Optimization of Passenger-like Container Train Running Plan Considering Empty Container Dispatch

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Abstract: Railway container transportation plays an important role in the sustainable development of transportation. In order to improve the efficiency of container transportation and maximize the transportation revenue of railway enterprises, taking the passenger-like container train running plan as the research object, we established an optimization model. The model considers the transportation requirements of empty and heavy containers, aiming at the maximum revenue of railway transportation enterprises, the conservation of container flow, train stops, container reloading, and other constraints. It is a mixed-integer linear programming optimization model. First, the shortest path between nodes was solved by the Floyd algorithm as the candidate set of the train to be run, and then the particle swarm algorithm was designed to solve the model. Numerical experiments were carried out by taking a container network with 34 nodes as an example to verify the validity of the model and algorithm. The experimental results showed that when the minimum average loading rate of trains is 70%, 47 lines need to be run, which is 163 less than the candidate lines. The running cost of all trains is 31,901,200 yuan, and total revenue of the transportation enterprise is 10,930,568 yuan. Compared with the existing container transportation mode, the passenger-like container transportation mode has a higher average number of trains and faster velocity. However, it has a lower average loading rate and proportion of direct container flow. The results were compared in three different minimum average loading rate values: 50%, 60%, and 70%. It was found that with the increase of the minimum average loading rate, the number of lines to be opened decreases, the cost of running decreases, and the revenue of transportation enterprises increases.

Keywords: container transportation; passenger-like container train; train running plan; particle swarm algorithm

1. Introduction

Transportation is an important foundation for the development of the national economy. At present, China’s freight transportation market is overly dependent on roads, and the proportion of railways is still low, accounting for only 9.6% in 2020. It is necessary to adjust the structure of freight transportation. Gradually changing from road-based freight transportation to railway-based freight transportation relying on container transportation will effectively reduce carbon emissions and further improve the sustainable development of transportation.

At the present stage, the organization mode of existing railway container transportation in China mainly consists of the point-to-point direct type and sub-node aggregation type. The point-to-point direct train is a direct train between two container stations without stopping in the middle, which can reduce the transportation time of container flow and improve customer satisfaction. The sub-node assembly type is to divide the container stations into different levels. The goods are first transported to the node station, and the short-circuit train transports the goods from the node station to the hub station. Containers marshalled at the hub are transported to other hubs by long-distance container trains.
However, the reorganization operation is carried out in the middle, which prolongs the time of cargo transportation. Neither of these two container transportation modes has obvious advantages in cargo transportation. The existing container transportation mode cannot meet the requirements of sustainable development.

Railway container transportation has the characteristics of a single organization object, convenient organization method, centralized operation site, and stable system structure, and has certain similarities with passenger transportation. Therefore, we can learn from the organizational principle of passenger transportation to form a new container transportation train. The passenger-like container trains are grouped in a fixed manner and do not undergo disassembly operations. The operation mode of fast loading and unloading of goods on the arrival and departure lines is adopted. The container stations passing by on the way can be stopped and loaded and unloaded. Containers are like passengers waiting on the platform, getting on and off, and the container can also get off the train like a passenger and wait for another train at the platform and transfer.

In the passenger-like container transportation system, the delivery speed of goods has been improved, which can attract a large number of suitable cargo sources to be transferred to railway container transportation and enhance its market competitiveness. At the same time, the state and railway departments vigorously promote the "roads to railways" and "bulk to containerized". The research on railway container transportation systems can effectively promote the sustainable development of railway freight transportation, which can not only promote the adjustment of railway transportation structure, but also effectively reduce carbon emissions and protect the environment.

Based on the passenger-like container transportation mode, on the basis of the known OD volume of heavy and empty containers, and considering the characteristics of the passenger-like container transportation system, a mixed integer linear programming model with the goal of maximizing the revenue of the railway transportation enterprises was established. Then, the solution of the passenger train running plan and the container flow distribution scheme in the network was obtained. Particle swarm algorithm is a search algorithm established to solve optimization problems by simulating the predation behavior of flocks of birds, and it can solve the path optimization problem and has a fast convergence speed [1]. Therefore, the particle swarm optimization was designed to solve the optimization model of the running plan in this paper. The research of this paper can improve the transportation efficiency of railway containers, increase the revenue of transportation enterprises, and continuously expand the market share of railway transportation.

The research contents of this paper are as follows. Section 2 summarizes literature on route planning, container transport organization, and the empty container dispatch problem. Section 3 provides the problem statement, model assumptions, and mathematical formulas of the passenger-like container train running plan. Section 4 designs a particle swarm algorithm to solve the model. Finally, in Section 5, numerical experiments are analyzed to verify the feasibility of model and algorithm. The train line, the number of trains, the station plan, and the container flow distribution scheme are obtained at the same time. Section 6 presents the conclusion of this paper.

2. Literature Review
2.1. Route Planning Problem

Route planning is to match the railway transportation capacity with the passenger or cargo transportation demand and determine the train’s operation zone and stop situation according to the passenger or cargo transportation demand. Typical solution methods include the branch and bound method and column generation method. Considering the expansion of the problem scale, the time required to solve the problem increases rapidly. Therefore, it is an NP-hard problem, which has the characteristics of great time complexity, and many scholars use heuristic algorithms to solve the model.

