),  $Z_1$  can be divided into four sections, namely, the transport cost of routes from countryside to cities and cities to countryside of rural subnet ( $Z_{11}$ , Eq. (8)); the transport cost of routes from nonhub urban nodes to hub urban nodes ( $Z_{12}$ , Eq. (9)); the transport cost of routes between hub urban nodes ( $Z_{13}$ , Eq. (10)); and the transport cost of direct routes ( $Z_{14}$ , Eq. (11)). Here, the cost of direct routes and transshipment through hub nodes equal the cost of two

transport routes. Hence, it does not double count. Second,  $Z_2$  is the construction cost of hub nodes, as shown in Eq. (12). Third,  $Z_3$  is the environmental cost, as shown in Eq. (13), which is similar to the transport cost and is also calculated in four sections, namely, Eqs. (14)-(17). Finally,  $Z_4$  is the damage cost of fresh agricultural products. Fresh agricultural products are assumed to adopt cold-chain transportation for the whole-process. Hence, the damage of goods generated in the transport process is very small, and it is not considered. Only the cost of goods damage generated in the loading, unloading, and handling links is considered, as shown in Eq. (18). The model has four constraint conditions. Eq. (19) is the quantity constraint of hub nodes, indicating that the total number of nodes in the network is  $p$ . Eq. (20) is a single allocation constraint, indicating that a nonhub urban node can only be connected to a hub urban node. Eq. (21) is the constraint of the hub-and-spoke network. Thus, nonhub nodes cannot be connected with each other and can only be connected to hub nodes. Eq. (22) is the constraint of the value range of the decision variable, indicating that their value should be within a fixed range.

### 3.4 Solution of Network Planning Model of URL Based on Hub-and-Spoke Network

#### 3.4.1 Design of the Algorithm for Solving the Model

The network planning model of URL established in this study is a mixed integer programming model. Metaheuristic algorithms and estimation of distribution algorithms [26] can be designed to solve this problem. The currently used metaheuristic algorithms are the genetic algorithm, simulated annealing algorithm, and TS algorithm [27]. Skorin-kapov D., and Skorin-kapov J. [28] has proven that a solution with less than one percent error than the optimal solution can be found via TS algorithm. Hence, the TS algorithm is selected to solve the model in this study. The TS algorithm design mainly includes settings for the initial solution, neighborhood, adaptive value function, taboo table, taboo length, amnesty criterion, and termination criterion.

First, the initial solution is the result of the first iteration of the TS algorithm, and its construction can be generated randomly or calculated by other heuristic algorithms. In this study, the random function is chosen to generate an initial solution. The neighborhood is composed of the objects that the TS algorithm needs to achieve the optimal solution to a problem. At present, it is generated by moving the commonly used neighborhood moving methods, namely, substitution, insertion, and exchange. In this study, the design of neighborhood structure is generated by the single point replacement of hub nodes. If the problem is the site selection of two hub nodes from four alternative nodes, and the initial solution is (2,3), then its fields are (2,1), (2,4), (1,3), and (4,3). The neighborhood produced by a single point substitution has a solution set of  $p^*(n-p)$ , where  $p$  is the number of hub nodes, and  $n$  is the total number of alternative nodes.

Second, the core of the TS algorithm is the setting of the adaptive value function, taboo table, and taboo length. Among them, the adaptive value function is mainly used to evaluate the searched solution, that is, to determine if the searched solution is the optimal solution. For the sake of

intuition, the objective function is used as the adaptation value function. The taboo table is used to store taboo objects searched in each iteration. The taboo length refers to the number of iterations in which taboo objects are not searched. It can generally be regarded as the term of taboo objects in the taboo table. In this study,  $Tabulenth = \text{round}(\sqrt{p^*(Citynum-p)}) = 5$ , where  $Citynum$  is the number of alternative nodes and is set to 9;  $p$  is the number of hub nodes and is set to 5 in this study. When the solution goes from (2,3) to (2,4), point 3 is the taboo object and cannot be selected during the five iterations (unless pardoned).

