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Optimization Model of Hybrid Hub-and-Spoke Transportation Network of Road Less-Than-Truckload Cargo with Different Transportation Time Limits

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Abstract

With the growth of large parcel transportation, it is vital for road LTL (less-than-truckload) cargo transportation to improve operational efficiency and effectiveness. In order to investigate the influence of transportation network structure on transport efficiency and cost, a hybrid hub-and-spoke transportation network optimization model was proposed in this study. The capacity of freight hubs and the restriction of cargo in-transit transportation time were considered, and the lowest cost was used as optimization goal in this model. The artificial fish swarm algorithm (AFSA) was applied to solve this model. A case study of Guangdong Shunxin Express Company in China was conducted to compare the transportation cost and transit strategy obtained using different transportation network structures. Results demonstrate that, the operating cost of the transportation network with different time limits reduces by 4.04% and 3.02% when compared with that of the all-direct transportation network and actual network, respectively. The operating cost of the transportation network with different time limits increases by 3.59% compared to that of the transportation network with equal time limit. The number of routes in the transportation network with different time limits that include direct transportation and transit via one freight hub increase by 9 and 6, and the number of routes with transit via two freight hubs decreases by 15 when compared with that based on the transportation network with equal time limit. These findings indicate that transportation network with different time limits saves operating cost based on timeliness of transportation. This study provides a good reference for the operation optimization of road LTL cargo transportation enterprises.

Keywords: Network optimization, AFSA, Hybrid hub-and-spoke logistics network, Road LTL cargo, Transportation time limit

1. Introduction

As an important part of the logistics industry, LTL (less-than-truckload) cargo transportation provides support for the daily production and supply of living materials for urban residents. In the primary development stage of China's road LTL cargo transportation system, with fierce competition and low concentration in the market, price wars, transport timeliness wars and service quality wars between enterprises have led to a narrow profit space and difficult survival for most of the road LTL cargo transportation enterprises. Cargo transportation is a vital component of most logistics enterprises, and it generates costs that account for approximately 50% of all logistics costs. Moreover, time spent on cargo transportation accounts for more than 60% of all logistics time. Therefore, reducing the costs incurred in the transportation process is an important for reducing the operating costs of logistics enterprises, and reducing the transportation time is an important way to improve the timeliness of enterprise transportation and customer experience.

Currently, China's road LTL cargo transportation enterprises are based on two types of operation network: hub-and-spoke and dedicated lines. The hub-and-spoke transportation network structure can significantly boost transportation efficiency and lower transportation cost [1]. A hub-and-spoke cargo transportation network that can not only minimize the cost of transportation transit but also satisfy the customer's time requirement, and it is extremely useful for road LTL cargo transportation enterprises to seek a broader space for development. For road LTL cargo enterprises, considering the timeliness and cost of the LTL cargo transportation network can help reduce the costs of fuel, labour and other expenses incurred in the transportation process, improve the efficiency of transportation and ensure the timeliness of transportation. For customers, an effective and rational cargo transportation network offers high-quality services and enables cargo to arrive on time. For society and the public, a rationally structured cargo transportation network also contributes to environmental protection by reducing air pollution and fuel cost.

Hub-and-spoke transportation networks are classified into two categories: pure hub-and-spoke and hybrid hub-and-spoke. Hybrid hub-and-spoke transportation network is a vital development direction for future cargo transportation network structure [2], because it has the advantages of both direct transportation and pure hub-and-spoke transportation. This approach can improve the utilization of transportation vehicles, loading and unloading equipment and reduce the transportation cost of the enterprise based on satisfying the requirements of the shipper's delivery time [3]. Scholars all over the world proposed numerous studies about how to build hub-and-spoke networks, and they typically aimed to minimize the total cost of network transportation and considered factors such as hub capacity restrictions and multilayer hub-and-spoke network construction [4,5].

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However, there were situations that did not consider the limitations of the in-transit transportation time or considered the time limit of cargo in-transit was compatible with the practical situation. Hence, it is necessary to simultaneously consider hub capacity limitation and different in-transit transportation time limitation for network optimization.

Based on the above information, in the present study, a hybrid hub-and-spoke transportation network optimization approach considering the actual demand of road LTL cargo enterprises is designed to minimize the cost of cargo transportation and satisfy the customer requirements for different time limitations.

The rest of this study is organized as follows. Section 2 gives the relevant background. Section 3 proposes the mathematical model and algorithm. Section 4 discusses the applicability of the method through case studies. Section 5 summarizes the conclusions.

2. State of the art

Due to the high connectivity of hub-and-spoke transportation networks, a balance between efficiency and cost can be achieved, and such networks are widely used in air and road transportation [6]. In previous studies, the optimization of cargo transportation networks mainly involved constructing pure or hybrid hub-and-spoke cargo transportation network optimization models, and the typical hub-and-spoke network design problem originated from aviation network design [7]. In the optimization of the pure hub-and-spoke cargo transportation network, the lowest cost is generally selected as the optimization objective, and optimization models are constructed. For example, Elhedhli et al. [8], Alkaabneh et al. [9], and Wu et al. [10] proposed a single-allocation optimization model for hub-and-spoke network that considered the congestion cost incurred when a hub node's cargo volume was excessive, but the capacity constraints of hub nodes were not considered. Silva et al. [11] improved a heuristic algorithm to solve the two-stage pure hub-and-spoke network hub node location problem, and the algorithmic model was used to determine the optimal hub node locations in a short period. However, the model lacked node capacity constraints. Kratica et al. [12] proposed an improved genetic algorithm to solve the single assignment P-hub median problem. However, the constraints did not consider fixed cost and capacity, and the model only allowed straight-line transportation between central nodes. Azizi et al. [13] proposed a single-allocation pure hub-and-spoke cargo transportation network that only considered stochastic demand and congestion cost and did not involve node capacity. An et al. [14] used an algorithm for Lagrange relaxation and a method for branch delimitation to solve single-allocation and multi-allocation cargo transportation network models. However, this approach lacked a comparative analysis of the unfixed capacity of central nodes.