Schobel, Anita [2] reviewed the existing literature on route planning problems for public transport systems (bus, railway, tram, or underground), introduced basic route
planning models, and proposed that the main objectives of the route planning model are to improve passenger satisfaction and reduce operating costs. Pu, Zhan [3] established a two-stage robust optimization model with the goal of minimizing the total cost, and obtained the operation zone, frequency, stop time, and passenger distribution of the train. Wang et al. [4] considered constraints such as train capacity and the number of vehicles, and studied the route planning problem of trains under the condition of uncertain passenger demand. Li, Zhang [5] combined railway operation, pricing, and carbon emission policies to build a model to solve the frequency, quantity, and price of train operation. Su, Tao, and Hu [6] considered the demand for time, proposed a route planning method for a high-speed railway network with capacity constraints, and established a two-level planning model with the lowest cost. Khaled et al. [7] built models in the case of infrastructure damage in the network, determining the routes, segments, and numbers of freight trains. Drabek, Janos [8] comprehensively considered passengers and freight, and proposed a hierarchically structured method for combining regular freight train paths. Lin et al. [9] comprehensively considered the train connection services problem in the railway network to determine the optimal intermodal plan for freight trains, allocating freight transportation needs to trains and determining the service frequency of trains. Yu et al. [10] comprehensively considered the train running time and cargo flow distribution scheme, and studied the optimization problem of high-speed railway freight train lines. He, Huang, and Chang [11] studied the optimization problem of multi-level container supply chain networks.

2.2. Container Transport Organization Problem

Container transportation occupies an important position in the transportation of goods, which can greatly improve the speed of transportation and market share. The efficiency of transportation depends on the transportation route and the mode of transportation.

Merkulina et al. [12] specifically discussed the organization of container trains, which involved a series of activities, including selecting suitable vehicles and developing suitable routes. At present, container transportation can meet the requirements of the modern international transportation market, so it has received extensive attention. Zhang, Li, and Zhang [13] proposed an optimization model of container transportation with the goal of maximizing the profit of transportation enterprises and minimizing the waiting time of customers and conducted research on the real transportation network. Cao, Gao, and Li [14] established a random integer programming model for the capacity allocation problem under the random transportation demand of railway containers.

Xie, Tang [15] built a multi-objective linear programming model to find out how the liner company can increase ships, optimize routes, and allocate ships. Hao, Yue [16] established a mixed integer programming model with minimum generalized cost, and obtained the optimal transportation route and transportation mode of the container by designing a dynamic programming algorithm. Wang et al. [17] considered the single tax rate and the progressive tax rate on carbon emissions, and established a multimodal transport scheme selection model with the goal of minimizing the cost and carbon emissions under different tax rates. Zhao, Zhu, and Wang [18] considered the location of different central stations and the ability to attract goods, and studied the organization of railway container assembly under multimodal transportation.

Xia et al. [19] proposed a passenger transportation method to improve the competitiveness of the railway container transportation market, mainly studied the allocation of container trains under the fluctuating daily demand of containers, established an integer linear programming model, and obtained the transport plans of containers under different demand situations by designing algorithms to solve them.

2.3. Empty Container Dispatch Problem

In the process of container transportation, the unpacking and packing operations are often at different times and places. If the empty containers are not dispatched in time, the site goods cannot be transported. Therefore, in the system of container transportation,
improving the operation efficiency of empty containers has become one of the key issues of research.

Scholars' research on the empty container dispatch for land transportation began with railway transportation in the 1970s. White, Bomberault [20] was the first to study the optimization problem of railway empty container dispatch. This kind of problem can be solved by using the network flow analysis method. Jordan, Turnquist [21] considered randomness and proposed a dynamic network planning model for freight empty container dispatch. Joborn et al. [22] proposed an optimization model for empty container dispatch in the railway freight system considering economies of scale by increasing the amount of marshalling. Tang et al. [23] considered the sharing of containers, built an optimization model for empty container transportation with the goal of the lowest total cost, and took China Railway Express as an example to conduct research. Khakbaz, Bhattacharjya [24] reviewed the relevant research on the cost of empty shipping containers and analyzed the future development trends and possible research directions. Shintani [25] discussed the planning of the container transportation network while considering the dispatch of empty containers. Du et al. [26] considered the exchange of empty containers between liner shipping companies, proposed a multi-stage solution, and built a model to solve the transportation route of the goods.

Choong et al. [27] considered the three transportation modes of road, railway, and sea, analyzed the level of empty container management in multimodal transportation, and studied the problem of the planning lead time of empty container transportation. Xie et al. [28] studied the coordination problem of shared empty containers in multimodal transport and the optimal distribution strategy between land ports and sea ports. Peng et al. [29] proposed an optimization scheme for the intermodal transportation of empty and heavy containers by rail and road, which can effectively improve the total profit.

2.4. Research Ideas

On the issue of train route planning, existing research mainly aims at the running cost of trains and travel cost of passengers. The research content focuses on the number, frequency, interval, stops of trains, etc., and gradually goes deeper and begins to consider the problem of route planning under uncertain conditions.

On the issue of container transportation organization, research in the relevant literature focuses on transportation modes and transportation routes, and most of it considers the relationship between supply and demand, cost, time, and carbon emissions. In recent years, passenger-like container transportation has been proposed and studied, but the transportation of empty containers has not been considered in the research process.

On the issue of empty container transportation, most studies mainly consider the constraints of empty container quantity and empty container transportation capacity. The studies gradually began to consider the situation of container sharing and empty container transportation in uncertain environments. Although some studies have considered the combination of empty and heavy containers for related research, there are still few types of research on the collaborative optimization of empty and heavy containers.

The contributions of this paper are summarized as follows:

- This paper adopted railway container trains similar to passenger transport, which do not need to be disassembled and marshalled during operation, and can effectively shorten the transit time of goods and convert the original “cargo flow-vehicle flow-train flow” into “container flow-train flow”.
- In the optimization model, the transportation requirements of empty and heavy containers were considered at the same time, and the minimum average loading rate of the train was constrained to obtain the running line, stop plan, the number of trains, and container flow distribution scheme.
- According to the basic principle of particle swarm optimization, an effective solution algorithm was designed for the mixed-integer linear programming model optimized for container trains.
3. The Proposed Mathematical Model

3.1. Problem Statement

The passenger-like container train is a fixed marshalling and fixed bottom. It does not dismantle and the marshalling station operates during the operation process. It has a definite departure and final station. Different trains will choose different stopping methods according to the different terminal stations of the transported containers. At the stopping stations, the fast loading and unloading mode of the arrival and departure line is adopted, and the containers can wait for the train at the platform like passengers and carry out loading, unloading, and reloading operations, as shown in Figure 1.

