Hindawi
Journal of Advanced Transportation
Volume 2022, Article ID 6602387, 13 pages
https://doi.org/10.1155/2022/6602387

Research Article

A Metro Freight Plan for Mixed Passenger and Freight Transportation

Yutao Ye, Junhua Guo, and Lixin Yan

School of Transportation & Logistics, East China Jiaotong University, Nanchang, Jiangxi Province, China

Correspondence should be addressed to Junhua Guo; gjhtougao@163.com

Received 6 August 2021; Accepted 17 February 2022; Published 18 March 2022

Academic Editor: Maria Vittoria Corazza

This study proposes a metro freight plan for mixed passenger and freight transportation. First, this study explores the problem of single-line metro train service under mixed passenger and freight transportation. Then, comprehensively considering the constraints of metro train freight capacity, loading and unloading time, and train schedules, a metro freight service model was established, and an efficient and accurate train schedule and freight distribution plan were developed to minimize metro freight costs. Finally, through actual case studies, an improved variable neighborhood search algorithm (VNS) was used to verify the effectiveness of the model, and the sensitivity of different train capacities, train headway, and cargo operation cost to the cost of metro freight was also discussed. The cost of cargo operation is the main factor that affects the cost of metro freight. The metro freight plan proposed in this study can provide decision support for the setting of train schedules and freight distribution plans.

1. Introduction

1.1. Background. With the rapid development of e-shopping, the number of goods transported has continued to sharply increase. The number of express delivery services in China has ranked first in the world for five consecutive years since 2015 [1]. Increasingly, the circulation of urban goods has gradually been called a key link in urban development, but most urban freight transport is completed by vehicles such as trucks, vans, and electric vehicles [2]. Such freight transportation methods not only cannot meet the development and demand of the freight market [3] but also increase road congestion and urban pollution [4, 5]. Therefore, urban freight transportation needs to develop diversified transportation methods to promote the efficient development of urban freight transportation without affecting the normal operation of the city.

Currently, in order to cope with the increasing demand for freight in urban areas, introducing cargo transportation into the urban passenger transportation network is one of the important ways to absorb the current demand for freight transportation, such as urban rail transit network [6]. In addition, of China's 34 rail transit cities, only Beijing, Guangzhou, Shenzhen, and Wuhan have profitable metro operations [7]. In most cities, low passenger flow, empty train carriages, and idle station resources exist during rail transit operation, which is more obvious during off-peak hours [8]. Therefore, under the premise of ensuring the demand for passenger flow, the idle transportation capacity of urban rail transit is tapped, and a new and effective urban freight transportation method is built for the transportation of small- and medium-sized parcels and low-density high-value-added freight demand.

The main idea of this study is to propose a train service plan for mixed passenger and freight transportation for a single metro line. Therefore, a study on the freight service of metro trains has been carried out. This study comprehensively considers factors such as train capacity, cargo loading cost, and train service frequency. In order to formulate accurate and efficient train schedules and freight distribution plans, with the goal of optimal freight costs, a metro train freight service model is proposed. Taking a rail transit line in Ningbo as an example, the improved variable neighborhood search algorithm (VNS) is used to solve the model. Meanwhile, the sensitivity of train transportation capacity, train headway, and freight operation cost to metro freight cost is separately analyzed. To build the groundwork for the contributions of this study, a literature review is provided in Section 1.2 and the contributions of this study are discussed in Section 1.3.

1.2. Literature Review. Regarding the distribution service of urban rail transit, many scholars and cities have verified the feasibility and economy of subway freight service from theory and practice. Rijsenbrij and Pielage [9] discussed the feasibility of using the subway for mixed passenger and freight transportation, which aroused the attention of domestic and foreign scholars on rail transportation. Robinson and Mortimer [10] envisage a method of transporting freight by underground railways, including plans for future underground freight transportation in the nighttime. Subsequent research analyzed and evaluated the underground logistics system exploration project and evaluated its implementation effects through interviews [11]. Egbunike and Potter [12] combine the UK and European environmental policies to address the feasibility of pipeline freight transportation. However, further research is needed before actual implementation. For the metro distribution service, Motraghi and Marinov [13] and Dampier and Marinov [14] combined with the Newcastle metro network to theoretically analyze urban freight transportation. Through the event-based simulation test, it is feasible to use the urban railway network to transport goods.

There are some successful cases of metro freight transportation. An urban underground cargo distribution system based on a passenger railway network was proposed to alleviate urban environmental problems such as traffic congestion and pollution emissions in Tokyo [15]. Sapporo, Japan, set up a special freight area in the subway car and launched the subway freight distribution service in 2010 [16]. Subsequently, Kyoto launched a light rail freight service in 2011, using existing light rail cars to deliver freight every morning before the peak passenger flow [17]. In New York, converted subway cars are used for subway waste collection and transportation [18]. Two boxes are tied to the outer wall of the passenger train carriage of the Hokuetsu Express [19]. The boxes can be used for cargo transportation. The above research shows that it is feasible to introduce goods into the urban rail transit system. However, the operable metro freight services need further research.

In railway transportation, the scheduling of passenger and freight trains is very common. Barber et al. [20] used simulation software Módulo Optimizador de Mallas (MOM) and set a series of parameters including train type, equipment type, terrain and track conditions, train speed, acceleration and deceleration, and traffic signals, reflecting the real-world train dispatch operation condition. Canca et al. [21] suppose the travel demand between two stations increases to the point where a new shuttle service is needed to meet the new demand. Considering different goals such as passenger flow minimization and service quality assurance, a model that can obtain periodic and nonperiodic timetables is proposed. Talebian and Zou [22] studied the strategic-level train planning for efficient operation of American passenger and freight trains on shared-use corridors and developed a two-level hypergraph-based method to minimize passenger and freight costs when arranging train services. Liu and Dessouky [23] discussed the joint dispatching of passenger and freight trains under a complex railway network and proposed a two-step decomposition heuristic algorithm to solve this problem. The above research has conducted an in-depth discussion on the operation and dispatch of passenger and freight trains on the railway. However, the railway system is different from the urban rail transit system in that there are obvious differences in requirements such as headway, departure frequency, and punctuality. Therefore, freight transportation based on the urban rail transit system needs to be further explored.