Hybrid hub-and-spoke cargo transportation network is effective and reliable, and its optimization can promote the economic efficiency of scale and decrease costs [15]. In the existing literatures, the main choices of algorithms used to optimize hybrid hub-and-spoke network are the heuristic [4], metaheuristic [16], Lagrange relaxation heuristic [17], genetic [18] algorithms. A hybrid hub-and-spoke cargo transportation network is generally built with the objectives of minimizing transportation cost and distance, and capacity constraints, transportation mode differences, and transportation cost discount factors are considered. Zhao et al. [19] proposed a metro logistics hub-and-spoke network with the goal of minimizing the transportation distance in the entire network and considered capacity constraints. However, it only considered one transportation and distribution mode based on demand determination. Dai et al. [20] built a hub-and-spoke network model with the objective of minimizing the overall cost, and central node locations, distribution relationships and the direct route schedule were the decision variables. However, the variation in the discount factor associated with the per-unit transportation cost was not considered. Additionally, Günther et al. [21] put forward a hybrid hub-and-spoke transportation network to reduce transportation cost, but it only considered the cost of the hub-and-spoke transportation network, and straight-line transportation mainly occurred between depots other than hubs. Lee et al. [22] constructed an optimization model of hybrid hub-and-spoke cargo transportation network with capacity constraints and compared two modes of transportation, namely, straight-line transportation and transhipment, by considering the balance between demand and capacity. However, the model excluded direct connections between hub nodes. Li et al. [23] presented a hybrid hub-and-spoke network that considered both transportation time constraint and transportation cost. However, the time consumption and cost of consolidation and transhipment were not considered.

Thus, a model that closely simulates real flows in a cargo transportation network is developed in this study. In this model, the cargo hub capacity and cargo in-transit time are limited. The different cargo in-transit times at different nodes are related to the transportation distance between the nodes. Furthermore, the model considers the scale effect of trunk line transportation and the scale effect for all lines in the practical transportation network.

3. Methodology

3.1 Problem description

For a road LTL cargo transportation enterprise has deployed a freight station in a specific area, cost minimization is selected as the optimization objective, and the capacity limitations of freight hubs and transportation time limitation are considered. A single-allocation hybrid hub-and-spoke road transportation network for road LTL cargo and that allows direct access is designed. The network structure is shown in Figure 1. The problems that need to be solved are selecting a certain number of freight hubs from the set of alternative freight hubs, assigning the remaining non-freight hubs to freight hubs to meet the time limit of cargo in transit considering freight hub capacity constraints, designing specific transportation routes between node pairs (direct transportation, transit through one freight hub, and transit through two freight hubs) and establishing a hybrid hub-and-spoke transportation network for road LTL cargo that allows direct access to minimize costs.

For an established freight hub and a general freight station allocated to the freight hub according to the principle of single allocation, the specific transportation routes between node pairs can be determined in turn. In Figure 1, $N_1 \cdots N_n$ represent the standard freight stations in the network, $K_1 \cdots K_n$ are the freight hubs in the network, and the connections between nodes indicate the possible transportation routes.

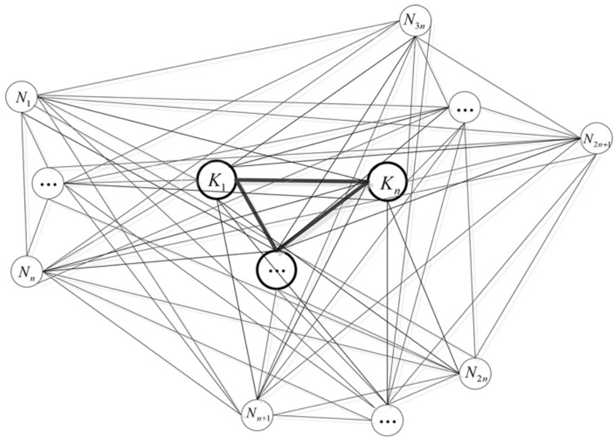

Fig. 1. Diagram of a hybrid hub-spoke network for highway LTL freight

3.2 Model assumptions

Before establishing an optimization model for a hybrid hub-and-spoke transportation network for road LTL cargo with different time limits of cargo in-transit, the following assumptions need to be satisfied:

(1) The flows of road LTL cargo between all freight terminals are known.

(2) All freight stations with road LTL cargo flows are linked, with direct transit, transit through a freight hub, or transit through two freight hubs via one direction.

(3) All freight hubs are interconnected.

(4) The same maximum cargo capacity limit exists for all cargo hubs.

(5) Any general freight station can be assigned to only one freight hub; i.e., a single-assignment hybrid hub-and-spoke transportation network is established.

(6) All transport sections are associated with scale effects, and the scale effect coefficient is determined with a segment-specific function related to cargo flows.

(7) The construction cost of freight hubs is not considered.

(8) The same transit time exists for all shipments from a single freight hub.

(9) Transport capacity limitations are not considered for transport routes.

(10) The unit transportation cost is the same for all transportation routes.

(11) The average vehicle travel speed is the same for all transport routes.

(12) Different cargo transit time limits exist between different freight stations and the cargo transit time limit is determined with a segment-specific function related to the transport distance.

3.3 Parameter descriptions

Let N be the set of all freight stations in the LTL cargo transportation network, S be the set of alternative freight hubs, c be the transportation cost per unit kilogram LTL cargo transportation per kilometre (yuan/kg·km), and μ be the transit fee needed for a unit kilogram of less than truckload cargo to be transported through a single freight hub (yuan/kg·km).

$$\alpha(u)=\begin{cases}\alpha_1, l_1 < F_{ij}^1 \le r_1 \\ \cdots \\ \alpha_u, l_u < F_{ij}^u \le r_u\end{cases}$$ Section-specific transportation factor, with a segment function related to cargo flows.

d_{ij} : Road transport distance between freight station i and freight station j (km).

v : Average speed of a vehicle (km/h).

P : Number of selected freight hubs.

Q_k : The maximum volume of cargo that can be accommodated at freight hub k (kg).

T : In-transit time limit for LTL cargo (h).

t_z : LTL cargo transit time through a single freight hub (h).

h_{ij} : Cargo flow between freight station i and freight station j (kg).

l_u : Discount interval μ corresponding to the lower bound of cargo flows (kg).

r_u : Discount interval μ corresponding to the upper bound of cargo flows (kg).

F_{ij}^u : LTL cargo flow between sections i and j when using the discount factor corresponding to the discount interval μ (kg).