![Passenger-like container train transportation organization mode.](Image)

**Figure 1.** Passenger-like container train transportation organization mode.

The research on the passenger-like container train running plan is based on the OD transportation volume of empty containers and heavy containers in the research network, and the train running line, the number of running, the stop plan, and the distribution of the container flow on the train are obtained by establishing a model and solving.

For convenience, an example is given to illustrate. The railway network is defined as an undirected graph, the node is the container station, the arc is the running path between two points, and some nodes can be used as the starting and ending points of the train. In Figure 2, there are eight container stations. Assuming that container stations 1, 2, 5, and 8 can be used as the starting and ending points of the train, the shortest path can be found between these nodes, which can be used as the candidate set for running the train, from which the route of the train can be found. Assuming that two lines are now selected, namely Train1 and Train2 in the figure, then the number of trains on each line and the stop plan can be determined according to the OD transportation volume in the network, and the OD container flow can be allocated to the trains at the same time. In the passenger-like container transportation system defined in this paper, it is possible for the container flow to carry out in-transit loading operations. In Figure 2, if 1 to 8 have container transportation requirements, the container flow will take Train1 from container station 1 to container station 4, where the reloading operation is performed, and then take Train2 to reach container station 8.
3.2. Model Assumptions and Notations

3.2.1. Model Assumptions

(1) Closed assumption

It is assumed that the railway operation section in the passenger-like container transportation system studied in this paper is relatively closed and independent, and there is no exchange of container flow with other networks.

(2) Capability assumption

It is assumed that the capacity of the container station to store containers is large enough; it is assumed that the passing capacity of the train running path is known, and the station capacity can be converted into the passing capacity, so the constraints of the station capacity are not considered.

(3) Deterministic assumption

It is assumed that the flow of heavy and empty containers transported between OD pairs in the container railway transport network is known; it is assumed that the transport prices of heavy containers between stations are known. The train only considers the situation in one running direction, and the other running direction is similar. It is assumed that the trains are all made up of fixed groups and the number of groups is the same.

(4) Uniqueness assumption

It is assumed that for arbitrary container flow, the container flow path is unique, and the container flow selection transportation mode is unique, that is, a certain container flow must be all direct or all reloading.

3.2.2. Model Notations

Some model notations used in this paper are defined as follows, as shown in Table 1.

Table 1. Notations in this model.

| Notations | Definition |
|-----------|------------|
| $R$       | The transportation revenue of railway enterprises |
| $I$       | The transportation income |
| $C_1$     | The running cost of all trains |
| $C_2$     | The reloading cost of the heavy containers |
Table 1. Cont.

| Notations | Definition |
|-----------|------------|
| C₃        | The reloading cost of the empty containers |
| C₄        | The detention cost of the heavy containers |
| C₅        | The detention cost of the empty containers |
| N         | The collection of container station nodes |
| N₀        | Train departure or terminal station, N₀ ∈ N |
| Nₜ        | The number of segments of train t |
| P         | The collection of train paths |
| T         | The collection of lines that can open trains |
| 𝑡| 0–1 variable; 1 if train goes through the container station 𝑖; 0 otherwise |
| tᵢ         | The unit transport price of the heavy container flow through the running train, CNY per TEU per kilometer |
| cᵣ         | Running costs of all trains, CNY per train per kilometer |
| cₕ         | Reloading cost of heavy container flow, CNY per TEU |
| cₑ         | Reloading cost of empty container flow, CNY per TEU |
| cₜ         | Detention cost of container flow, CNY per TEU |
| δ         | Penalization factor of reloading |
| dᵢⱼ       | Distance of container station 𝑖 and 𝑗, kilometers |
| dᵣ         | Distance of train 𝑡 runs, kilometers |
| dₕ         | Heavy container flow running distance, kilometers |
| vᵢⱼ       | Velocity of train, kilometers per hour |
| T_w        | The average working time of container departure, hours |
| T_p        | Average stop time of trains at the container station, hours |
| qᵣ         | The heavy container flow uses the train to run through the path (𝑖,𝑗) |
| qₑ         | The empty container flow uses the train to run through the path (𝑖,𝑗) |
| lᵢ         | Quantity of empty containers in the container station, TEU |
| Qᵢ         | Empty container demand quantity in the container station, TEU |
| Qₜ         | The total quantity of heavy containers to be transported, TEU |
| Qₑ         | The total quantity of empty container to be transported, TEU |
| α         | The reference value of the time limit for the delivery of heavy containers |
| β         | The reference value of the time limit for the delivery of empty containers |
| λ         | The minimum average loading rate of trains |
| C         | Train maximum loading capacity, TEU |
| γ         | Quantity of railway container cars |

The following are the decision variables for the model, shown in Table 2.

Table 2. Decision variables in this model.

| Decision Variables | Definition |
|--------------------|------------|
| 𝑥ᵣ         | 0–1 variable; 1 the train is selected and run; 0 otherwise |
| fᵣ         | The frequency of the train |
| yᵣᵢⱼ       | Heavy container flow uses the train to run through the path (𝑖,𝑗) |
| yᵣᵢ       | Heavy container flow at the container station 𝑖 from train 𝑡 reloading to train 𝑙 |
| yₑᵢ       | Heavy container flow uses the train stop at container station 𝑖 |
| yₑᵢⱼ       | Empty container flow uses the train to run through the path (𝑖,𝑗) |
| yₑᵢ       | Empty container flow at container station 𝑖 from train 𝑡 reloading to train 𝑙 |
| yₑᵢ       | Empty container flow uses the train stop at container station 𝑖 |
3.3. Model Formulation

3.3.1. Objective Function

In this paper, the objective function was established with the maximum revenue of the railway passenger-like container train transport system, which is obtained by subtracting the cost from the transportation revenue.

