# Research on Location Optimization of Metro-Based Underground Logistics System With Voronoi Diagram

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**ABSTRACT** This paper develops a location optimization method about the metro-based underground logistics system (MULS) to transport freight by metro during off-peak periods. First, we make qualitative and quantitative feasibility analysis of the MULS through questionnaires and field surveys in metro stations. The analysis result shows that more than 85.22% of interviewees support logistics delivery by the metro. An improved $p$-median model is developed, which considers four influencing factors. The shortest path algorithm is used to minimize the transport costs while the costs of the remaining factors are calculated using the collected data. Then, the Voronoi diagram is adopted to optimize the location of candidate metro stations and redraw the logistics service scope by adding weighted terms. Finally, the Nanjing metro is chosen as a case study to validate the effectiveness of the developed method. The optimization result shows the total cost of the logistics delivery is reduced by 33. 27% suggesting that the method can be used to reduce logistics costs and improve delivery efficiency in urban areas.

**INDEX TERMS** Metro-based underground logistics system, Voronoi diagram, improved $p$-median model, location Optimization.

## I. INTRODUCTION

The underground logistics system (ULS) is known as the underground freight transport system (UFTS) [1]. The earliest underground logistics system was the London mail rail system in 1930. As a new transportation mode, the ULS can be used as an effective solution to alleviate traffic congestion, improve logistics delivery efficiency, and reduce delivery expenses in the urban areas.

The general ULS transported in automated guiding vehicles or amphibious trucks through large-caliber pipes has some drawbacks. Due to the vast number of investment, operation cost, and lengthy construction cycle, the transport carrier and development pattern of the ULS still needs to be further studied. In recent years, with the extension of the metro lines and rapid exploitation of underground space, metro stations, and underground complexes are under widespread construction in urban areas, which have unique

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superiorities of operation on the ULS. Therefore, research on Metro-based ULS (MULS) has attracted the interest of scholars. The MULS is defined as an intermodal mechanism of mixed passengers and freight, in which batch driving or attachment carriages are enabled by utilizing metro railways. Kikuta *et al.* [2] proposed a novel city logistics system by integrating the public metro service with conventional freight vehicles to transport goods effectively from the suburbs to the city center. Dampier and Marinov [3] selected the Tyne and Wear Metro system located in the Newcastle upon Tyne as the case study and discussed the feasibility of a metropolitan railway network to transport freight from the surrounding businesses to a city center. Fatnassi *et al.* [4] investigated the potential benefits of integrating shared goods and passengers on-demand rapid transit systems in urban areas. Savelsbergh and Van Woensel [5] pointed out that city logistics were to find efficient and effective approaches to transport goods in urban areas while considering the negative effects of goods delivery in urban areas on congestion, safety, and environment.

At present, research on freight transport by the MULS mostly focuses on summing up previous research experience and feasibility analysis. Some existing studies have proposed concept designs and quantitative approaches. Corresponding case studies that use public transport infrastructure (metro) for freight deliveries have also conducted. For example, Masson *et al.* [6] proposed a city logistics transportation system with passengers and cargoes by designing a mathematical model and solved the two-tiered transportation problem. Dong *et al.* [7] developed a hybrid algorithm with a combination of E-TOPSIS, exact algorithm. A heuristic algorithm was employed to solve an evaluation model of metro system-based ULS network freight volume with constraints to the service capacity, freight flow, and regional accessibility. Zhao *et al.* [8] determined the location using the TOPSIS model and chose the final metro delivery hubs from the candidate metro delivery hubs. Pan *et al.* [9] designed an underground container transport system to realize the road underground-ocean container multimodal transport using the 0-1 planning model and simulation model.

A summary of existing studies shows that scholars developed different models with different location optimization goals and network complexity. Different from the above research efforts, we account for more influencing factors, which make location optimization of logistics delivery nodes more accurate and reasonable. Moreover, compared with previous studies, the Voronoi diagram is easily operated, and the optimization result presented in a figure is visualization. In this paper, we propose an improved *p*-median model to minimize the total cost of the system. The model is solved by the influencing range characteristics of the Voronoi diagram. Nanjing Metro is selected as a case study to verify the effectiveness of the model.

The remainder of this paper is organized as follows. Section II describes the background, study site, and data used in this study. In Section III and Section IV, we propose the research methods, including the improved *p*-median model and Voronoi diagram. In Section V, we describe an empirical study of MULS, present the results of locating delivery nodes, and discuss the optimized results.