U : Set of discount intervals.

$$Z_{ij}^u=\begin{cases}1, \textit{ The LTL cargo flow between transport sections } i-j \\ \textit{uses the discount factor corresponding to interval } \mu \\ 0, \textit{ else}\end{cases}$$

$$x_{ij}^{km}=\begin{cases}1, \textit{ LTL cargoe between freight stations } i-j \textit{ is} \\ \textit{transported through freight hubs } k \textit{ and } m \\ 0, \textit{ else}\end{cases}$$

$$x_{ij}^{kk}=\begin{cases}1, \textit{ LTL cargo between freight stations } i-j \textit{ is} \\ \textit{transited through freight hub } k \\ 0, \textit{ else}\end{cases}$$

$$x_{ij}=\begin{cases}1, \textit{ LTL cargo between freight stations } i-j \textit{ is} \\ \textit{directly transproted} \\ 0, \textit{ else}\end{cases}$$

$$x_{ik}=\begin{cases}1, \textit{ General freight station } i \textit{ assigned to freight hub } k \\ 0, \textit{ else}\end{cases}$$

$$x_{kk}=\begin{cases}1, \textit{ Alternative freight hub } k \textit{ is selected as a freight hub} \\ 0, \textit{ else}\end{cases}$$

$$T^r=\begin{cases}T^1, d_{l1} < d_{ij}^1 \le d_{u1} \\ \cdots \\ T^r, d_{lr} < d_{ij}^r \le d_{ur}\end{cases}$$ The in-transit time limit for LTL cargo is an r-segment function related to the transport distance (h).

d_{lr} : The lower bound of the transport distance corresponding to the time limit of cargo in transit for T^r (km);

d_{ur} : The upper bound of the transport distance corresponding to the time limit of cargo in transit for T^r (km).

d_{ij}^r : The distance of road transport between freight stations i and j when using the interval r corresponding to the time limit of cargo in transit (m).

R : The set of time limits for cargo in transit.

3.4 Model Construction

The costs are divided into three main components: transportation costs arising from direct transportation Z_1, transportation costs arising from transportation via freight hubs Z_2 and transit costs Z_3.

Freight transportation costs are incurred by direct transportation between freight stations

$$Z_1 = \sum_{u\in U}\sum_{i\in N}\sum_{j\in N} F_{ij}^u d_{ij} c\alpha(u)$$

The transportation costs calculated with the transit method can be divided into three types: the transportation cost between the originating freight station and a freight hub, the transportation cost between freight hubs, and the transportation cost between a freight hub and the destination freight station.

$$Z_2 = \sum_{u\in U}\sum_{i\in N}\sum_{k\in S} F_{ik}^u d_{ik} c\alpha(u) + \sum_{u\in U}\sum_{k\in S}\sum_{m\in S} F_{km}^u d_{km} c\alpha(u) + \sum_{u\in U}\sum_{m\in S}\sum_{j\in N} F_{mj}^u d_{mj} c\alpha(u)$$

Transit charges at freight hubs can be divided into two cases: one-time charges for transit via one freight hub and two charges for transit via two freight hubs. In the latter case, the transit fee is calculated twice. Therefore, the total cost is: $Z = Z_1 + Z_2 + Z_3$.

To meet the cargo-in-transit time limit, the standard freight single-station allocation limit, maximum capacity limit for freight hubs, station number limit for freight hubs, and other appropriate limits, an optimization model of the hybrid hub-and-spoke transportation network with different time limits for cargo in-transit is built as follows. Objective function:

$$\begin{aligned} Min Z = &\sum_{u\in U}\sum_{i\in N}\sum_{j\in N} F_{ij}^u d_{ij} c\alpha(u) + \sum_{u\in U}\sum_{i\in N}\sum_{k\in S} F_{ik}^u d_{ik} c\alpha(u) + \\ &\sum_{u\in U}\sum_{k\in S}\sum_{m\in S} F_{km}^u d_{km} c\alpha(u) + \sum_{u\in U}\sum_{m\in S}\sum_{j\in N} F_{mj}^u d_{mj} c\alpha(u) + \\ &\sum_{i\in N}\sum_{j\in N}\sum_{k\in S}\sum_{m\in S} 2h_{ij} x_{ij}^{km}\mu - \sum_{i\in N}\sum_{j\in N}\sum_{k\in S} h_{ij} x_{ij}^{kk}\mu \end{aligned} \tag{1}$$

Restrictions:

$$\sum_{u\in U} F_{ij}^u = h_{ij} x_{ij} \tag{2}$$

$$Z_{ij}^u l_u < F_{ij}^u \le Z_{ij}^u r_u, u\in U \tag{3}$$

$$\sum_{u\in U} Z_{ij}^u = 1 \tag{4}$$

$$\sum_{u\in U} F_{ik}^u = \sum_{m\in S}\sum_{j\in N} h_{ij} x_{ij}^{km}, k, m\in S \tag{5}$$

$$Z_{ik}^u l_u < F_{ik}^u \le Z_{ik}^u r_u \ \forall i\in N; k\in S; u\in U \tag{6}$$

$$\sum_{u\in U} Z_{ik}^u = 1, k\in S \tag{7}$$

$$\sum_{u\in U} F_{km}^u = \sum_{i\in N}\sum_{j\in N} h_{ij} x_{ij}^{km}, k, m\in S \tag{8}$$

$$Z_{km}^u l_u < F_{km}^u \le Z_{km}^u r_u \ \forall k, m\in S; u\in U \tag{9}$$

$$\sum_{u\in U} Z_{km}^u = 1, \forall k, m\in S \tag{10}$$

$$\sum_{u\in U} F_{mj}^u = \sum_{i\in N}\sum_{k\in S} h_{ij} x_{ij}^{km}, k, m\in S \tag{11}$$

$$Z_{mj}^u l_u < F_{mj}^u \le Z_{mj}^u r_u, m\in S; u\in U \tag{12}$$

$$\sum_{u\in U} Z_{mj}^u = 1, m\in S \tag{13}$$

$$\sum_{k\in S} x_{ik} = 1 \tag{14}$$

$$x_{ik} \le x_{kk}, k\in S \tag{15}$$

$$\sum_{k\in S} x_{kk} = p \tag{16}$$

$$\sum_{i\in N}\sum_{j\in N}\sum_{m\in S} h_{ij} x_{ij}^{km} \le Q_k, \forall k\in S \tag{17}$$