Researchers conducted research on urban rail transit freight for different research directions. In the location and path selection direction, Zhao et al. [24] established a metro integrated logistics system by positioning the distribution hub. Dong et al. [25] developed a subway system-based underground logistics system network planning method, which can make full use of the potential of subway stations and underground tunnels to achieve higher logistics benefits. In the direction of system operation, Fatnassi et al. [26] integrate personal rapid transportation and freight rapid transportation mode (PRT-FRT) and use electric vehicles to achieve mixed passenger and freight transportation on automatic rails. Zhou et al. [27] took into account constraints such as the remaining capacity of subway trains, the capacity of trucks, the maximum travel distance of trucks, and the customer service time window and designed the subway-truck intermodal service.

At this stage, most of the research studies on metro train scheduling problems are widely carried out for passenger trains [28–31], but there are few research studies on metro freight service dispatching problems. Behiri et al. [6] studied an environmentally friendly urban freight transportation alternative using a passenger rail network and established a mixed-integer linear programming model. A heuristic algorithm based on scheduling rules and a heuristic algorithm based on single column decomposition are proposed. Two sets of numerical experiments verify the effectiveness of the proposed method. Ozturk and Patrick [32] consider the operation of passenger trains and freight trains on the same rail line with a fixed passenger train timetable. Numerical results are provided to prove the speed of various methods to solve the problem of different sizes. The above two types of metro freight services have not considered the stop plan of metro trains when there is freight transportation, which will affect the normal operation of the trains. Therefore, it is necessary to establish a better and more efficient metro freight plan.

1.3. Contributions. According to the abovementioned literature review, the main contributions of this study are summarized as follows:

(1) Compared with previous studies on metro freight service plans [6, 32], this study considers the stop

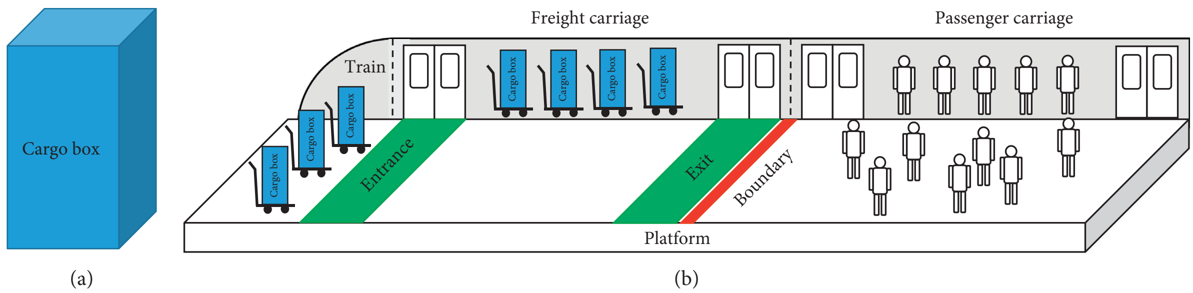

FIGURE 1: Schematic diagram of cargo loading.

plan of metro trains with freight tasks and further optimizes the train operation schedule.

(2) Compared with the models constructed by Behiri et al. [6] and Li et al. [33], the model proposed in this study further considers factors such as the number of freight carriages, train stop plan, and freight distribution plan on the basis of considering metro train schedules. It provides a decision support tool for logistics companies to develop metro freight plans and propose better cargo distribution and transportation plans.

(3) The metro freight plan proposed in this study can potentially reduce freight costs and bring additional revenue to metro operations [34].

The remaining parts of this study are organized as follows. Section 2 gives a description of the problem. In Section 3, a metro freight service model is established. The related process of the improved VNS algorithm is given in Section 4. Section 5 shows the results of case analysis and sensitivity analysis. Finally, conclusions and directions for future research studies are made.

2. Problem Description

In this section, the operation process of the metro freight plan is introduced in detail. In order to facilitate the statistics of the quantity of goods, it is assumed that all the goods that need to be delivered are uniformly quantified into standardized cargo boxes with the same volume [6, 19, 34, 35], as shown in Figure 1(a). The goods used for metro distribution should be small goods such as documents and digital products [36]. In addition, the metro freight plan proposed in this study is to select a single metro line during a certain idle period, and in order to ensure the normal operation of passenger flow, only one train carriage is selected for freight transportation, as shown in Figure 1(b). In Figure 1(b), the train carriage loaded with cargo is called freight carriage, and the remaining carriage in normal operation is called passenger carriages. In the platform area, the passenger and cargo boarding boundary line is divided, thereby reducing the impact of cargo flow on passenger flow. The platform is also equipped with a dedicated entrance and exit area, and goods can be placed on and off the freight carriage in an orderly manner via trolleys.

The train runs according to the established timetable. The relevant information of goods such as the quantity of goods, departure station, arrival station, start time, and end time are assumed to be known in advance. Start time refers to the earliest time when the goods can be loaded and transported, and the end time refers to the latest time when the goods arrive at the destination station. The freight process of a single metro line with one freight carriage is shown in Figure 2. In Figure 2, after the goods are waiting for the train to enter the station at the originating station, they are loaded into the freight carriage in an orderly manner via trolleys and then unloaded after being transported to the destination station by the train.

3. Model Formulation

In this section, this study takes the optimal freight cost as the goal and formulates the constraint of metro train freight capacity, loading and unloading time, transportation time, and headway to construct a feasible metro freight plan. According to the freight demand, the train schedule is determined and the metro freight plan is formulated. The loading and unloading of goods at each station must be completed within the train stop time. To facilitate problem formulation, the following assumptions are made.

(1) The setting of the train freight carriage and the adjustment of the departure frequency are assumed to be set within the acceptable range of passengers, and the freight transportation will not change the passenger flow.

(2) When the goods are waiting for the train to enter the station, the station platform is assumed to provide goods storage function for a short time.

Table 1 summarizes the parameters used throughout this study.