Transportation income is the freight income from all heavy containers. The transportation income $I$ can be expressed as Equation (1).

$$I = \sum_{t \in T} \sum_{h \in H} c^t_h q^t_h d^t_h x^t_h b^t_h$$  \hspace{1cm} (1)

The total cost includes the running cost of all trains, the reloading cost of the heavy and empty containers, and the detention cost of the heavy and empty containers. The running cost is generated by the train, including maintenance costs, resource consumption costs, and etc. The reloading cost is generated by the loading and unloading of the containers during the reloading process. The detention cost is the storage cost incurred when the train does not meet the loading rate conditions for the trip, and the containers originally transported by it will be left for the next day’s transportation.

The running cost of all trains $C_1$ can be expressed as Equation (2).

$$C_1 = \sum_{t \in T} c^t_i d^t_i f^t_i$$  \hspace{1cm} (2)

The reloading cost of the heavy containers $C_2$ can be expressed as Equation (3).

$$C_2 = \sum_{h \in H} \sum_{t \in T} \sum_{\hat{t} \in T} \sum_{i \in N} c^t_h q^t_h y^h_{i\hat{t}}$$  \hspace{1cm} (3)

The reloading cost of the empty containers $C_3$ can be expressed as Equation (4).

$$C_3 = \sum_{e \in E} \sum_{t \in T} \sum_{\hat{t} \in T} \sum_{i \in N} c^t_e q^t_e y^e_{i\hat{t}}$$  \hspace{1cm} (4)

The detention cost of the heavy containers $C_4$ can be expressed as Equation (5).

$$C_4 = \sum_{h \in H} \sum_{t \in T} c_d (Q_h - q^t_h)$$  \hspace{1cm} (5)

The detention cost of the empty containers $C_5$ can be expressed as Equation (6).

$$C_5 = \sum_{e \in E} \sum_{t \in T} c_d (Q_e - q^t_e)$$  \hspace{1cm} (6)

In summary, the revenue of the transportation system can be expressed as Equation (7).

$$\max R = I - C_1 - C_2 - C_3 - C_4 - C_5 = \sum_{t \in T} \sum_{h \in H} c^t_h q^t_h d^t_h x^t_h b^t_h - \sum_{t \in T} c^t_i d^t_i f^t_i - \sum_{h \in H} \sum_{\hat{t} \in T} \sum_{i \in N} c^t_h q^t_h y^h_{i\hat{t}} - \sum_{e \in E} \sum_{\hat{t} \in T} \sum_{i \in N} c^t_e q^t_e y^e_{i\hat{t}} - \sum_{h \in H} \sum_{t \in T} c_d (Q_h - q^t_h) - \sum_{e \in E} \sum_{t \in T} c_d (Q_e - q^t_e)$$  \hspace{1cm} (7)

3.3.2. Container Flow Conservation Constraints

Container flow conservation constraints ensure that the same container flow of transport direction and transport path determined, and the same number of containers arriving and leaving at the container station.

$$y^h_{ij} + y^e_{ij} \leq 2b^t_{ij} x^t_i$$  \hspace{1cm} (8)
when containers are transferred from container stations the stopping.

3.3.4. Train Stop Constraints

The train stop constraints are mainly constraints on the operating conditions of the stopping. Equations (8) indicate that when train \( t \) is selected and run through the path \((i, j)\) at the same time, the container flow can use the train \( t \) to run through the path \((i, j)\).

Equations (9) and (10) indicate that container flow cannot be transported in opposite directions on the same section using different trains. Equations (11) and (12) indicate that train \( t \) can only use a running path from a certain fixed container station \( i \) to any container station \( j \). Equations (13) and (14) indicate that train \( t \) can only use a running path from any container station \( i \) to a certain fixed container station \( j \). Equations (15) and (16) indicate that when containers are transferred from container station \( s \), the number of containers arriving at container station \( s \) is equal to the number of containers leaving container station \( s \).

3.3.3. Container Transportation Volume Constraints

The container transportation volume constraints contain constraints the number of containers transported and the average train loading rate.

Equation (17) indicates that the number of empty containers transported from the container station \( i \) to the container station \( j \) is less than or equal to the empty container holdings of container station \( i \). Equation (18) indicates that the total transport volume of empty containers is equal to the demand for empty containers. Equation (13) indicates that the actual average loading rate in a train must be greater or equal to the minimum average loading rate limit of the train.

3.3.4. Train Stop Constraints

The train stop constraints are mainly constraints on the operating conditions of the stopping.
Equations (20) and (21) indicate that when the containers use train $t$ to arrive at a container station and leave, it means the train stops at the container station. Equation (22) indicates that train $t$ is selected to run through the container station $i$, and the train can stop at container station $i$.

3.3.5. Reloading Constraints

The reloading constraints mainly contain the container reloading conditions and the number of reloading constraints.

$$2y_{hti}^i \leq \sum_{i,(i,j) \in P} y_{hs}^{ht} + \sum_{j,(i,j) \in P} y_{ji}^{ht} \leq y_{hti}^i + 1$$  (23)

$$2y_{eti}^i \leq \sum_{i,(i,j) \in P} y_{etj}^{eti} + \sum_{j,(i,j) \in P} y_{ji}^{eti} \leq y_{eti}^i + 1$$  (24)

$$\left(y_{hti}^i + y_{eti}^i\right) \leq \left(x_{i}^{t} \times x_{i}^{\hat{t}}\right)$$  (25)

$$\sum_{i \in N} \sum_{t \in T} \sum_{\hat{t} \in T} y_{hti}^i \leq 2$$  (26)

Equations (23) and (24) indicate when a container arrives at a container station using train $t$ and leaves the container station using another train, a reloading occurs for the container at the container station. Equation (25) indicates when train $t$ and train $\hat{t}$ are selected to run and through container station $i$, containers can reload at container station $i$. Equation (26) indicates every container flow can only reload a maximum of twice.