Finally, when the partial solution is contraindicated, the state of the contraindication solution will be better than the state of the currently searched solution. When all the searched objects are contraindicated, several taboo solutions need to re-enter the search space to ensure the effectiveness of the search, and an amnesty criterion is introduced into the algorithm. The amnesty rule in this study is that the corresponding taboo solution be amnestied when the best solution appears. In addition, searching all the solutions in the space is not practical when solving the model is a NP-hard problem [29]. Hence, a termination criterion is needed to terminate the algorithm when a satisfactory solution is obtained. Due to the huge amount of data to be calculated in this study, the maximum number of iterations is set to 50 ( $Maxiter = 50$ ) to save the parameter debugging time.

#### 3.4.2 The Model Solving Process Based on TS Algorithm

The problem of applying the TS algorithm to solve the hub-and-spoke network model of URL can be divided into three subproblems, namely, the direct connection subproblem, the hub node location subproblem, and the nonhub node allocation subproblem. The specific solving process is as follows:

Step 1: Initialize parameters, input data, solve direct connection subproblems, and record the results for later use.

Step 2: Use the random function to generate the initial solution  $y_0$  of the hub location subproblem randomly, and empty the taboo table.

Step 3: Solve the nonhub allocation subproblem corresponding to the initial solution of hub location selection, and calculate the value of the objective function.

Step 4: Identify if the current iteration number is less than or equal to the maximum iteration number. If so, then execute Step 5. Otherwise, output the result.

Step 5: Generate  $p^*(n-p)$  neighborhood results of the current solution through the exchange between the hub and the nonhub nodes. Then proceed to Step 3 to calculate the objective function values of the neighborhood solution, and select the optimal objective function value and the corresponding solutions using the sort function to arrange the size of the objective function values.

Step 6: Determine if the optimal movement from the current solution to the candidate solution set is contraindicated. If not, then update the taboo list. The taboo length of the solution is  $Tabulenth = L$ , and the taboo length of the remaining contraindicated objects in the taboo list is  $Tabulenth - 1$ . Return to Step 5. If contraindicated, identify if the amnesty criteria are met.

Step 7: Add 1 to the current iteration number and execute Step 4.

Step 8: End the operation and output the result.

The steps are displayed in Fig. 3.

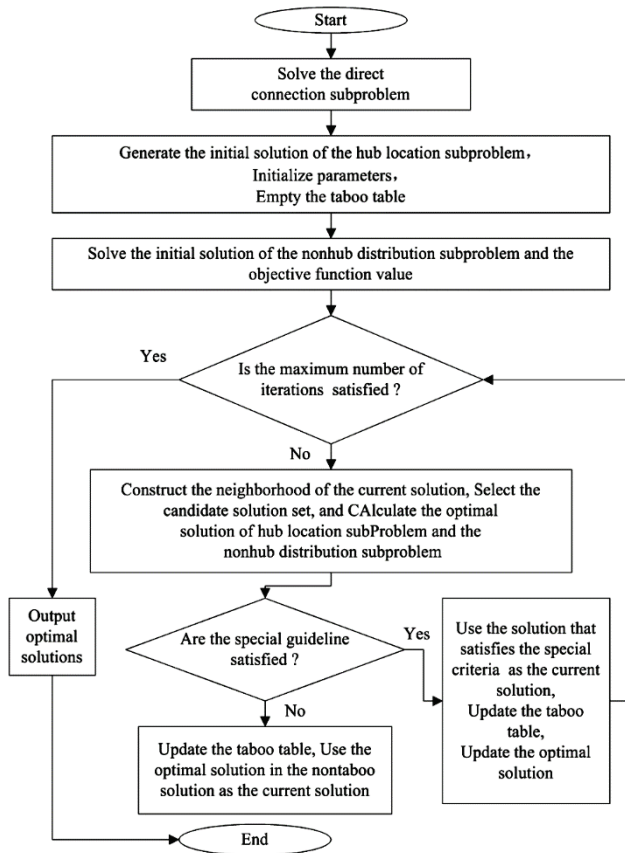


Figure 3 The flow chart of network planning model of URL based on TS algorithm

## 4 RESULT ANALYSIS AND DISCUSSION

### 4.1 Case Analysis

The NZY area is located in the middle and lower reaches of the Yangtze River, and it is the core area of the metropolitan formed around Nanjing. This region has 51 alternative urban and rural nodes, which are numbered as  $c_1, c_2, c_3, \dots, c_9$  and  $x_1, x_2, x_3, \dots, x_{42}$ . The specific names and distribution of these nodes are shown in Fig. 4.