$$x_{ij}^{km}\left(\frac{d_{ik}}{v} + \frac{d_{km}}{v} + 2t_z + \frac{d_{mj}}{v}\right) + x_{ij}\frac{d_{ij}}{v} \le T, k, m\in S, k\ne m \tag{18}$$

$$x_{ij}^{kk}\left(\frac{d_{ik}}{v} + t_z + \frac{d_{kj}}{v}\right) + x_{ij}\frac{d_{ij}}{v} \le T, k\in S \tag{19}$$

$$x_{ik}, x_{kk}, x_{ij}, x_{ij}^{km}, x_{ij}^{kk}, Z_{ij}^u = \{0,1\} \tag{20}$$

$$x_{ij}^{km}\left(\frac{d_{ik}}{v} + \frac{d_{km}}{v} + 2t_z + \frac{d_{mj}}{v}\right) + x_{ij}\frac{d_{ij}^r}{v} \le T^r, \quad k, m\in S, k\ne m; r\in R \tag{21}$$

$$x_{ij}^{kk}\left(\frac{d_{ik}}{v} + t_z + \frac{d_{kj}}{v}\right) + x_{ij}\frac{d_{ij}^r}{v} \le T^r, k\in S; r\in R \tag{22}$$

$$y_{ij}^r d_{lr} < d_{ij}^r \le d_{ur} y_{ij}^r, r\in R \tag{23}$$

$$\sum_{r\in R} y_{ij}^r = 1 \tag{24}$$

$$x_{ik}, x_{kk}, x_{ij}, x_{ij}^{km}, x_{ij}^{kk}, Z_{ij}^u, y_{ij}^r = \{0,1\} \quad \forall i, j\in N \tag{25}$$

Equation (1) is the objective function, indicating that the optimization objective is to minimize the total operating cost of the transportation network for road LTL cargo. Equation (2) indicates that for the discount interval μ, an LTL flow occurs between direct sections *i* and *j*. Equation (3) indicates that when the discount coefficient corresponding to interval μ is used for the LTL flow between sections *i* and *j*, the LTL flow between the direct sections must be within the range of the interval. Equation (4) indicates that a direct section can only fall within one discount interval. Equation (5) indicates that for the discount interval μ, an LTL cargo flow occurs on road segment *i-k*. Equation (6) indicates that when an LTL cargo flow occurs on road segment *i-k* with a discount coefficient corresponding to the interval μ, the LTL cargo flow between segments *i* and *k* must be within the range of the interval μ. Equation (7) indicates that road segment *i-k* can only fall within one discount interval. Equation (8) indicates that for the discount interval μ, an LTL cargo flow occurs on the hub road segment *k-m*. Equation (9) indicates that when a discount coefficient corresponding to the interval μ is adopted for a cargo flow, an LTL cargo flow from hub *k* to hub *m* must be within the range of interval μ. Equation (10) indicates that only one discount interval can be selected for hub section *k-m*. Equation (11) indicates that for the discount interval μ, an LTL flow occurs on road section *m-j*. Equation (12) indicates that when an LTL flow occurs between *m* and *j* and a discount coefficient corresponding to interval μ is considered, the LTL flow between *m* and *j* must be within the range of interval μ. Equation (13) indicates that only one discount interval can be selected for road segment *m-j*. Equation (14) indicates that any ordinary freight station can only be assigned to one freight hub. Equation (15) indicates that when alternative freight hub *k* is selected as the freight hub, ordinary freight station *i* can be allocated to alternative freight hub *k*. Equation (16) indicates that a total of *P* freight hubs are selected. Equation (17) indicates that the total LTL flow through freight hub *k* cannot exceed the predetermined maximum allowable capacity. Equations (18) and (19) indicate that a freight station operator can choose direct transportation, transportation through one freight hub, or transportation through two freight hubs, and the time limit for cargo in transit cannot be exceeded. Equation (20) represents the 0-1 constraint for the decision variable. Equations (21) and (22) indicate that direct transportation between freight stations, transit through one freight hub, or transit through two freight hubs cannot exceed the specified time limit for the in-transit transportation of cargo. Equation (23) indicates that when the time limit for the in-transit transportation of cargo between freight stations *i* and *j* is based on the interval *r*, the road transportation distance between freight stations *i* and *j* must be within the range of interval *r*. Equation (24) indicates that the in-transit time limit for cargo transported between freight stations *i* and *j* can only fall within one interval. Equation (25) is the 0-1 constraint for the decision variables.

3.5 Solution algorithm

3.5.1 Algorithm Design

(1) Coding and decoding design

The AFSA (artificial fish swarm algorithm) is employed to solve the model, and real numbers between 0 and 1 are used for encoding. It is assumed that there are *N* freight stations, *P* freight hubs, *N-P* general freight stations, and *S* alternative freight hubs in the hub-and-spoke transportation network for road LTL cargo. Each artificial fish is a nonnegative decimal series, and the encoding process can be divided into three segments. The first segment is encoded with a length of *S*, indicating the selection of freight hub stations. Random generation is employed to generate *S* decimals between 0 and 1, and the first *P* is selected as the freight hub station; then, additional *P* selections are sorted in order from smallest to largest. The second segment is coded with length *N-P*, which is an assignment approach commonly used for freight stations. Randomly generated *N-P* decimals in the range of 0 to 1 are assigned to the first selected hub if the value falls between 0 and 1/*P*, to the second selected hub if the value falls between 1/*P* and 2/*P*, to the third selected hub if the value falls between 2/*P* and 3/*P*, to the third selected hub if the value falls between 3/*P* and 4/*P*, to the fourth selected hub if the value falls between 4/*P* and 5/*P*, and so on for values falling between (*P*-1)/*P* and *P*/*P*, which are assigned to the *P*th selected freight hub. The third segment is coded as *N*(N-1)*, which is the transportation route between the origin and destination freight stations. Random generation is employed to generate *N*(N-1)* decimals between 0 and 1. If a value is less than 0.5, the route is direct. Otherwise, transit routing is needed.