3.3.6. Delivery Time Constraints

The delivery time constrains the maximum delivery time for containers.

$$T_w + \sum_{t \in T} \sum_{(i,j) \in P} y_{hti}^i \frac{d_t}{v_t} + \sum_{t \in T} \sum_{\hat{t} \in T} \sum_{i \in N} y_{hti}^i + \sum_{t \in T} \sum_{i \in N} y_{hti}^i T_p \leq \alpha$$  (27)

$$T_w + \sum_{t \in T} \sum_{(i,j) \in P} y_{eti}^i \frac{d_t}{v_t} + \sum_{t \in T} \sum_{\hat{t} \in T} \sum_{i \in N} y_{eti}^i + \sum_{t \in T} \sum_{i \in N} y_{eti}^i T_p \leq \beta$$  (28)

Equations (27) and (28) indicate heavy and empty containers’ delivery time constraints.

3.3.7. Train Frequency Constraints

The frequency of train is bounded by the number of containers transported.

$$\sum_{h \in H} \sum_{t \in E} \left(q_h y_{hti}^i + q_e y_{eti}^i\right) \leq 2f' \gamma$$  (29)

Equation (29) indicates the running frequency of the train is calculated based on the maximum number of containers transported by the train on the entire transport path, and each container flatbed can be loaded with two containers.

4. Materials and Methods

4.1. Floyd–Warshall Algorithm

Fang, Li, and Wei [30] adopted the candidate set-oriented method when designing freight train services. By constructing the candidate train service set in advance, they established a linear programming model and decided the interval and route of the train. The Floyd–Warshall algorithm is a method to find the shortest path between any two points in a given weighted graph based on the idea of dynamic programming. Compared with the Dijkstra algorithm, it can not only find the path between multiple source points, but also have efficiency for dense graphs. The core idea of the algorithm is to obtain the
shortest path matrix between every two points of a graph through the weight matrix of the graph, starting from the weighted adjacency matrix of the graph, recursively performing \( n \) updates, and also recording the shortest path between the two points. Since the Floyd algorithm focuses on the solution of the multi-source shortest path, it can determine the shortest path between nodes in the railway network and the sections it passes through. In this paper, the Floyd–Warshall algorithm was selected to calculate the shortest path between any two points in the physical network, and the shortest path was taken as the candidate set of train.

4.2. Particle Swarm Algorithm

The particle swarm optimization algorithm starts from a random solution and finds the optimal solution through iteration. It also evaluates the quality of the solution through fitness. Its rules are relatively simple, and it finds the global optimal by following the currently searched optimal value. This algorithm has attracted the attention of academia because of its advantages of easy implementation, high precision, and fast convergence, and it has shown its superiority in solving practical problems.

(1) Initialization

During initialization, this paper set the maximum number of iterations to 100, the number of individuals in the population to 50, that is, a fixed grouping of a train is 50, the maximum speed of the particle, and the position information for the entire search space as random in the speed interval and search space. The speed and position were initialized, and the particle fitness value was calculated according to the fitness function. The fitness function in this paper is Equation (7).

(2) Individual extremum and global optimal solution

Each particle is searched separately in the search space, and the individual extremum is the optimal solution found by each particle, and the optimal individual extremum is called the global optimal solution. Compared with the historical global optimal solution, the optimal solution is selected as the current historical optimal solution for updating.

(3) Formulas for updating velocity and position

The particle has two properties, the velocity \( v_i \) and the position \( x_i \). Through continuous loop iteration, the velocity and position of the particle are updated, and the update formulas are Equations (30) and (31).

\[
\begin{align*}
v_i &= \omega \times v_i + c_1 \times \text{rand()} \times (pbest - x_i) + c_2 \times \text{rand()} \times (gbest - x_i) \quad (30) \\
x_i &= x_i + v_i \quad (31)
\end{align*}
\]

Among them, \( \omega \) is the inertia factor, \( c_1 \) and \( c_2 \) are the acceleration constants. In this paper, \( \omega \) was set to 0.8, and \( c_1 = c_2 = 1.2 \).

(4) Termination conditions

There are two termination conditions to choose from: one is the maximum number of generations and the other is that the deviation between two adjacent generations stops within a specified range. This paper chose the first one, and the maximum number of iterations was set to 100.

The flow of particle swarm algorithm is shown in Figure 3.
5. Numerical Experiments

5.1. Description

In the numerical experiments, we assumed that there are 34 nodes in the network, of which 21 nodes serve as the origin and destination of the passenger-like container train. Other nodes can be used as transit or terminal for container transportation. The selection of nodes was determined according to the economic development level, express delivery business volume, total cargo transportation volume, and railway cargo transportation volume of each city, and needed to include the 18 container center hubs proposed in the “Medium and Long-Term Railway Network Planning (2016)” as well as important ports and port stations. The container transportation network is shown in Figure 4. The number of the container station is in parentheses. The number on the line between stations is the road segment number.

The nodes that can be used as the origin and destination of the passenger-like container train are Beijing(1), Tianjin(2), Qingdao(4), Lianyungang(6), Shanghai(8), Ningbo(10), Xiamen(11), Zhengzhou(13), Wuhan(14), Guangzhou(16), Xi’an(20), Kunming(23), Baotou(24), Wulumuqi(25), Lanzhou(27), Xining(28), Chengdu(29), Harbin(30), Jilin(32), Shenyang(33), and Dalian(34). The shortest path between them constitutes a candidate set of train lines, with a total of 210 candidate lines.

Firstly, according to the railway line distance between each point, the Floyd algorithm was used to obtain the shortest paths between the two nodes that can be used as the starting point and the ending point of the passenger container train.