## II. STUDY SITE AND DATA
The reason for using the metro to deliver goods during the off-peak periods is metro and ULS have system compatibility, mainly show in the network layout and transportation characteristics. Taking advantage of the metro's underutilized capacity to deliver goods and passengers at the same time can make full use of the surplus capacity of the metro and reduce the delivery cost. In Section II, we introduce the background, study site, and collected data, to lay a foundation for the theoretical research in the subsequent section.

### A. BACKGROUND
Nanjing has a huge demand for urban logistics delivery. In contrast, it has an excellent foundation of the metro network, and most of the residents express expectations and

approval of the shared passengers and goods transport by the metro.

The Nanjing logistics business has maintained a stable speed of development in recent years. In 2018, the cumulative volume totaled 766.3453 million pieces. Compared with 2017, it has increased by about 20.84%, which indicates the residents have growing logistics demands. However, the overall logistics infrastructure service capacity has not worked at full capacity in urban areas, and this phenomenon has brought great pressure on urban logistics delivery.

Additionally, the network of Nanjing Metro is basically shaped; the coverage rate is huge. As of June 2019, Nanjing Metro has opened 10 lines, 174 metro stations, and the total length of lines has been up to 378 kilometers. The length ranks 4th in China and 5th in the world. It constitutes a metro network covering 11 municipal districts in Nanjing. In addition, Nanjing has become the first province of China in which all districts are open metro lines.

What's more, residents' acceptance of freight transport by metro counts a great deal with MULS's operation. Residents are not only the demanders of logistics delivery in urban areas but also the passengers on the metro. Therefore, we conducted a random questionnaire of the passengers at the metro station and received 115 valid data totally. By sorting out the statistical results of 115 questionnaires, we obtained the interviewees' acceptance of logistics delivery by MULS.
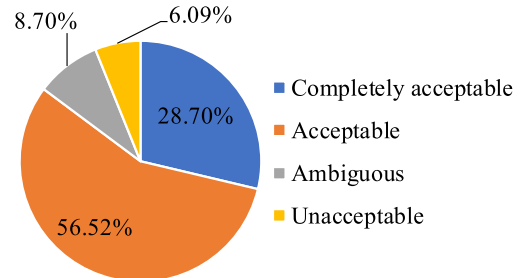


**FIGURE 1.** Interviewees' acceptance of logistics delivery by MULS.

FIGURE 1 shows the degree of acceptance, which divided into four categories: completely acceptable, acceptable, ambiguous, and completely unacceptable. From the result of questionnaires, 28.7% of interviewees were completely acceptable for the use of metro for goods delivery; 56.52% passengers agreed to operate, but may retain some comments or suggestions; 8.7% of interviewees held an ambiguous attitude, they concerned about the negative impact on logistics delivery; only 6.09% of the respondents are totally unacceptable, they believed that logistics delivery by MULS can't operate in urban areas.

In addition, we conduct a survey for interviewees about the concerns for logistics delivery by MULS. The interviewees' occupations including teachers, students, civil servants, white collars, civil servants, liberal professions, and others.

FIGURE 2 shows the interviewees' concern about logistics delivery by MULS. It divides into four categories.
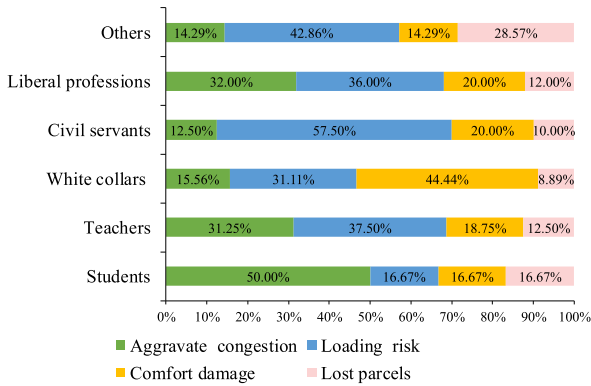
**FIGURE 2.** Interviewees' concerns on logistics delivery by MULS.

Interviewees from different occupations also have various interests. 50% of students worry about using metro carriages for goods transport to aggravate passenger congestion; 57.5% of civil servants worry about nonstandard goods loading may lead to personal safety threat to passengers. At the same time white collars are most worried that the mixed passengers and goods transport will damage the comfort of metro taking.

It can be seen that most interviewees accept and approve this new logistics delivery mode, although someone still has reservations about it.