(2) Adaptation function design

The objective function of a model generally corresponds to the fitness function of the underlying algorithm. To effectively simplify the model solution process and algorithm design, the in-transit time limit for cargo and a freight hub capacity limit are added to the fitness function and multiplied by a very large value to eliminate solutions that exceed these limits. Thus, in this study, very small values are transformed into very large values to simplify the calculation process. The fitness function is shown in Equation 26.

$$Fit = -(Z + A_1 T_c + A_2 Q_c) \tag{26}$$

where Z represents the objective function and the specific expression is shown in formula (1). A_1 and A_2 are penalty coefficients, which are usually large values and are set to 10^5 in this study. T_c is the maximum allowable transit time, which is calculated with formula (27), and Q_c represents the sum of the actual capacity of each freight terminal, which should not exceed the specified capacity and is calculated based on formula (28).

$$T_c = \sum_{i,j \in N} \sum_{k,m \in S} Max \left\{ \begin{pmatrix} x_{ij}^{km} \left(\frac{d_{ik}}{v} + \frac{d_{km}}{v} + 2t_z + \frac{d_{mj}}{v} \right) + \\ x_{ij}^{kk} \left(\frac{d_{ik}}{v} + t_z + \frac{d_{kj}}{v} \right) + x_{ij} \frac{d_{ij}}{v} - T \end{pmatrix}, 0 \right\} \tag{27}$$

$$Q_c = \sum_{k \in S} Max \left\{ \left(\sum_{i \in N} \sum_{j \in N} \sum_{m \in S} h_{ij} x_{ij}^{km} - Q \right), 0 \right\} \tag{28}$$

(3) Behaviour design

The four basic behaviours of artificial fish include foraging behaviour, clustering behaviour, tail-chasing behaviour, and random behaviour. X_i denotes the location of artificial fish *i*, $X_{i|next}$ denotes the location of the artificial fish at the next moment, Y_i denotes the nutrient concentration of the artificial fish (adaptation of the artificial fish), $\|X_j - X_i\|$ denotes the distance between artificial fish i and fish j, Rand () denotes a random number generated between 0 and 1, λ_f denotes the total number of artificial fish within the field of view, and X_c denotes the central location of the artificial fish within the field of view.

(4) Behaviour selection

By simulating the aggregation and tail-chasing behaviours of artificial fish, the fitness levels of the fish can be calculated and compared. Then, the behaviour that improves the fitness of the artificial fish the most is selected for execution. If neither clustering nor tailing improves fitness, then foraging is performed. If foraging does not improve the fitness level of the artificial fish, then random behaviours are performed.

(5) Design of the algorithm termination condition

The maximum number of iterations is used as the condition for algorithm termination. When the number of iterations of the algorithm reaches 500, the algorithm stops and outputs the calculated minimum operating cost of the network, the selected freight hubs, and the transportation modes between node pairs.

3.5.1 Algorithm Design

Step 1): Set the value of each parameter in the AFSA while establishing the initial artificial fish using random generation. Set the values of parameters such as the visual field (Visual), maximum movement step (Step), artificial fish school size (M), maximum number of allowed attempts for foraging (Try number), crowding factor ( ) and maximum number of iterations (Max gen). Then, establish M initial artificial fish using random generation.

Step 2): Calculate the fitness function to obtain the fitness levels of the artificial fish. The fitness function is designed based on the objective function of the model and the related constraints, and the fitness levels of the initial artificial fish are quantitatively measured.

Step 3): Record the location of the optimal initial artificial fish and the corresponding nutrient concentration for that fish.

Step 4): Evaluate the behaviour of the initial artificial fish and select the behaviour that moves the fish closer to an area with a high nutrient concentration. Simulate the behaviours of the updated artificial fish and choose a behaviour that moves the artificial fish closer to an area with a high nutrient concentration.

Step 5): Execute the behaviour chosen for the artificial fish and update the position information. Each initial artificial fish executes the behaviour selected in step 4 separately. Once the execution of each initial artificial fish is completed, update the position of each initial artificial fish.

Step 6): Calculate the fitness levels of the artificial fish after updating their positions.

Step 7): Compare the results with the recorded values; if a value is better than the previous best value, then update the new best value; otherwise, proceed directly to the next step. If the nutrient concentration in the artificial fish after updating locations is higher than the previously recorded value, update the location and nutrient concentration information. If the nutrient concentration in the artificial fish after updating locations is lower than or equal to the previously recorded value, proceed directly to the next step without updating.

Step 8): Determine whether the algorithm stopping condition is reached. If the algorithm stopping condition is reached, output the result; if not, go to step 4.

The solution steps of the AFSA are shown in Figure 2.