Freight transportation in the NZY area is mainly via highway. Hence, the transportation distance is expressed by highway mileage, and the data are derived from Google Maps. Transport volume data between cities, urban, and rural areas are randomly generated by Matlab software. In addition,  $c_a$ , which is set at 0.2 yuan/ton/km, represents the unit transport cost of industrial products, and the unit transport cost of fresh agricultural products  $c_b$  is set as 0.6 yuan/ton/km (according to the website of China Logistics and Procurement Association, the unit transport cost of highway is about 0.45 yuan/ton/km). The discount coefficient of unit transport cost between nodes of hub cities is set as  $\alpha = 0.45$ . The discount coefficient of unit transport cost between nodes of nonhub cities is set as  $\beta = 0.75$ . The unit production cost of fresh agricultural products is set as  $s = 500$  yuan/ton, and the unit loss rate is set as  $\theta = 0.25$  (this is the loss ratio of fresh agricultural products during loading, unloading and handling). The unit

construction cost of a hub node is set as  $w = 9110$  yuan (the construction cost of a single hub node is averaged to 180 months, according to a 15-year depreciation period). The carbon tax rate is set as  $\varphi = 10$  yuan/ton (refer to the linear carbon tax rate of European countries). Correspondingly, the carbon emission coefficient of the transportation of industrial products is set as  $f_a = 0.00158$  ton/km, and the carbon emission coefficient of the transportation of fresh agricultural products is set as  $f_b = 0.00183$  ton/km.

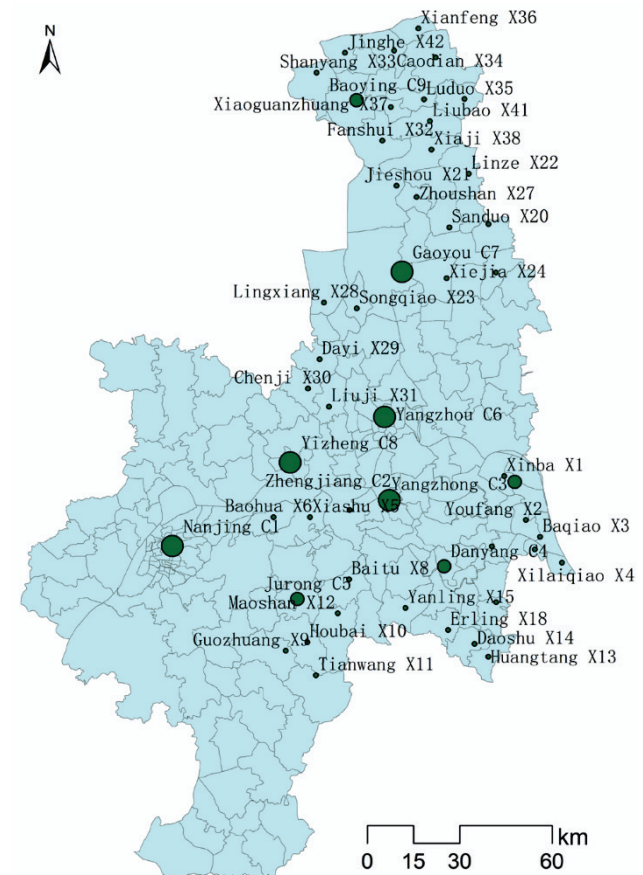


Figure 4 The spatial distribution of urban and rural nodes in NZY area

### 4.2 Result Analysis

According to the TS algorithm designed in Section 3.4, the corresponding program is written on Matlab, and the case data are read to solve the hub-and-spoke network planning model of URL constructed in Section 3.3. As shown in Fig. 5, the optimal solution of the model gradually converges after 50 iterations of the algorithm. At this time, the optimal total cost of the hub-and-spoke network of the URL is 592.2 million yuan. In addition, five urban hub nodes should be built, which are located in  $c_1, c_2, c_6, c_7,$  and  $c_8$ . The remaining four urban nodes  $c_3, c_4, c_5,$  and  $c_9$  are regarded as nonhub nodes, and  $c_3, c_4,$  and  $c_5$  are assigned to  $c_2$ .  $c_9$  falls into the radiation range of  $c_7$ .