### B. STUDY SITE
This paper selects 12 stations on Line 1, Line 2 and Line 3 from Nanjing Metro as a case study. These lines are located in the urban area and surrounded by residential, commercial as well as business facilities. We number these stations from S1 to S12. The detailed longitude and latitude coordinates are shown in TABLE 1.

**TABLE 1.** Longitude and latitude coordinates of metro stations.

| Station | Xinjiekou | Daxinggong | Sanshanjie |
|---|---|---|---|
| Number | S1 | S2 | S3 |
| Longitude | 118.77917 | 118.78971 | 118.77645 |
| Latitude | 32.04381 | 32.04363 | 32.02517 |
| Station | Zhangfuyuan | Yunjinlu | Zhujianglu |
| Number | S4 | S5 | S6 |
| Longitude | 118.7789 | 118.74218 | 118.77896 |
| Latitude | 32.03305 | 32.03706 | 32.05291 |
| Station | Shanghailu | Changfujie | Fuzimiao |
| Number | S7 | S8 | S9 |
| Longitude | 118.77107 | 118.78744 | 118.78575 |
| Latitude | 32.04437 | 32.03564 | 32.02562 |
| Station | Mochouhu | Fuqiao | Hanzhongmen |
| Number | S10 | S11 | S12 |
| Longitude | 118.75378 | 118.79107 | 118.76154 |
| Latitude | 32.03944 | 32.05093 | 32.04482 |

Notes: To simplify the process, serial numbers are used instead of station names.

Then, we convert longitude and latitude coordinate into rectangular plane coordinates in order to reduce the complexity and improve the accuracy of the calculation. It's convenient for programming calculation by MATLAB. The plug-in

of ArcGIS is also used to find the demand points and network contained in the research area.
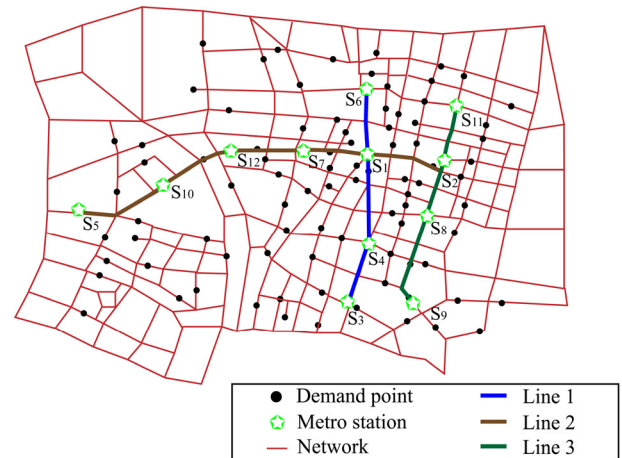


**FIGURE 3.** Specific location of demand points and metro stations.

FIGURE 3 shows the specific location of demand points and metro stations. 118 demand points are marked by black points that represent residential quarters or office buildings. The blue line, brown line, and green line represent the network, Line 1, Line 2, and Line 3, respectively.

On the basis of the network and specific location, we can build the underground logistics system by the metro. The system is composed of metro stations, metro carriages, metro networks, clients, and couriers. Goods are collected from different clients by couriers and loaded at metro stations, transported by metro carriages and unloaded at stations, and delivered to end clients by couriers. The specific process of logistics delivery by the MULS is shown in FIGURE 4.

The MULS has three components, components I and III are ground transportation, and component II is using the metro network to transport goods from the departure station to the destination station. In this article, we mainly focus on components II and III to minimize system costs and delivery delays.

### C. COLLECTED DATA
We collect the necessary data from 12 selected metro stations. These data are vital to the calculation of influencing factors in Section III. Due to the lack of previous research on logistics delivery by MULS, we make assumptions about the value of workforc and materials' cost and rent. The assumption of the workforce andmaterials' fee is based on the capacity of metro stations, general logistics factor cost, and the rent is determined by land price situation around the metro. The collected data is shown in TABLE 2.