3.1. *Metro Train Freight Capacity Constraints.*

Within a certain period of time, the metro train can transport a certain number of cargo boxes. Therefore, the freight capacity of the train is shown in constraints (1) and (3).

$$\sum_{j\in q_s} x_{l,j}\, g\, b_{l,j} \le \text{cap}^c, \quad s \in [1, S-1], l \in [1, L], \tag{1}$$

$$q_s = \left\{ j | o_j < s < d_j, \quad j \in [1, J] \right\}, \tag{2}$$

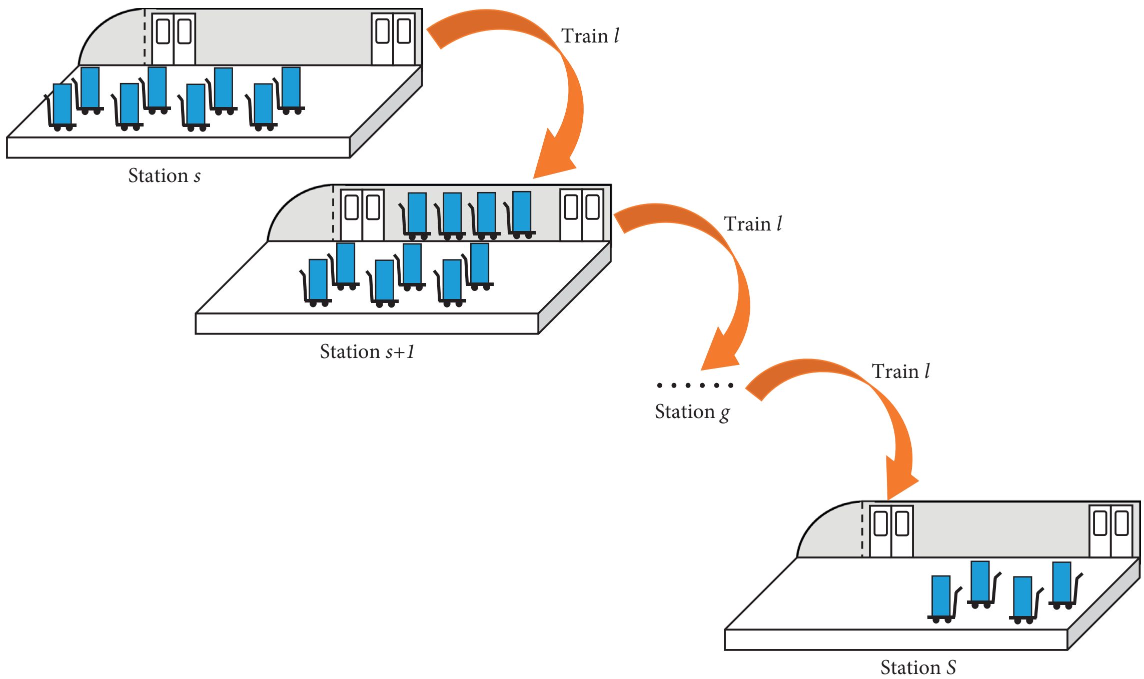

FIGURE 2: The process of a single metro line with one freight carriage.

TABLE 1: Notations.

Index sets	S:	Set of metro stations $g, s \in S$
	J:	Set of the goods $i, j \in J$
	L:	Set of metro trains $l \in L$
	M:	A large positive number
Parameters	$b_{l,j}$:	Number of cargo boxes j in train l
	q_s:	Set of goods should be loaded when the train departs from the station s
	o_j:	Originating station of goods j
	d_j:	Destination station of goods j
	cap^c:	Maximum number of cargo boxes in a carriage of metro train
	a_s:	Set of goods loaded at station s
	z_s:	Set of goods unloaded at station s
	t_{load}:	The time of loading and unloading each cargo box
	$t_{l,s}^{A}$:	Arrival time at station s for metro train l
	$t_{l,s}^{D}$:	Departure time at station s for metro train l
	$t_{L,S}^{\text{Alast}}$:	Arrival time of the last metro train L to station S
	t_j^{o}:	Departure time of goods j at the originating station
	t_j^{d}:	Arrival time of goods j at the destination station
	$t_{\text{min}}^{\text{stop}}$:	Minimum stop time for metro trains
	$t_{\text{max}}^{\text{stop}}$:	Maximum stop time of metro trains
	$t_{\text{min}}^{\text{departure}}$:	Minimum departure time of the metro train at the first metro station
	$t_{\text{max}}^{\text{departure}}$:	Maximum departure time of the metro train at the first metro station
	$t_{l,s}^{D}$:	Departure time of the metro train l at station s
	h_{min}:	Minimum headway between metro trains
	$t_{g,s}$:	Running time from station g to station s
	$u_{g,s}$:	Running distance from station g to station s
	c_{load}:	Loading and unloading cost for each cargo box
	$c_{\text{operation}}$:	Operation cost for each cargo box
Decision variables	$x_{l,j}$:	1 if goods j is transported by metro train l, 0 otherwise.
	$t_{l,s}^{\text{stop}}$:	Stop time of the metro train l at station s
	$t_l^{\text{departure}}$:	Departure time interval between metro train $j-1$ and train j at the first station

$$\sum_{j\in\{a_s\cup z_s\}} x_{l,j}g(a_s - z_s) \le \text{cap}^c, \quad s \in [1,S], l \in [1,L], \tag{3}$$

$$a_s = \{j|o_j = s, \quad j \in [1,J]\}, \tag{4}$$

$$z_s = \{j|d_j = s, \quad j \in [1,J]\}. \tag{5}$$

3.2. Loading and Unloading Time Constraints. The loading and unloading of goods at station s must be completed within the time the train stops at the station, as shown in constraint (6).

$$t_{\text{load}} \cdot \sum_{j\in\{a_s\cup z_s\}} x_{l,j}gb_{l,j} \le t_{l,s}^{\text{stop}}, \quad s \in [1,S], l \in [1,L], \tag{6}$$

$$a_s = \{j|o_j = s, \quad j \in [1,J]\}, \tag{7}$$

$$z_s = \{j|d_j = s, \quad j \in [1,J]\}. \tag{8}$$

3.3. Transit Time Constraints. The transportation time of cargo j from the originating station to the destination station should meet its own transportation needs, that is, the departure time and arrival time of the train should meet the time requirements of cargo j. The formula is as follows:

$$\begin{aligned} t_{l,d_j}^{A} + (1 - x_{l,j})gM \ge t_j^{o}, \quad l \in [1,L], j \in [1,J], \\ t_{l,d_j}^{D} + (1 - x_{l,j})gM \le t_j^{d}, \quad l \in [1,L], j \in [1,J]. \end{aligned} \tag{9}$$

3.4. Headway Constraints. In order to ensure the safe operation of metro trains, the headway of each train must be restricted. Assuming that the first train loaded with goods departs at $T = 0$, the arrival time, stopping time, and departure time of the train at each station should have the following constraints.

$$t_{\min}^{\text{stop}} \le t_{l,s}^{\text{stop}} \le t_{\max}^{\text{stop}}, \quad l \in [1,L], s[2,S-1], \tag{10}$$

$$t_{\min}^{\text{departure}} \le t_{l}^{\text{departure}} \le t_{\max}^{\text{departure}}, \quad l \in [2,L]. \tag{11}$$

Constraint (11) determines the stopping time of train l at station s. Constraint (12) ensures the headway of each train.