Then, we took the OD transportation requirements of heavy containers and empty containers between each point as the input parameter, which was obtained through investigation. Design particle swarm algorithm was used to solve the transportation path of the container flow and the line used, the loading rate of each train and filter was calculated, and the train running line was determined, number of trains, the station plan, and the distribution of the container flow on the train were determined. The flow chart is shown in Figure 5. The other main parameters of the model solution are shown in Table 3.
Figure 4. The container transportation network.

Figure 5. Flowchart of the numerical experiment solution.
Table 3. The main parameters of the model solution.

| Parameters | Value                        |
|------------|------------------------------|
| \( c^t \)  | 6 CNY per TEU per kilometer  |
| \( c^h \)  | 200 CNY per train per kilometer |
| \( c_h \)  | 100 CNY per TEU              |
| \( c_e \)  | 60 CNY per TEU               |
| \( c_d \)  | 20 CNY per TEU               |
| \( T_w \)  | 10 h                         |
| \( T_p \)  | 0.5 h                        |
| \( \delta \) | 10                           |
| \( v_{ij} \) | 120 km per hour              |
| \( \gamma \) | 50 cars per train            |
| \( C \)    | 100 TEU                      |

5.2. Results

In this paper, the particle swarm algorithm was designed to solve the problem by programming, and the revenue convergence of transportation enterprises is shown in Figure 6.

Figure 6. The revenue convergence of transportation enterprises.

Through the solution, a total of 47 lines needed to be opened, which is 163 lines less than the candidate lines. The cost of running the train is 31,901,200 yuan, and the total revenue of the transportation enterprise is 10,930,568 yuan. The starting and ending points, line distances, and the number of trains of the 47 lines opened are shown in Table 4. Among them, the lines from Ningbo to Baotou and Xiamen to Dalian had the largest number of trains per day, i.e., up to four trains.

There was a total of 1069 OD pairs to be transported in this paper, of which 108 OD pairs needed to be exchanged between the two trains. There was no OD pair that needed to be exchanged more than once. Due to space limitations, only the transportation of some OD pairs is listed, as shown in Table 5.

At the same time, this paper obtained the running line of each train, the stop situation, and the actual number of containers transported in each district. Due to space limitations, this article only listed the trains and container loading on three lines.
Table 4. Open line situation.

| Line                  | Distance (km) | The Number of Train | Line                  | Distance (km) | The Number of Train |
|-----------------------|---------------|---------------------|-----------------------|---------------|---------------------|
| Ningbo(10)–Baotou(24) | 2390          | 4                   | Xiamen(11)–Chengdu(29) | 3237          | 1                   |
| Wulumuqi(25)–Xiamen(11) | 5399          | 1                   | Zhengzhou(13)–Jilin(32) | 1846          | 1                   |
| Baotou(24)–Xiamen(11) | 3196          | 1                   | Wuhan(14)–Baotou(24)   | 1855          | 1                   |
| Xining(28)–Harbin(30) | 3154          | 3                   | Guangzhou(16)–Baotou(24) | 2490          | 2                   |
| Xining(28)–Jilin(32)  | 3040          | 1                   | Xiamen(11)–Dalian(34) | 2486          | 4                   |
| Jilin(32)–Wulumuqi(25) | 2402          | 2                   | Ningbo(10)–Chengdu(29) | 2431          | 1                   |
| Ningbo(10)–Dalian(34) | 2694          | 1                   | Harbin(30)–Chengdu(29) | 2367          | 1                   |
| Jilin(32)–Shanghai(8) | 2392          | 1                   | Lianyungang(6)–Xining(28) | 1974          | 1                   |
| Xining(28)–Xiamen(11) | 3518          | 1                   | Qingdao(4)–Harbin(30) | 1980          | 1                   |
| Wulumuqi(25)–Kunming(23) | 4906         | 1                   | Ningbo(10)–Jilin(32)  | 2711          | 2                   |
| Ningbo(10)–Xining(28) | 2712          | 1                   | Wuhan(14)–Dalian(34) | 2308          | 1                   |
| Shanghai(8)–Harbin(30) | 2506          | 1                   | Qingdao(4)–Chengdu(29) | 2404          | 1                   |
| Wulumuqi(25)–Qingdao(4) | 3885          | 1                   | Jilin(32)–Lianyungang(6) | 1809          | 1                   |
| Xining(28)–Wulumuqi(25) | 2384          | 1                   | Kunming(23)–Xining(28) | 2756          | 3                   |
| Jilin(32)–Qingdao(4)  | 1992          | 1                   | Baotou(24)–Qingdao(4) | 1526          | 1                   |
| Lianyungang(6)–Baotou(24) | 1652         | 1                   | Qingdao(4)–Guangzhou(16) | 2547        | 1                   |
| Lianyungang(6)–Kunming(23) | 2613         | 1                   | Wuhan(14)–Qingdao(4) | 1556          | 1                   |
| Xining(28)–Guangzhou(16) | 3001          | 2                   | Lianyungang(6)–Xiamen(11) | 1974          | 1                   |
| Jilin(32)–Xian(20)    | 2324          | 2                   | Ningbo(10)–Kunming(23) | 2632          | 1                   |
| Qingdao(4)–Xining(28) | 2456          | 1                   | Chengdu(29)–Guangzhou(16) | 2348         | 2                   |
| Dalian(34)–Chengdu(29) | 2827          | 1                   | Beijing(1)–Chengdu(29) | 2015          | 1                   |
| Xining(28)–Qingdao(4) | 1911          | 1                   | Chengdu(29)–Shanghai(8) | 2093          | 1                   |
| Ningbo(10)–Qingdao(4) | 1650          | 1                   | Baotou(24)–Xining(28) | 1254          | 1                   |
| Guangzhou(16)–Lianyungang(6) | 2179       | 1                   |                         |               |                     |

Table 5. The container flow transportation situation.