The corresponding network planning diagram is shown in Fig. 6. The countrysides in the subnet are connected with the cities to which they belong, thereby achieving the first level of commodity traffic concentration. In the main network,  $c_1, c_2, c_6, c_7,$  and  $c_8$  are set as hub urban nodes and intercommunicate with one another. The remaining  $c_3, c_4, c_5,$  and  $c_9$  are set as nonhub urban nodes, and  $c_9$  is connected with  $c_7$  and  $c_3, c_4,$  and  $c_5$  are connected

with  $c_2$ . As a result, the freight volume is further concentrated among the hub cities, thereby forming the scale transport on the axis. The entire network also presents a typical form of two-level hybrid hub-and-spoke with multi hubs and single distribution.

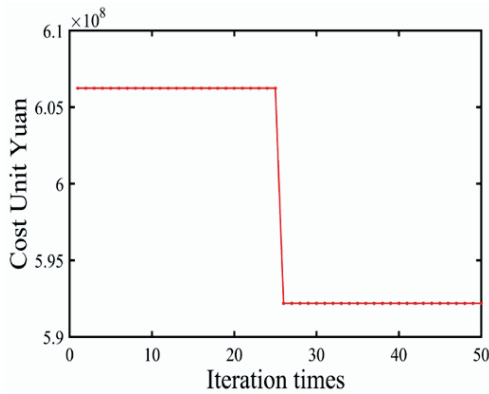


Figure 5 The optimal cost convergence curve

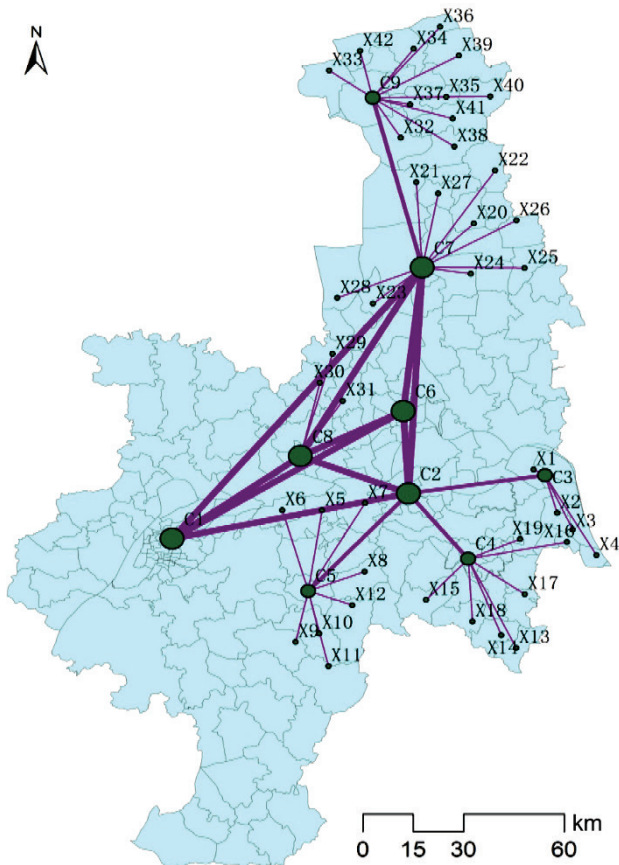


Figure 6 The hub-and-spoke network planning diagram of URL in NZY area

To illustrate the superiority of the hub-and-spoke network planning model of URL, the network structure of the two logistics networks and the optimal total cost are compared and analyzed. The first network is the hub-and-spoke network of URL built in this study, which is named network1 for convenience. When the urban part of network 1 is changed to a fully connected network, the second type of network is formed and named network2. The comparison of the shape of the urban parts of networks 1 and 2 is shown in Fig. 7. The figure shows that the urban network structure of network2 is relatively complex, whereas the urban network of network1 is simplified after