$$t_{l,1}^{D} = \sum_{i=1}^{l} t_i^{\text{departure}}, \quad l \in [1,L], \tag{12}$$

$$t_{L,S}^{A} = t_{L,S}^{\text{Alast}}. \tag{13}$$

Constraint (13) gives the departure time of train l at the first station. Constraint (14) specifies the arrival time of the last train.

$$t_{l,s}^{D} = \sum_{i=1}^{l} t_i^{\text{departure}} + \sum_{w=2}^{s} t_{l,w}^{\text{stop}} + t_{1,s}, \quad l \in [1,L], s \in [2,S]. \tag{14}$$

$$t_{l,s}^{D} = t_{l,s}^{A} + t_{l,s}^{\text{stop}}, \quad l \in [1,L], s \in [1,S]. \tag{15}$$

Constraints (15) and (16) are used to calculate the departure time of train l at station s.

$$t_l^{\text{departure}} - t_{l,1}^{\text{stop}} \ge h_{\min}, \quad l \in [2,L], \tag{16}$$

$$t_{l,s}^{A} - t_{l-1,s}^{D} \ge h_{\min}, \quad l \in [2,L], s \in [2,S]. \tag{17}$$

Constraints (17) and (18) represent the time headway constraints between trains.

3.5. Objective Function. The goal of this model is to minimize freight costs, which are mainly composed of cargo handling costs and cargo operation costs. Cargo operating cost refers to the transportation cost of goods consumed on metro trains. The objective function is formulated as follows:

$$\begin{aligned} \text{Min Cost} = c_{\text{load}}g\sum_{j=1}^{J}\sum_{l=1}^{L} x_{l,j}gb_{l,j} + c_{\text{operation}} \\ g\sum_{j=1}^{J}\left(u_{o_j,d_j}g\sum_{l=1}^{L} x_{l,j}gb_{l,j}\right). \end{aligned} \tag{18}$$

4. Solution Procedure

A mixed nonlinear programming model of metro freight is then proposed, and an improved variable neighborhood search (VNS) algorithm is designed to solve the model. VNS provides a flexible framework for constructing heuristics for approximately solving combinatorial optimization problems and nonlinear optimization problems [37].

In this study, the VNS algorithm includes the following three parts: initial solution, shaking process, and variable neighborhood descent (VND) process. We use c, c', c'' to denote the solutions generated in the algorithm. N represents the neighborhood structure set included in the shaking process, where $N = \{1, 2, 3, \ldots, k, \ldots, |N|\}$. The detailed structure of the improved VNS algorithm is shown in algorithm 1.

The shaking process is a perturbation operator in the VNS. The process is used to generate different neighborhood solutions. The remaining initial solution and VND process are described in detail in the next section.

4.1. Initial Solution. According to the model and related constraints, let R be the initial plan, $x_{l,j}$ represents whether the cargo j is transported by train l in the initial plan, where "1" means transport, and "0" means no transport. The initial plan is shown in Figure 3.

(i) Step 1: A solution c is randomly generated in a given range, and the initial solution is brought into the objective function calculation program to obtain the initial target value $f(c)$, go to Step 2.
(ii) Step 2: Let $k = 1$ until $k = |N|$, go to Step 3.
(iii) Step 3: Substitute the initial solution c into Shaking (Algorithm 2), and perform the k-th neighborhood operation of Shaking to generate a new solution c', go to Step 4.
(iv) Step 4: Substitute c' into the VND (Algorithm 3), generate multiple neighborhood solutions related to c', and perform a local search among the generated multiple neighborhood solutions to obtain the local search optimal solution c', go to Step 5.
(v) Step 5: If $f(c'') < f(c)$, it means that c' is better than the current optimal solution c, then let $c = c''$ and continue to search within the current neighborhood structure ($k = 1$); otherwise, let $k = k + 1$. Meanwhile if $k = |N|$, go to Step 6. Otherwise, go to Step 3.
(vi) Step 6: Until the termination criterion is met, the optimal solution c is returned.

Algorithm 1: Procedure of VNS algorithm

In Figure 3, the matrix on the left represents the initial plan, where the matrix horizontally represents goods code and the vertical direction represents metro trains. The matrix on the right shows an example of an initial plan. For example, the first train loading scheme is $[1, 0, \ldots, 1, \ldots, 0]$, which means that the first train is only loaded with goods numbered 1 and i.

4.2. Neighborhood Structure. In the improved VNS algorithm designed in this study, two types of neighborhood structures are applied. The first type of neighborhood exchanges strategies on existing freight plans. The second type of neighborhood is obtained by updating an existing freight plan.

For the first neighborhood structure, Swap-2 and Inserting-t are designed for generating neighborhoods. Swap-2 refers to the random swap of two adjacent or nonadjacent columns in the initial solution. Inserting-t means that a column is randomly deleted from the initial solution, and then, the deleted column is randomly inserted into other positions, and the operation is repeated t times. In addition, in order to prevent the value of t from being too large and destroying the stability of the obtained domain structure, the value of t is controlled in the range of [0, 5]. The specific processes of Swap-2 and Inserting-1 are shown in Figures 4 and 5.

For the second type of neighborhood structure, the Alter-t method is designed to generate neighborhood solutions. Alter-t means that a position is randomly selected from the initial solution, then, a number is regenerated to replace the original number of the position, then, the operation is repeated t times, and the value range of t is [0, 5]. The Alter-1 operation is shown in Figure 6.

4.3. Shaking. The shaking procedure generates different neighborhood solutions through the dither operator. The purpose of this process design is to make the algorithm jump out of the local minimum trap. When a smaller improvement scheme cannot be found in the variable neighborhood descent (VND) algorithm, the perturbation procedure is activated. In this algorithm, $N = \{\text{Alter} - 3, \text{Alter} - 4\}$ is used as the set of neighborhood structures in the shaking process. For each structure $N_v \in N$, it maps a given solution R to a series of neighborhoods $N_v(c)$. When the shaking procedure is applied, a solution will be randomly chosen from the neighborhoods. Accordingly, the detailed procedure is given as follows.

4.4. Variable Neighborhood Descent (VND). During the local search process, the VND process explores several neighborhood structures, in which case the obtained local optimum is more likely to be the global optimum. When performing a local search in VND, if a better solution than the current solution cannot be found in this neighborhood, it is skipped to the next neighborhood solution and the search is continued. Conversely, if a better solution than the current solution is found in this neighborhood, it is returned to the first neighborhood solution and the search is restarted. The local optimal solution obtained through such a search process is likely to be the global optimal solution. Algorithm 3 gives the detailed operation process, and P represents the neighborhood structure set included in the VND process, where $P = \{1, 2, 3, \ldots, k, \ldots, |P|\}$.