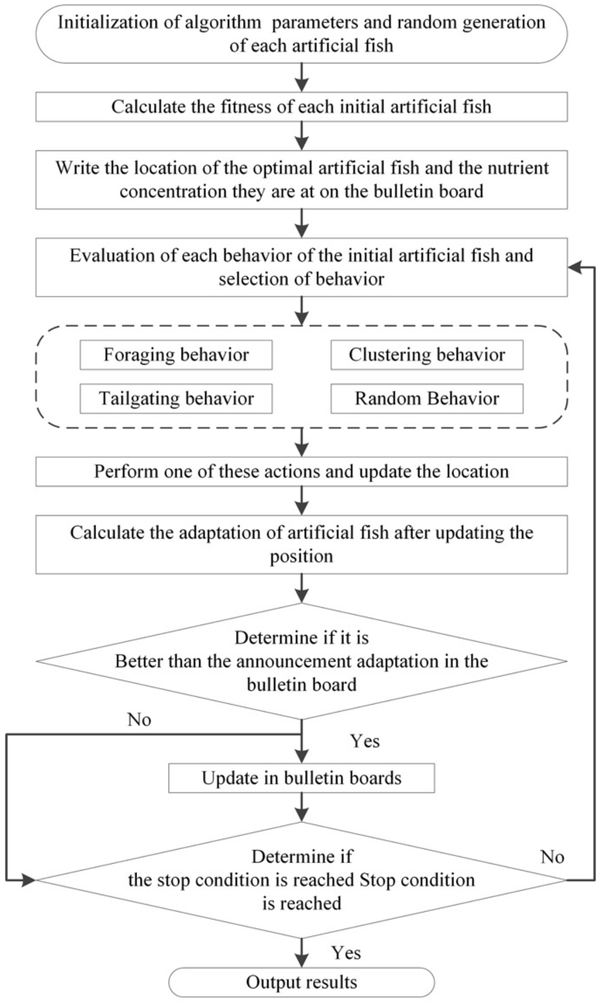

Fig. 2. Execution steps of the AFSA

4. Result Analysis and Discussion

4.1 Case introduction

The China Guangdong Shunxin Express Company is selected as an example. The enterprise has been committed to domestic road LTL cargo transportation since its establishment and has formed a nationwide road LTL freight network, with service areas spanning Hong Kong, Macao and Taiwan and 31 provinces (municipalities and autonomous regions) in the mainland, mainly providing standard express, full trucking, and door-to-door pickup and delivery logistics services. The market scale and industry influence of this road LTL cargo enterprise has been expanding continuously and it has opened more than 150 transit collection and distribution yards and opened more than 1,300 direct routes. This enterprise has a yard area of well over 400,000 square metres, with more than 6,200 physical outlets and an average daily cargo throughput of more than 10,000 tons. To optimize the cargo transportation network and verify the superiority of the hybrid hub-and-spoke transportation network, this model assume that the original case is based on the full direct transportation method and compare the freight transportation network transportation costs of the two transportation methods.

In the present study, a cargo network consisting of 29 freight stations in East China (Shanghai, Jiangsu, Zhejiang, and Anhui provinces and cities within) is selected as an example. An evaluation index system for alternative freight hubs is constructed from three perspectives: the operation scale of freight stations, the traffic convenience of freight stations, and the development potential of freight stations. An entropy weight-based TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) composite evaluation method is used to score each freight terminal, and the top 15 freight stations are selected to form the set of alternative freight hubs. The 15 freight stations in Hangzhou, Wuxi, Shanghai, Ningbo, Jinhua, Hefei, Nanjing, Suzhou, Jiaxing, Taizhou, Wenzhou, Nantong, Fuyang, Changzhou, and Huai'an were selected as alternative freight hubs. By comparing the administrative divisions of Shanghai, Jiangsu, Zhejiang, and Anhui provinces, the study find that there are six alternative freight hubs in Jiangsu, six alternative freight hubs in Zhejiang, two alternative freight hubs in Anhui, and one alternative freight hub in Shanghai. Additionally, there are alternative freight hubs in Shanghai, Zhejiang, Jiangsu, and Anhui in the study area. The spatial distribution of the 29 terminals is shown in Figure 3.

Fig. 3. The spatial distribution of the 29 freight stations in East China

(1) Set of freight terminals and alternative freight hubs

Set of freight stations *N*= {Anqing, Bengbu, Bozhou, Changzhou, Fuyang, Hefei, Huzhou, Huaian, Huangshan, Jiaxing, Jinhua, Lianyungang, Nanjing, Nantong, Ningbo, Quzhou, Shanghai, Taizhou, Taizhou, Wenzhou, Wuxi, Wuhu, Suzhou, Hangzhou, Suqian, Xuzhou, Xuancheng, Yancheng, Zhenjiang}

Set of alternative freight hubs *S*= {Hangzhou, Wuxi, Shanghai, Ningbo, Jinhua, Hefei, Nanjing, Suzhou, Jiaxing, Taizhou, Wenzhou, Nantong, Fuyang, Changzhou, Huaian}.

(2) Transportation and transit costs

According to the monitoring data from the Price Monitoring Center of the National Development and Reform Commission of the People's Republic of China, the price of road LTL cargo transportation is set to 0.00063 yuan/kg-km. It is assumed that the transit cost of road LTL cargo is 0.0001 yuan/kg.

(3) Discount factor

Based on the scale of LTL cargo flows between freight stations, the discount factor used in the calculation example is assumed to span 4 segments, as shown in the following equation (29):

$$\alpha(u)=\begin{cases}1, 0 < F_{ij}^{1} \le 3000 \\ 0.9, 3000 < F_{ij}^{2} \le 6000 \\ 0.8, 6000 < F_{ij}^{3} \le 9000 \\ 0.7, 9000 < F_{ij}^{4}\end{cases} \tag{29}$$

(4) Cargo flows and road transport distances between freight stations

Based on the actual operation data for the selected road LTL cargo enterprise in the first half of 2018, the average daily cargo flows among 29 freight stations were obtained, and some sample data for flows among freight stations are shown in Table 1. Additionally, some sample data for road transport distances among some freight stations are shown in Table 2.

(5) The average speed of vehicles

The level of road transportation infrastructure development varies between freight terminals, which leads to differences in vehicle speeds. To facilitate subsequent analysis, it is assumed that the average speed of vehicles is 55 km/h.

(6) Number of freight hubs and maximum capacity

The setting of the number of freight hubs has an enormous impact on the choice of transportation routes and the operating costs among freight stations. Therefore, it is important to reasonably set the number of freight hubs. Usually, the most reasonable number of hubs in a hub-and-spoke network is $p=\sqrt{N}$. Since there are 29 freight stations in the example used in this study, i.e., $N=29$, where $p=\sqrt{N}=\sqrt{29}$, the reasonable number of freight hubs is 5 or 6. Combined with the current spatial distribution of freight stations and the actual cargo flows, the number of freight hubs in this study is set to 6. Additionally, the capacity limit of freight hubs is considered and is assumed to be 1000000 kg based on the practices of the studied road LTL cargo transportation enterprise.

(7) Time and distance limits for cargo in transit

The time limit for the in-transit transportation of cargo used in the calculation example is assumed to be three segments, and this limit combines requirements for road transportation distances and transport timeliness between cargo terminals. The time limit for cargo at a single freight hub is assumed to be 6 hours:

Table 1. Freight volume between some freight stations (unit: kg)

	Anqing	Bengbu	Bozhou	Changzhou	Fuyang	Hefei	Huzhou	Huaian
Anqing	0	116	6	111	48	213	52	440
Bengbu	81	0	31	69	104	312	54	137
Bozhou	32	158	0	31	16	435	13	161
Changzhou	48	71	9	0	47	227	27	476
Fuyang	69	70	5	125	0	271	38	148
Hefei	320	640	110	243	461	0	85	269
Huzhou	30	24	14	46	23	51	0	55
Huaian	139	181	104	191	151	420	72	0

Table 2. Highway transport distance between some freight stations (unit: km)

	Anqing	Bengbu	Bozhou	Changzhou	Fuyang	Hefei	Huzhou	Huaian
Anqing	0	315	489	385	383	171	340	472
Bengbu	315	0	237	320	193	150	427	250
Bozhou	489	237	0	528	118	322	634	379
Changzhou	385	320	528	0	455	300	136	253
Fuyang	383	193	118	455	0	219	548	456
Hefei	171	150	322	300	219	0	347	337
Huzhou	340	427	634	136	548	347	0	378
Huaian	472	250	379	253	456	337	378	0

$$T^r = \begin{cases} 48hours, 0 < d_{ij}^1 < 500 \\ 72hours, 500 \le d_{ij}^2 < 1000 \\ 96hours, 1000 \le d_{ij}^3 \end{cases} \quad (30)$$

4.2 Case analysis

(1) Hybrid hub-and-spoke transportation network with different time limits for in-transit road LTL cargo

Using the designed AFSA, the solution is obtained in the MATLAB programming software platform, and the relevant parameters are set as shown in Table 3.