eliminating most of the pass-through transport routes. The comparison of the optimal total costs of networks1 and 2 under different values of  $p$  and  $\alpha$  is shown in Tab. 1. When  $p = 5$ ,  $\alpha = 0.45$ , the optimal total cost of network1 is 592.2 million yuan, and the optimal total cost of network2 is 1323 million yuan. Hence, the total cost of network1 is reduced by 731 million or 55.25% in contrast with network2. The scattered logistics demands can be effectively gathered by applying the hub-and-spoke network theory to the network planning of URL, thereby significantly reducing URL costs.

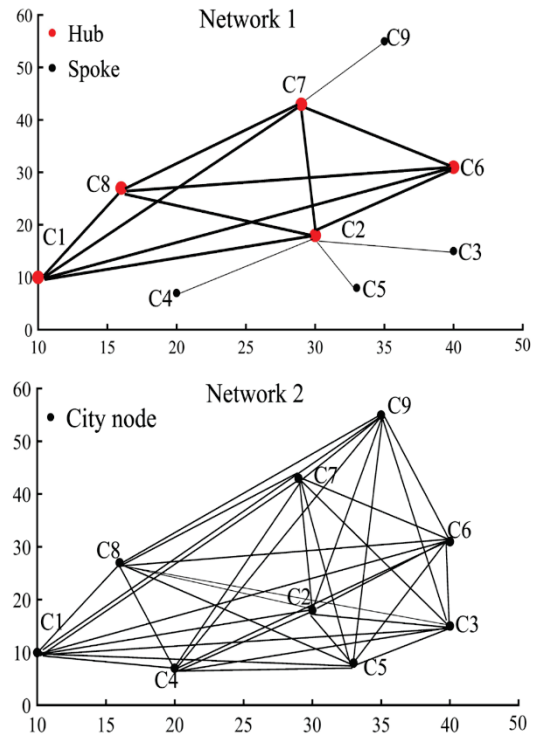


Figure 7 The comparison of the shape of the urban part of networks 1 and 2

Table 1 The effect of the number of hubs and the discount coefficient on the total cost of network

$p$	$\alpha$	The total cost of network 1/10 million yuan	The total cost of network 2/10 million yuan	The cost saving rate /%
3	0.25	106.3	132.3	19.65%
	0.45	108.0	132.3	18.37%
	0.65	109.6	132.3	17.16%
	0.85	111.3	132.3	15.87%
4	0.25	82.0	132.3	38.02%
	0.45	83.1	132.3	37.19%
	0.65	84.2	132.3	36.36%
	0.85	85.3	132.3	35.53%
5	0.25	58.5	132.3	55.78%
	0.45	59.2	132.3	55.25%
	0.65	59.9	132.3	54.72%
	0.85	60.6	132.3	54.20%

### 5 CONCLUSION

To establish a planning scheme that can meet scattered logistics demands, the network planning model of URL was proposed by extending and improving the traditional hub-and-spoke network model. Besides, the TS algorithm was designed to solve this model. The feasibility and applicability of the model were verified by the network planning example of the NZY area. The following research conclusions can be drawn:

(1) The network planning scheme of URL that can meet the scattered demands can be provided by the network planning model established in this study, and a certain degree of theoretical and technical support can be obtained.

(2) The one-sided cognition of demand attributes of the traditional network planning model of URL can be further corrected by the network planning model established in this study, and the decision making process for the network planning of URLs can be expanded.

(3) The network planning model established in this study can also be applied to other network planning problems with scattered demands.

In conclusion, the network planning model of URL established from the perspective of the hub-and-spoke network is in line with real planning needs, and additional targeted decision references for the construction of URL networks can be provided. However, this work has several shortcomings. For example, the discount coefficient of unit transport cost between hub nodes is assumed to be a fixed value. These constraints should be released, and the construction of network planning models with other structural forms should be researched in future studies.

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