5. Case Study

In this section, a certain section of a rail transit line in Ningbo is selected as the freight section of the case study. This case is implemented to illustrate the applications of the proposed model and algorithm. On this basis, the sensitivity analysis related to freight costs is also studied.

5.1. Example Calculation. The Ningbo Rail Transit Airport Line connects Lishe International Airport and Ningbo Railway Station, as shown in Figure 7. The stations are numbered S1 to S10 from the airport to the railway station. The running distance and running time between each station are shown in Table 2.

Based on the announcement issued by Ningbo Rail Transit, the passenger flow is underground during off-peak hours. Therefore, the train operated by Ningbo Rail Transit consists of 6 carriages, and one carriage of each train is selected for freight transportation between 9:00 am and 10:00 am. During this time period, the headway of the train is 6 minutes, and the shortest departure interval is 4 minutes. As shown in Figure 8, according to the size of the carriage, a single metro train carriage can accommodate 20 cargo boxes. The loading/unloading time of each carriage is assumed to be

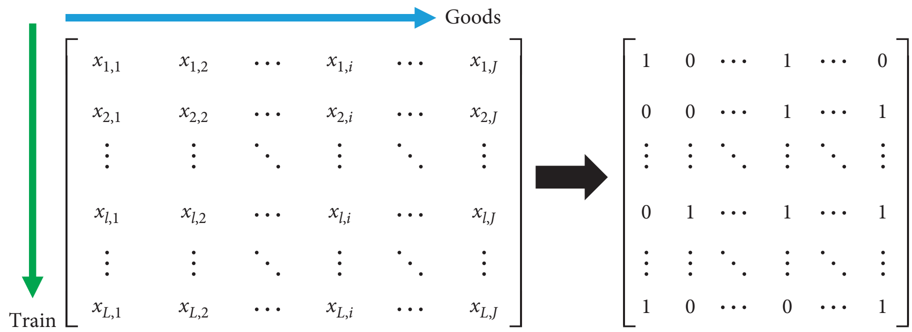

Figure 3: Initial plan.

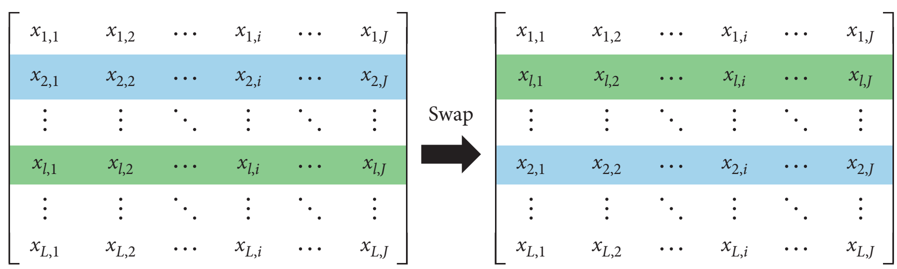

Figure 4: Swap-2.

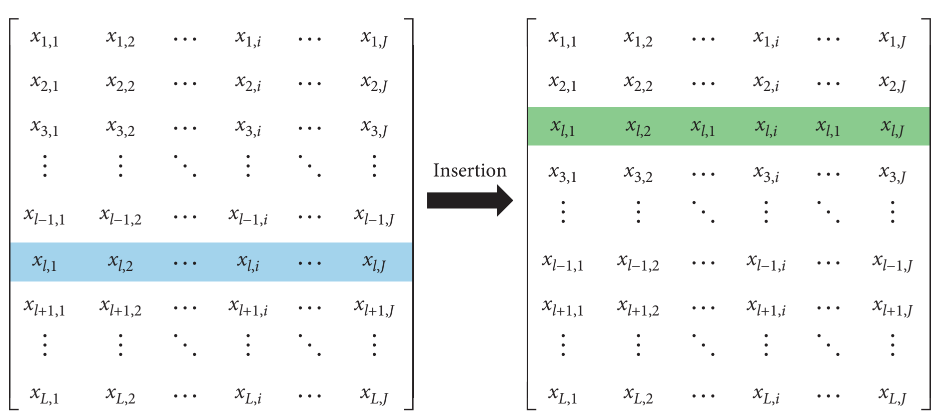

Figure 5: Insertion-1.

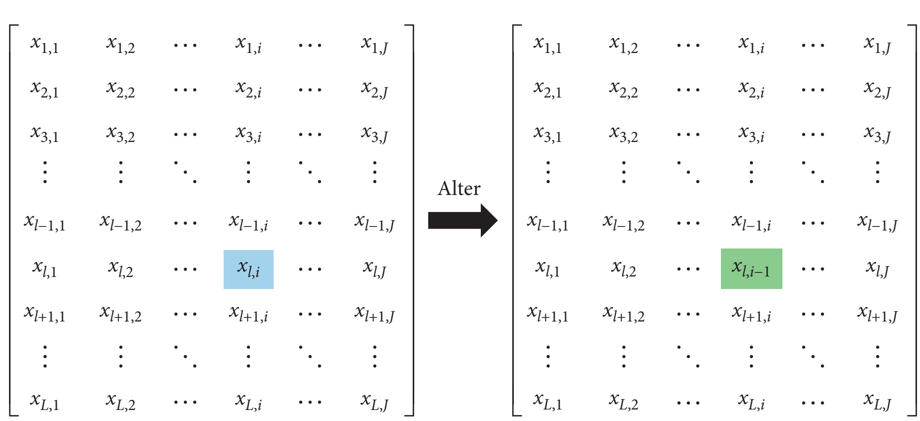

Figure 6: Alter-1.

(i) Step 1: Enter the initial solution c and the index of neighborhood structure N, go to Step 2.
(ii) Step 2: Select a solution from $N_v(c)$ at random, and then go to Step 3.
(iii) Step 3: A random chosen solution c' is returned.

Algorithm 2: Shaking procedure

(i) Step 1: Enter the initial solution c' and neighborhood structure set P of the VND, go to Step 2.
(ii) Step 2: Let $k = 1$ until $k = |P|$, and then go to Step 3.
(iii) Step 3: Use the neighborhood structure P to perform a local search to generate a new solution c', and then go to Step 4.
(iv) Step 4: If $f(c') < f(c)$, it means that c' is better than the current optimal solution c', then let $c' = c'$ and continue to search within the current neighborhood structure ($k = 1$); otherwise, let $k = k + 1$. Meanwhile if $k = |P|$, go to Step 5; otherwise, go to Step 3.
(v) Step 5: Until the termination criterion is met, the optimal solution c' is returned.