Table 3. Parameter settings for the AFSA

Parameters	Set values
Visual	15
Step	0.5
M	100
Try_number	30
δ	0.2
Max_gen	500

To make the algorithm solution process clear and intuitive, when writing the code to produce the output plot, a negative sign is added in front of the derived fitness value to transform it into a positive value.

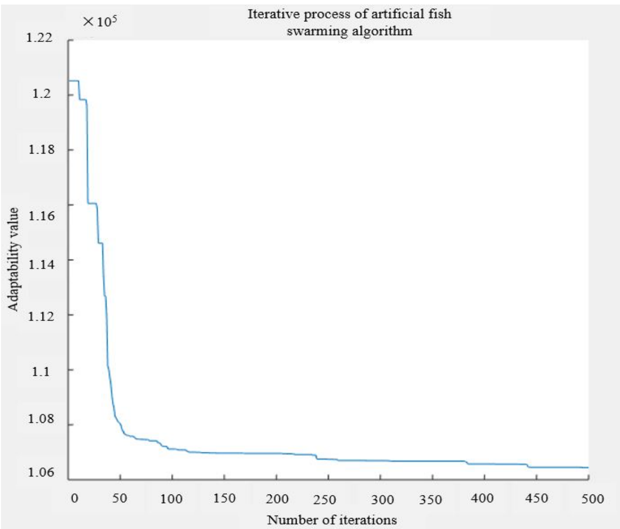

Fig. 4. Iterative process of the AFSA

As shown in Figure 4, the optimization curve decreases sharply before 50 iterations of the AFSA, indicating rapid convergence. Then, the solution results are gradually optimized, and the algorithm converges at a comparatively slower rate. When the algorithm reaches the 445th iteration, the optimal solution to the problem is obtained.

Table. 4. Results of the AFSA (different time limits of cargo in transit)

	Cost (yuan)	The hubs of choice
Result	106438.470	Hangzhou, Changzhou, Wuxi, Nanjing, Ningbo, Jiaxing

The results of the solution are shown in Table 4, and the optimal operating cost of the hybrid hub-and-spoke road transportation network with different time limits for cargo in transit is \$106,438.470. Without changing any conditions in the algorithm, the cost is \$110,915.251 for all transportation routes with direct transportation. The company's actual operating cost is \$109,758.56 when removing irrelevant costs. The optimized hybrid hub-and-spoke transportation network operating cost, which considers the different time limits of cargo in transit, is reduced by 4.04% and 3.02% compared to the total direct and actual operating costs, respectively.

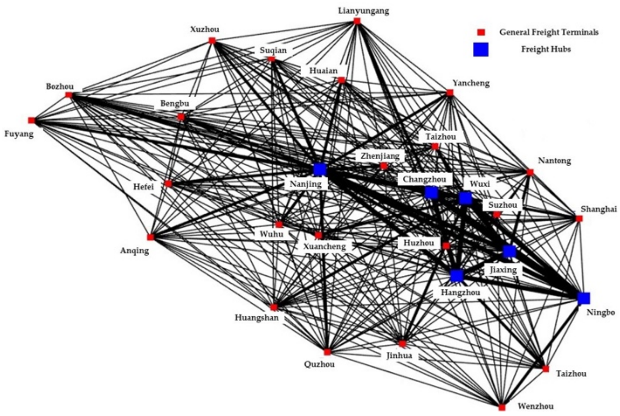

Fig. 5. Hybrid hub-and-spoke transportation network with different time limits of cargo in transit

Table 4 and Figure 5 show that the six selected freight hubs are Hangzhou, Changzhou, Wuxi, Nanjing, Ningbo, and Jiaxing. Among them, Hangzhou, Ningbo, and Jiaxing are located in Zhejiang Province, and Changzhou, Wuxi, and Nanjing are located in Jiangsu Province. The freight stations connected to each freight hub are shown in Table 5.

Table 5. The freight stations connected to freight hubs (different time limits of cargo in transit)

Selected freight hubs	Connected freight stations
Hangzhou	Taizhou
Hangzhou	Lianyungang
Wuxi	Huangshan, Jinhua, Shanghai, Taizhou, Suzhou, and Xuancheng
Nanjing	Anqing, Bengbu, Bozhou, Fuyang, Hefei, Huzhou, Huaian, Quzhou, Wuhu, Suqian, Xuzhou, Yancheng, and Zhenjiang
Ningbo	Wenzhou
Jiaxing	Nantong

(2) Hybrid hub-and-spoke transportation network with the same time limit of cargo in transit

For comparison with the previous case, in this case, the cargo-in-transit time limit is set to 72 hours without changing other assumptions or constraints.

Table 6. Results of the AFSA (same time limit of cargo in transit)

	Cost (yuan)	The hubs of choice
Result	102614.031	Changzhou, Jiaxing, Nantong, Shanghai, Wuxi, and Hangzhou

The solution in this case is shown in Table 6. The optimal cost of the hybrid hub-and-spoke transportation network with the same time limit of cargo in transit is $102,614.031.