| OD                             | Trains                             | Loading Station |
|--------------------------------|------------------------------------|-----------------|
| Beijing(1)–Shijiazhuang(12)    | Zhengzhou(13)–Jilin(32)           | –               |
| Xuzhou(5)–Changsha(15)         | Guangzhou(16)–Lianyungang(6)      | –               |
| Nanjing(7)–Xiamen(11)          | Lianyungang(6)–Xiamen(11)         | –               |
| Hangzhou(9)–Chendu(29)         | Ningbo(10)–Chengdu(29)            | –               |
| Hangzhou(9)–Shenzhen(17)       | Xiamen(11)–Dalian(34)             | Xiamen(11)      |
|                                 | Baotou(24)–Xiamen(11)             |                 |
| Shijiazhuang(12)–Xiamen(11)    | Wulumuqi(25)–Xiamen(11)           | –               |
| Shenzhen(17)–Shijiazhuang(12)  | Xiamen(11)–Dalian(34)             | Wuhan(14)       |
|                                 | Xian(12)–Baotou(24)               |                 |
|                                 | Wuhan(14)–Baotou(24)              | Baotou(24)      |
|                                 | Ningbo(10)–Baotou(24)             |                 |
|                                 | Baotou(24)–Xining(28)             |                 |
| Taiyuan(19)–Kunming(23)        | Wulumuqi(25)–Kunming(23)          | –               |
| Lianyungang(6)–Xian(20)        | Lianyungang(6)–Xining(28)         | –               |
| Chengqin(21)–Baotou(24)        | Kunming(23)–Xining(28)            | Xian(20)        |
|                                 | Chengdu(29)–Baotou(24)            |                 |
|                                 | Jilin(32)–Xian(20)                | Xian(20)        |
|                                 | Kunming(23)–Xining(28)            |                 |
|                                 | Kunming(23)–Shanghai(8)           |                 |
|                                 | Xining(28)–Shenyang(33)           | Lanzhou(27)     |
|                                 | Xining(28)–Harbin(30)             |                 |
|                                 | Lanzhou(27)–Taiyuan(19)           | –               |

The dotted box in Figure 7 represents the maximum loading capacity of the train, the box represents the number of containers on the train in different sections, and the percentage is the average loading rate of the train. The stop of the train will change according to the destination of the box flow, such as the Jilin–Shanghai train, because as the departure point of the box flow is Jilin, Changchun, and Shenyang, and the destination is Shanghai, there is no need to stop at stations 2, 3, 5, and 7. When a train on the same line
cannot meet the transportation needs of the container flow, multiple trains will run. For example, Kunming–Xining needs to run three trains, and their stops will also be transported according to the different container flows being transported.

![Figure 7. Trains and container loading situation.](image)

The comparison of the passenger-like container transportation mode with the existing container transportation mode is shown in Table 6.

| Indicator                          | Passenger-like Container Train | Existing Freight Train         |
|------------------------------------|--------------------------------|--------------------------------|
| Average number of trains           | 1.4 trains/day                  | 0.1–1 trains/day                |
| Velocity                           | 120 km/h                        | <80 km/h                       |
| Minimum average loading rate       | <100%                           | 100%                           |
| Proportion of direct container flow| 89.89%                          | 100%                           |

The passenger-like container trains run faster, and do not require the assembly of goods and the drop-and-hang marshalling operation, making the average number of trains reach 1.4 per day. Compared with 0.1–1 trains per day in the existing container transportation mode, the number of trips has increased, and the efficiency of container transportation has improved. Although the minimum average loading rate and the proportion of direct container flow under the passenger-like container transportation mode are lower than those of the existing container transportation mode, this mode will attract more transport demand and transport more total containers, thereby increasing the revenue of transportation enterprise.

5.3. Discussion

On the basis of the above analysis, in this section, the minimum average loading rate of trains selected for the sensitivity analysis, and the minimum average loading rate of trains was set to 50%, 60%, and 70%, respectively, and the influence of the value of the different average loading rate of trains on the model was studied.
When the minimum average loading rate of train was set to 50%, a total of 67 lines needed to be opened through the solution, which is 143 lines less than the candidate lines. The running cost of the train is 68,481,066 yuan, and the total revenue of the transportation enterprise is 8,001,486 yuan. The highest frequency of running lines is four trains/day. The revenue convergence of transportation enterprises is shown in Figure 8. Among all the trains in running, the lowest loading rate was 50.80%, and the highest loading rate was 98.80%.

![Figure 8](image_url)

**Figure 8.** The revenue convergence of transportation enterprises (the minimum average loading rate of train is set to 50%).

When the minimum average loading rate of train was set to 60%, a total of 66 lines needed to be opened through the solution, which is 144 lines less than the candidate lines. The running cost of the train is 59,893,512 yuan, and the total revenue of the transportation enterprise is 8,756,332 yuan. The highest frequency of running lines is four trains/day. The revenue convergence of transportation enterprises is shown in Figure 9. Among all the trains in running, the lowest loading rate was 60.20%, and the highest loading rate was 97.40%.

![Figure 9](image_url)

When the minimum average loading rate of train was set to 70%, a total of 47 lines needed to be opened through the solution. Compared with the candidate lines, 163 lines were reduced. The highest frequency of running lines is four trains/day. The revenue convergence of transportation enterprises is shown in Figure 10. Among all the trains in running, the lowest loading rate was 70.17%, and the highest loading rate was 96.33%.

![Figure 10](image_url)

To sum up, the minimum average loading rate of the train took values of 50%, 60%, and 70%, the train lines opened, and the running cost of all trains and the total revenue of transportation companies changed, as shown in Table 7. Comparing the minimum average loading ratios of 50%, 60%, and 70%, as the minimum average loading value constraint increased, the number of train lines opened showed a downward trend, which reduced the running cost of all trains and improved the overall revenue of railway transportation enterprises. Under the determination of the minimum average loading rate of the train, the minimum average loading ratio of the actual trains was close to the constraint parameter, indicating that the minimum average loading ratio of train is necessary. Although the highest average loading rate of the actual trains decreased with the increase of the value,
when the minimum average loading rate of the train was set at 70%, the overall result was better.