Algorithm 3: Procedure of VND

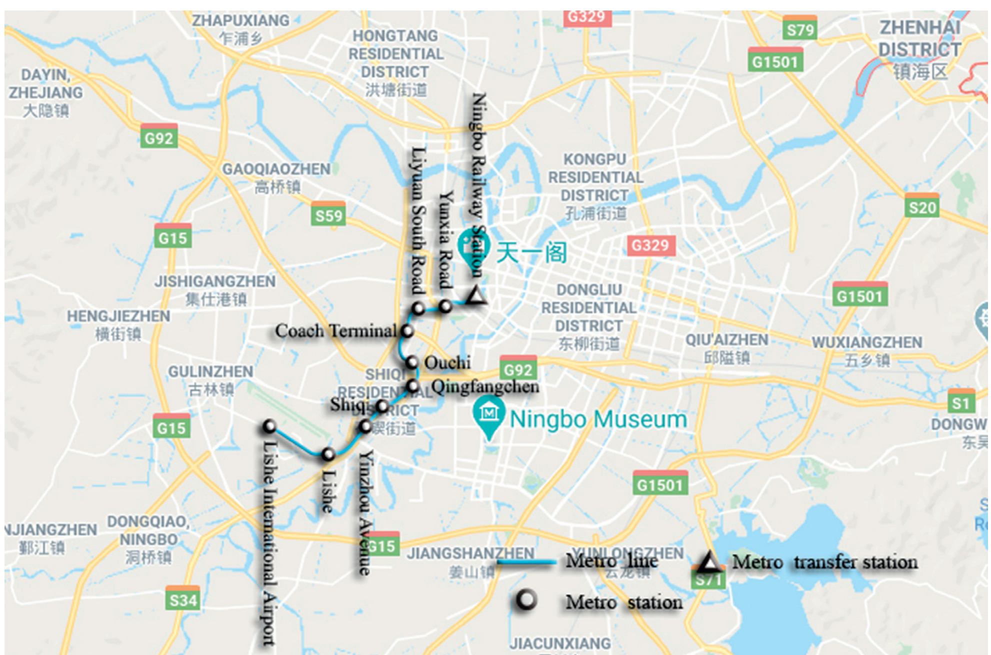

Figure 7: Ningbo rail transit route map.

Table 2: Information about the metro operation.

Metro station section	Running distance (km)	Running time (min)
S1-S2	2.5	3
S2-S3	1.7	3
S3-S4	1.1	2
S4-S5	1.3	2
S5-S6	1.5	3
S6-S7	1.2	2
S7-S8	1.3	2
S8-S9	0.8	2
S9-S10	1.2	3

24 s. The operating cost of each freight carriage is assumed ¥15/km, and the operating cost of each cargo box is assumed ¥5/km [33]. The loading and unloading of goods between the platform and the carriage can be performed by trolleys. The loading cost is assumed to be ¥20 for each cargo box. Assumed freight information is shown in Table 3, including the quantity, stations, and times.

In the algorithm parameter setting process, this study set the number of neighborhood solutions in one iteration to 100, and the total number of iterations to 50. The neighborhood structures of VND and shaking are as follows: VND: $\{Alter\_3, Alter\_5, Insertion\_2, Insertion\_1, Swap\_2\}$;

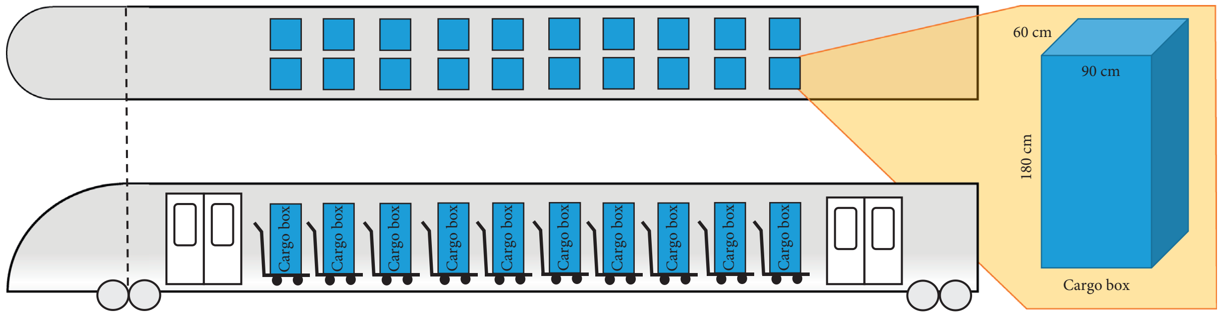

Figure 8: Schematic diagram of metro freight and freight box.

Table 3: Freight information.

Goods	Quantity (cargo box)	Originating station	Destination station	Start time	End time
1	2	S2	S8	9:08	9:43
2	2	S1	S9	9:03	10:03
3	11	S1	S10	9:47	10:24
4	16	S3	S8	9:16	10:04
5	19	S1	S8	9:15	9:51
6	3	S3	S8	9:17	9:57
7	12	S2	S9	9:24	10:08
8	10	S3	S10	9:33	10:14
9	1	S1	S9	9:02	9:33
10	7	S2	S9	9:42	10:26

shaking: {Alter_3, Alter_5}. For related problems in route planning and distribution, the simulated annealing algorithm (SA) is widely used. The initial temperature max t_{max} of SA is set to 50, the maximum number of annealing G_{max} is set to 200, and the cooling coefficient r is set to 0.96. The optimization results of the two algorithms were obtained by running 20 times, as shown in Table 4. Although SA has a shorter calculating time, VNS can obtain the best delivery cost of higher quality, and after many repeated trials, the results show that the stability of the optimal solution obtained by VNS is better than that of SA, which verifies the effectiveness of the algorithm.

Since the selected metro operating time period is 9:00 am to 10:00 am, the operation diagram of the metro freight plan is shown in Figure 9. There are a total of 10 in-service trains running from stations S1 to S10 that are considered and the departure interval between trains is 6 minutes. In Figure 9, the departure time of train L1 is 9:06 am. During this time period, goods J2 and J9 can be loaded on the train freight carriage, and the number of cargo boxes in trip S1⟶S2 is 3. Cargo J1 is loaded onto train L1 at station S2 and unloaded at station S8, and the number of loaded cargo boxes in trip S2⟶S8 is 5. There is no cargo box loaded in trip S9⟶S10, which means that the goods J2 and J9 are unloaded at the station S9, and the freight carriage can be converted to a passenger carriage in trip S9⟶S10.