### III. IMPROVED P-MEDIAN MODEL
Currently, several logistics companies in China have used the urban metro network to deliver parcels, but they usually locate the delivery nodes based on their own experience [8]. This method lacks a scientific basis and may lead to
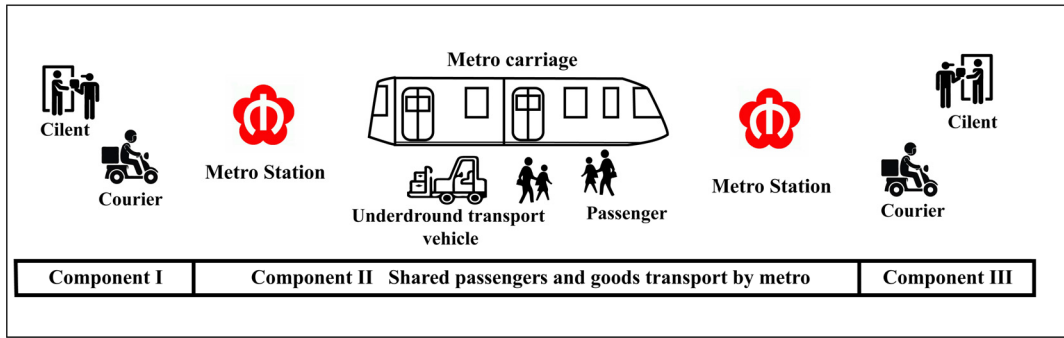
**FIGURE 4.** The component of the MULS.

**TABLE 2.** Basic data of logistics delivery by MULS.

| Number | $Q_1$ | $Q_2$ | $Q_3$ | $Q_4$ |
|--------|------|------|------|-------|
| S1  | 260 | 8   | 4349 | 76685 |
| S2  | 160 | 6.5 | 2175 | 11601 |
| S3  | 130 | 7   | 1269 | 12880 |
| S4  | 130 | 7   | 786  | 10601 |
| S5  | 80  | 6.5 | 783  | 10600 |
| S6  | 100 | 6   | 1374 | 11602 |
| S7  | 150 | 6   | 790  | 11140 |
| S8  | 80  | 4.5 | 536  | 8033  |
| S9  | 80  | 5   | 802  | 11610 |
| S10 | 70  | 2.5 | 548  | 12745 |
| S11 | 50  | 3.5 | 576  | 10550 |
| S12 | 150 | 4   | 782  | 14917 |

Notes: $Q_1$: Rent (Unit: yuan/(m².d)); $Q_2$: Cost of manpower and material in the process of logistics delivery (Unit: ten thousand yuan/d); $Q_3$: Quantity of passenger flow (Unit: person); $Q_4$: Area (Unit: m²).

delivery delays. Since the many quantities and wide distribution of metro stations, it is necessary to optimize the location of stations when carrying out underground logistics in the future.

Two significant problems need to be solved in this paper. One is how to choose a path around stations to minimize the transport cost. Another problem is how to take the points from candidate metro stations as delivery nodes and optimize each node's service scope, to reduce the total cost of the system when carrying out the logistics delivery process. The second problem is the critical point.

The conventional methods of location optimization for logistics delivery nodes include a qualitative and quantitative analysis method. The improved p-median model belongs to the latter. As an effective quantitative analysis method, the p-median model was used to location optimization widely. Drezner and Drezner [10] proposed a new model for the *p*-median problem, which assumed that customers divide their patronage among the facilities. Mladenović *et al.* [11] examined the *p*-median model, intending to provide an overview of advances in solving it using new procedures based on metaheuristic rules.

Hakimi [12] found *p* facility locations that minimize the sum of weighted distances between demand points (customers) and their respective nearest facilities. Similar to

most location problems, the *p*-median problem is classified as an NP-hard problem. We need to structure an improved *p*-median model to get the best location optimization result under the premise of meeting the logistics service level.

### A. MODEL HYPOTHESIS

The model programming of the improved *p*-median model is a complex process. To turn the real abstract problem into a mathematical model, some assumptions have been made as follows:

(1) The transport cost is proportional to the time and distance of transportation, and the delivery center is accessible to all demand points;

(2) The impact of traffic congestion, weather, and other factors on transport costs are not taken into account in the process of ground transportation.

(3) The storage facilities of the candidate metro stations will provide a specific storage time within the service range of the delivery center.

(4) The logistics service capacity of candidate metro stations is equal to carriages' surplus capacity.

(5) The capacity of the ground delivery vehicles meets the volume of transport by the metro per shift.

### B. DETERMINATION OF FACTORS

We find the optimization effect is not ideal by observing the optimization result by the general p-median model since the general *p*-median model only has a single decision variable.

In this paper, we define four factors that influence the location optimization result of logistics delivery nodes. The determination of factors will be based on the degree of impact on logistics service capability. Then we carry out the weight calibration and data standardization for factors.