![Figure 9](image1.png)

**Figure 9.** The revenue convergence of transportation enterprises (the minimum average loading rate of train is set to 60%).

When the minimum average loading rate of train was set to 70%, a total of 47 lines needed to be opened through the solution. Compared with the candidate lines, 163 lines were reduced. The highest frequency of running lines is four trains/day. The revenue convergence of transportation enterprises is shown in Figure 10. Among all the trains in running, the lowest loading rate was 70.17%, and the highest loading rate was 96.33%.

![Figure 10](image2.png)

**Figure 10.** The revenue convergence of transportation enterprises (the minimum average loading rate of train is set to 70%).

To sum up, the minimum average loading rate of the train took values of 50%, 60%, and 70%, the train lines opened, and the running cost of all trains and the total revenue of transportation companies changed, as shown in Table 7. Comparing the minimum average loading ratios of 50%, 60%, and 70%, as the minimum average loading value constraint increased, the number of train lines opened showed a downward trend, which reduced the running cost of all trains and improved the overall revenue of railway transportation enterprises. Under the determination of the minimum average loading rate of the train, the minimum average loading ratio of the actual trains was close to the constraint parameter, indicating that the minimum average loading ratio of train is necessary.

When the minimum average loading rate of train was set to 50%, the same line as above was selected to display the trains and container loading, as shown in Figure 11.
When the minimum average loading rate of train was set to 60%, the same line as above was selected to display the trains and container loading, as shown in Figure 12.

When the minimum average loading rate of train was set to 70%, the trains and container loading were determined, as shown in Figure 13.

It can be seen from Figures 11–13 that, under different minimum average rates of train value, the stopping situation of trains, the number of trains running, and the loading situation of containers all changed on the same line. Judging from the stopping situation, the train stops of Jilin–Shanghai increased, and the stops of Ningbo–Qingdao trains increased under the minimum average rate of train, set to 50%. Judging from the number of trains, Kunming–Xining trains increased by one under the minimum average rate of train set to 60% and 50%. Different container loading conditions also make the actual average loading rate of each train different.

Table 7. Results comparison.

| Minimum Average Loading Rate Value of Train | 50%         | 60%         | 70%         |
|-------------------------------------------|-------------|-------------|-------------|
| Number of lines                           | 67          | 66          | 47          |
| Running cost of all trains (CNY)           | 68,481,066  | 59,893,512  | 31,901,200  |
| Revenue (CNY)                             | 8,001,486   | 8,756,332   | 10,930,568  |
| Highest frequency (trains/day)             | 4           | 4           | 4           |
| Lowest loading rate                       | 50.80%      | 60.20%      | 70.17%      |
| Highest loading rate                       | 98.80%      | 97.40%      | 96.33%      |

Although the highest average loading rate of the actual trains decreased with the increase of the value, when the minimum average loading rate of the train was set at 70%, the overall result was better.

Figure 11. Trains and container loading situation (the minimum average loading rate of train is set to 50%).
Figure 12. Trains and container loading situation (the minimum average loading rate of train is set to 60%).

Figure 13. Trains and container loading situation (the minimum average loading rate of train is set to 70%).
6. Conclusions

This paper studied the running plan of passenger-like container trains. The goal was to maximize the total revenue of transportation enterprises. The particle swarm algorithm was designed to solve the problem. The main conclusions are as follows:

- The optimization model of the railway container passenger train running plan was constructed, taking into account the transportation needs of empty and heavy containers, taking the maximum total revenue of the transportation enterprise as the objective function, and the constraints included stopping, reloading, and delivery deadlines, etc. The train line, the number of trains, the stop plan, and the transportation situation of the container were determined. The design particle swarm algorithm was used to solve the model.

- Taking a container network containing 34 nodes as an example, a model was established and a particle swarm algorithm was designed to solve it. The results showed that 47 lines need to be opened, which is 163 less than the number of candidate lines. The cost of running trains reached 31,901,200 yuan, and the total revenue of transportation enterprises reached 10,930,568 yuan.

- The results were compared in three different minimum average loading rate values: 50%, 60%, and 70%. The research found that with the increase of the minimum average loading rate of trains, the number of lines opened dropped from 67 to 47. The running cost of all trains was reduced from 68,481,066 yuan to 3,901,200 yuan, and the total revenue of transportation enterprises increased from 800,148,486 yuan to 109,305,068 yuan.

- Compared with the existing container transportation mode, it was found that the passenger-like container transportation mode has a higher average number of trains running and faster velocity. However, it has a lower average loading rate and proportion of direct container flow. Under the passenger-like container transportation mode, trains run between fixed nodes without marshaling, which can improve the efficiency of cargo transportation and service quality. At the same time, it can attract more transportation demand and achieve the sustainable development of railway container cargo transportation.

- In the actual transportation of goods, various types of goods have different time sensitivities to transportation. Under the constraints of the delivery time constraints, it will have a certain impact on the train running plan and the container flow distribution plan. Although such problems increase the complexity of models and algorithms, they are also worthy of further study. Future work will focus on considering different types of goods, different values of goods, etc., and the running plan of passenger-like container trains.

Author Contributions: The authors confirm contribution to the paper as follows. Conceptualization, W.S., D.L. and W.R.; methodology, W.S., D.L. and W.R.; software, W.S.; validation, W.S., D.L. and W.R.; writing—original draft preparation, W.S., D.L. and W.R.; visualization, W.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research is financially supported by National Railway Administration of the People’s Republic of China. The name of the research project is “Research on railway Passenger Transport in countries along the ‘One Belt and One Road’” (YJ2019-43).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.
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