As shown in Figure 9, only 6 of the 10 metro trains have freight tasks, and the remaining four trains can be used and normally operated. The specific freight tasks are distributed as follows, train L1 transports goods J2, J9, and J1 with trip S1⟶S9, and goods J4 and J6 are transported by train L2 in trip S3⟶S8. Cargo J5 is distributed from station S1 to S8 by train L3, and cargo J7 is distributed from station S2 to S9 by train L5. Train L5 transports 8 cargo boxes of cargo J8 in trip S3⟶S10 and train L6 transports 2 cargo boxes of cargo J8 in trip S3⟶S10. Goods J3 and J10 are transported by train L8 in trip S1⟶S10 and S2⟶S9, respectively. Trains L4, L7, L9, and L10 have no freight tasks. In addition, all goods have been delivered under the metro freight plan, and the delivery time is 10:14 am.

In Table 5, the results of the freight plan with and without freight carriage are listed. Among them, all the carriages of the metro train are used for passenger transportation, and the cargo boxes can be inserted into the empty spaces of the carriages. This freight method is the metro freight plan without cargo carriages, and each train can accommodate up to 8 cargo boxes.

As shown in Table 5, there is a big gap in the freight cost of the two freight plan. The freight cost of the metro with freight carriage is nearly half of the freight cost without freight carriage, which is ¥5881.7. However, only 6 metro trains were used to complete the transportation of all goods under the freight plan with freight carriage. In the freight plan without freight carriage, all trains have freight tasks, and only 93% of cargo transportation has been completed. In addition, it takes 74 min to complete all freight tasks using freight carriage, which saves 11 min compared to the freight way without freight carriage. In summary, the metro freight plan with freight carriage has a better level of cargo transportation services and lower freight cost.

5.2. Sensitivity Analysis

5.2.1. Train Capacity. The size of the train carriage compartment directly determines the capacity of the train. The

Table 4: Comparison of optimization results for two algorithms.

Algorithm	Optimal calculating time (s)	Best delivery cost (yuan)	Worst delivery cost (yuan)	Average delivery cost (yuan)
VNS	162.3	5881.7	6261.8	6042.4
SA	76.2	6405.0	7645.1	6798.9

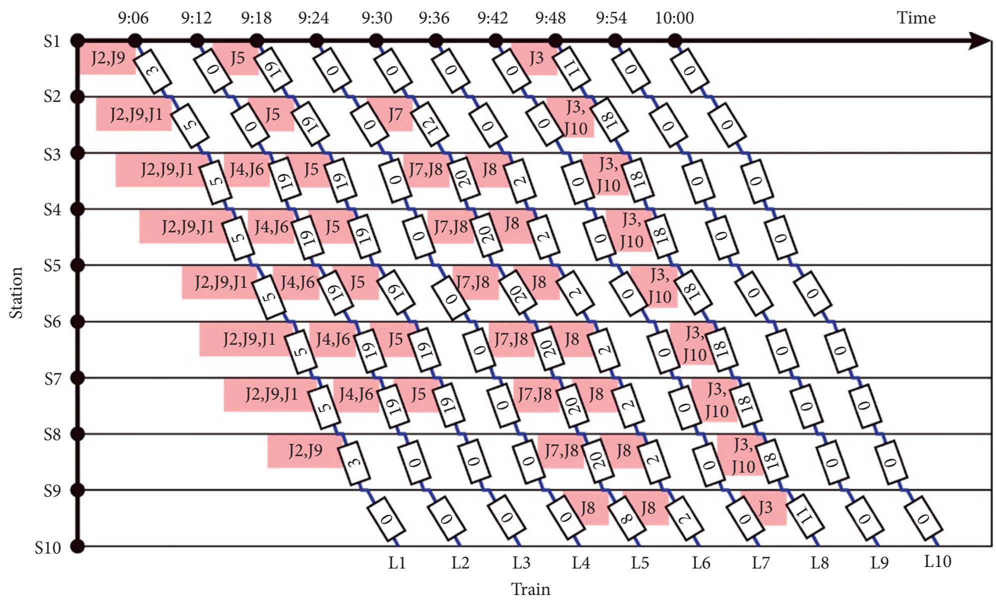

Figure 9: Metro freight plan operation diagram.

Table 5: Calculation results.

Freight carriage	Freight cost (¥)	Number of trains with freight	Proportion of goods delivered on time (%)	Time required to complete all shipments (min)
Yes	5881.7	6	100	74
No	13158	10	93	85

determination of cargo distribution and train schedule is also related to train capacity. Therefore, a sensitivity analysis was carried out on the cost of the metro freight plan for different train capacities. Based on the above case data, this study divides the train capacity with 20 freight boxes as the benchmark, half the number of freight boxes as the limit, and 2 freight boxes as the stage. As shown in Figure 10, the freight carriage capacity of the metro freight plan is varied from 10 to 30 cargo boxes. In the metro freight plan without freight carriage, the capacity of a train is varied from 10 to 30 cargo boxes for the convenience of comparison.

In Figure 10, as the train capacity increases, the freight costs of the two freight plan also decrease. Among them, the downward trend of freight costs without freight carriage is more obvious. When the metro capacity reaches 22 freight boxes, the minimum freight cost of freight plan without freight carriage is ¥9096. With the increase in train capacity, the downward trend of freight costs with freight carriage has become more gradual. The optimal freight cost is reached when the metro capacity is 22 cargo boxes, which is ¥5766.

In summary, the metro freight plan with freight carriage is better. The increase in the freight capacity of metro trains has quite a minor effect on freight costs, as the freight costs have only slightly reduced.

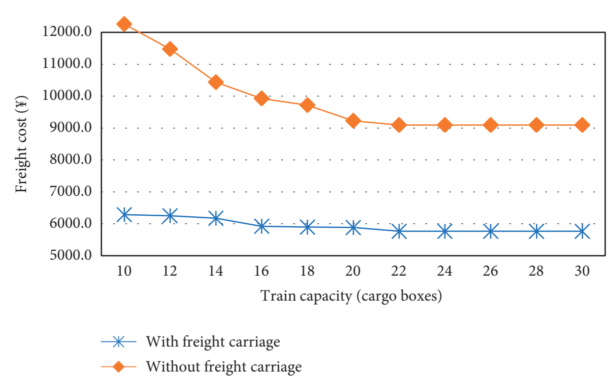

Figure 10: Schematic diagram of train capacity and freight cost.