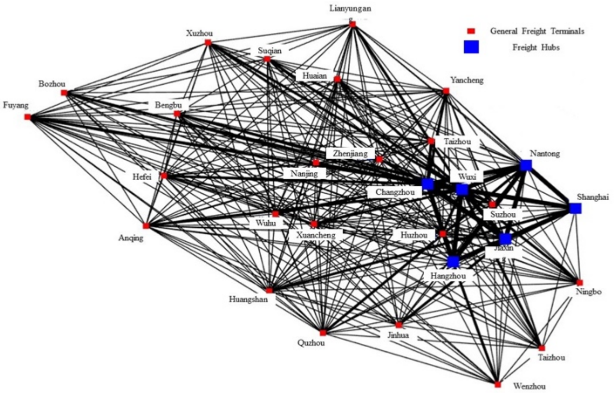

Fig. 6. Hybrid hub-and-spoke transportation network with the same time limits of cargo in transit

Table 7 and Figure 6 indicate that the six selected freight hubs are Changzhou, Jiaxing, Nantong, Shanghai, Wuxi, and Hangzhou. A comparison of the administrative divisions in the study area suggests that there is one freight hub station in Shanghai, two freight hub stations in Zhejiang, and three freight hub stations in Jiangsu. The freight stations connected to each of the selected freight hubs are shown in Table 7.

Table 7. The freight stations connected to freight hubs (same time limit of cargo in transit)

Selected freight hubs	Direct freight stations
Changzhou	Bozhou, Fuyang, Hefei, Nanjing, Taizhou, Wuhu, Yancheng, and Zhenjiang
Jiaxing	Jinhua
Nantong	Quzhou
Shanghai	Huangshan
Wuxi	Anqing, Bengbu, Huzhou, Huaian, Lianyungang, Ningbo, Taizhou, Suzhou, Suqian, Xuzhou, and Xuancheng
Hangzhou	Wenzhou

4.3 Analysis of the results

(1) Comparative analysis of cargo transportation network operation cost

The cargo transportation network operation cost of the all-direct transportation mode, hybrid hub-and-spoke transportation network with the same time limit for cargo in transit, actual transportation network, and hybrid hub-and-spoke transportation network with different time limits for cargo in transit is 110915.251, 109,758.56, 102614.031, and 106438.470 yuan, respectively.

(2) Comparative analysis of the selected freight hubs

The hybrid hub-and-spoke network with the same time limit for cargo in transit includes Changzhou, Jiaxing, Nantong, Shanghai, Wuxi and Hangzhou as freight hubs, and the hybrid hub-and-spoke network with different time limits of cargo in transit includes Hangzhou, Changzhou, Wuxi, Nanjing, Ningbo and Jiaxing as freight hubs. Notably, in both transport modes, Hangzhou, Changzhou, Hangzhou, Changzhou, Jiaxing and Wuxi are selected as freight hubs. The specific results are shown in Table 8.

(3) Comparative analysis of transit strategy selection results

Compared with the hybrid hub-and-spoke network with the same time limit for cargo in transit, in the hybrid hub-and-spoke network with different time limits for cargo in transit, the selection of a direct transportation mode between the origin and destination freight stations becomes more common than the use of a transit mode via one freight hub, and transit via two freight hubs decreases in frequency. There is no change in the transit strategy between 415 origin and destination freight stations. However, different transit strategies are established for 397 origin and destination freight stations, 158 origin and destination freight stations have changed transportation modes from direct to transit, and 171 origin and destination freight stations have changed transportation modes from transit to direct. The details of the changes are shown in Tables 9 and 10.

Table 8. Comparison of freight station hub selection schemes

Scheme	Same freight hubs	Different freight hubs
Constant time limit	Hangzhou, Changzhou, Wuxi, and Jiaxing	Nantong and Shanghai
Different time limits	Hangzhou, Changzhou, Wuxi, and Jiaxing	Nanjing and Ningbo

Table 9. Changes in transport pathways

Shipping method	Increase or decrease
Direct shipping	Increase by 9
Transit via a freight hub	Increase by 6
Transit via two freight hubs	Decrease by 15

Table 10. Changes in the transport pathways between origin-destination freight stations

Changes in transportation mode	Number of changes
Direct → transit via a freight hub	103
Direct→ transit via two freight hubs	55
Transit via a freight hub → direct transit → transit via two freight hubs	101
Transit via a freight hub → transit via two freight hubs	32
Transit via two freight hubs → direct transit	70
Transit via two freight hubs → transit via one freight hub	36

5. Conclusions

Based on the existing hub-and-spoke transportation network of Guangdong Shunxin Express Company, an optimization model of a hybrid hub-and-spoke transportation network for road LTL cargo was constructed with cost minimization as the optimization objective, and an AFSA was designed to solve this model based on freight hub capacity and cargo transit time limitations. The following conclusions were drawn from the analyses.

(1) The optimal operating cost of the different cargo transportation modes was ranked from smallest to largest as follows: hybrid hub-and-spoke transportation network with the same time limit of cargo in transit < hybrid hub-and-spoke transportation network with different time limits of cargo in transit < actual operating cost < full direct-

transportation mode. This shows that in the optimization model of the hybrid hub-and-spoke transportation network with different time limits for cargo in transit, to meet the transportation time limits of cargo, some of lower-cost routes must be replaced with higher-cost options. However, overall, the hybrid hub-and-spoke transportation network can effectively reduce the operation cost of the freight network.

(2) In the hybrid hub-and-spoke transportation network with a time limit for cargo in transit, the operating cost shows a trend of decreasing and then increasing as the number of freight hubs increases. These findings indicate that the algorithm still operates effectively as the number of iterations increases, which verifies the advantages of the algorithm's large adaptation range and fast calculation speed.

(3) For the hybrid hub-and-spoke network with different time limits of cargo in transit, compared with the hybrid hub-and-spoke transportation network with the same time limit for cargo in transit, the numbers of direct routes and routes via one freight hub increase by 9 and 6, respectively, and the number of routes via two freight hubs decreases by 15. Additionally, 415 transport modes between the corresponding origin and destination freight stations remain unchanged and 397 transport modes are changed. This funding indicates that a decrease in the number of freight hubs in the hybrid hub-and-spoke network can improve transportation timeliness to some extent.

Freight hub selection and transportation path selection are very complex and systematic tasks. In this study, freight hub capacity constraints and time limits for cargo in transit are considered in conjunction with the actual situation, which provides a reference for road LTL cargo transportation enterprises to optimize route operations. However, considering the difficulty and efficiency of obtaining computational solutions, multiple objectives, such as minimizing carbon emissions, minimizing transportation distance, minimizing transportation time and maximizing the resource utilization rate, could be explored in future studies. Moreover, the addition of constraints such as different capacity limits for freight hub stations and the existence of differences in the unit transportation cost of transportation road sections could be considered.

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