5.2.2. Train Headway. The headway of the train determines the safe distance of each train in operation and is also an important factor to ensure operation efficiency. Train

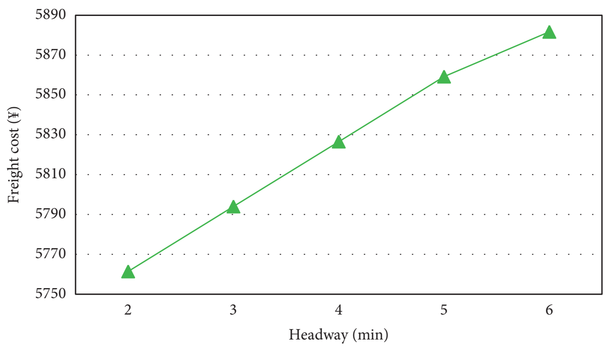

Figure 11: Schematic diagram of train headway and freight cost.

headway is varied from 2 to 6 minutes, the changing trend in freight costs with freight carriage under different train headway is analyzed, and the specific results are shown in Figure 11.

In Figure 11, with the reduction in the headway, the freight cost has been continuously reduced. As shown in Figure 11, the sensitivity of train headway to freight costs is not very obvious. When the train headway is 2 minutes, the optimal freight cost is ¥5761.4. Reducing the headway can increase the number of train departures, thereby helping to provide more freight services and better distribution of goods, so as to achieve the purpose of reducing freight costs.

5.2.3. Cargo Operation Cost. The transportation cost of cargo boxes and the operating cost of freight carriage fundamentally determine the level of cargo operating cost. Taking the metro freight plan with freight carriage as an example, the sensitivity of different transportation cost and operating cost to freight cost is separately analyzed. The analysis results are shown in Figures 12 and 13. The transportation cost of each cargo box is varied from ¥1 to ¥10 per kilometer. The operating cost for each freight carriage is analyzed from ¥5 to ¥30 per kilometer.

In Figure 12, freight costs increase as transportation costs increase. When the transportation cost of a single cargo box is 1¥/km, the freight cost is ¥3070.2, and when the transportation cost of one cargo box is 10¥/km, the freight cost is ¥9396. As shown in Figure 13, the increase in the operating costs of carriage will also increase freight costs. When the operating cost of each freight carriage is 5¥/km, the lowest freight cost is ¥5319.7, and when the operating cost is 30¥/km, the lowest freight cost is ¥6724.7.

According to the changing trends of freight costs in Figures 12 and 13, the increase in the transportation cost of the freight box is more sensitive to the increase in the freight costs than the increase in the operating costs of the freight carriage. With the increase in the transportation cost of freight box, the increasing trend of freight costs is significant, while the increase in the operating costs of freight carriage makes the increasing trend of freight costs relatively flat. Therefore, the freight company can choose the method of high operating cost for freight carriage and low transportation cost for the cargo box to obtain the optimal metro freight plan.

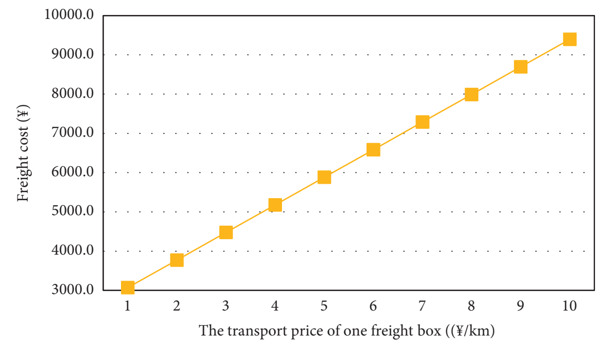

Figure 12: Schematic diagram of freight cost and transportation cost of per cargo box.

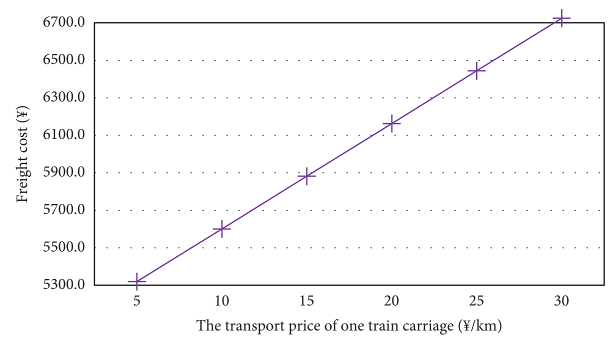

Figure 13: Schematic diagram of freight cost and operating cost of per train carriage.

6. Conclusion and Future Research

This study proposes a metro freight plan, in which urban freight is introduced into urban rail transit. Based on the train in a single metro line with one freight carriage, a train schedule and freight distribution plan were developed to realize the mixed passenger and freight transportation. According to freight demand, it is necessary to determine train capacity, train stopping plans, and operating schedules. A metro freight model with mixed-integer linear programming is established to optimize the freight cost. A certain metro line of Ningbo Rail Transit is selected, and the model is solved by VNS, which verifies the validity of the model. Through the sensitivity analysis of train capacity, train headway5 and cargo operation cost to metro freight cost, cargo operation cost is the key to the development of a metro freight plan. Therefore, the formulation of the metro freight plan can obtain a more efficient train schedule and freight distribution plan. The main contributions of the study are as follows.

Theoretically, compared with the related research on the train scheduling problem of mixed passenger and freight transportation [6, 32], this study considers the stopping plan of the train with freight task and further optimizes the metro freight plan.

In practice, the metro freight plan proposed in this study can provide decision support for train schedules and freight distribution plans. Freight companies can reduce freight costs by adjusting cargo operating costs. In addition, the implementation of the metro freight plan can also potentially bring additional freight revenue from metro operations [34].

Further studies can be focused on the following aspects. (1) The metro freight plan proposed in this study is developed for a single metro line, and the subsequent research can consider the formulation of the freight plan for multiple metro lines. (2) Currently, there is only one train carriage used for freight, and setting the number of freight carriages according to the changes in passenger flow is a reassuring study in the future. In addition, it is important to consider the cargo storage capacity constraints in metro stations. (3) According to the plan of regional rail transit integration, future research can combine high-speed railway with metro to transport freight.

Data Availability

The relevant data involved in this paper were collected from the official website of the National Bureau of Statistics of China and the China Urban Rail Transit Association. The specific connection is as follows. https://data.stats.gov.cn/easyquery.htm?cn=C01 and https://www.camet.org.cn/

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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