#### 1) DEFINITION OF FACTORS
##### a: INFRASTRUCTURE COST

The construction cost of new storage facilities and the cost of operation are indispensable factors, that is infrastructure cost. We assume that infrastructure cost is a constant value. Under the premise that the infrastructure and equipment of the metro have been built, when logistics companies carry on the freight

by metro, they should pay rents to the metro company, just like shops in the metro station. This method can reduce the transport cost caused by the single operation mode of logistics and increase the income of the metro company.

#### b: TRANSPORT COST

Transport costs will be produced in the process of goods delivery by the metro, which including underground and ground transportation costs. As shown in FIGURE 3, Underground transportation cost generates from the originating station to the target station, which is consistent with the cost incurred in the process of passenger transport, this part isn't considered in this paper. Ground transportation cost generates from the target station to the customer, and it is related to the metro's surplus capacity and ground delivery path.

We take maximum loading of carriage subtracts passenger loading as the surplus capacity of the metro, which is limited by the volume of the transport. As for the specification of the Chinese national standard [13], the maximum loading of carriage $L_{vt}$ is shown in (1).

$$L_{vt} = 1.1 \times (W_c + W_{p\,max}) - (W_{cb} + W_{et}) \qquad (1)$$

where $W_c$ is the weight of carriage, $W_{cb}$ is the weight of carriage structure equipment, $W_{et}$ is weight of experimental equipment, $W_{p\,max}$ is the maximum weight of passengers in the experiment, including stewards, passengers in seat, standing passengers.

Since the frequency of departure of the metro during off-peak periods is relatively low, we need to make a slight adjustment to the departure interval as like as TWs without undermining the metro running order, which can increase the efficiency of shared passengers and goods transport. Cancela *et al.* [14] proposed a set of time windows (TWs) to transit network design formulation for the public transportation system. The TW length could be increased or decreased depending on the demand of city logistics.

We assume the departure interval of the metro is cut down during the off-peak periods. The formula is used to calculate the weight of passengers in the metro after departure interval adjustment, as shown in (2).

$$\begin{cases} L_p = \left[ (n^p + n')^* C - u^p \right] W_{pa} \\ (n^p + n')^* C_p \geq u^p \end{cases} \qquad (2)$$

where $L_p$ is the total weight of passengers in the metro, $n^p$ is the number of running vehicles during the $p$th period, $n'$ is the number of additional vehicles plan, $C_p$ is the capacity of metro, $u^p$ is the number of passengers in platform. $W_{pa}$ is the average weight of each passenger.

In that way, the surplus capacity of carriage $L_t$ is the maximum loading of metro carriage minus the weight of passengers in metro. It is defined as (3).

$$L_t = L_{vt} - L_p \qquad (3)$$

While the goods transported have a specific volume, if we use loading as the single criterion for surplus capacity, it may lead to the amount of the goods too excessive to get on the carriage. So, some constraints are also included in the formula for calculating surplus capacity [15].

The main technical specifications of the metro are divided into model A and model B in national standard and Nanjing metro lines 1, 2 and 3 put the model A carriage into operation. The standard sets each carriage's length, width and height are 22.8m,3m, and 2.1m respectively, each carriage and has 56 seats, the size of each seat is 0.25m$^2$. Moreover, the total length is about 140 m which can hold up to 2460 people. According to the standard, each carriage has 56 seats, each carriage has a capacity of 310 passengers, the size of each seat is 0.25m2, and the number of stand-up passengers per square meter floor is 8.

At the same time, we stipulate that the freight can be stacked and take the No.6 container with the largest specification of SF Express as an example. Its length, width, and height, as well as the average weight, are 0.7 m, 0.4 m, 0.32 m and 15 kg.

In theory, each carriage can be placed 1140 containers totally after deducting the volume occupied by the seats. But the total area of the goods after stacking shall not exceed 80% of the remaining area of the carriage, and the total volume shall not exceed 70% of the remaining volume of the carriage, so as to minimize the impact on the comfort of passengers. We assume that the average number of passengers per carriage is $n$, the containers placed in each carriage is $i$. The length, width and height of each container is $l_i$, $w_i$, $h_i$. The constraints are given as follows:

$$\begin{cases} l_i \times w_i \leq 22, & n < 56 \\ l_i \times w_i \leq 22 - (56 - n) \times 0.125, & n \geq 56 \end{cases} \qquad (4)$$

$$\begin{cases} l_i \times w_i \times h_i \leq 81.9, & n < 56 \\ l_i \times w_i \times h_i \leq 81.9 - (56 - n) \times 0.263, & n \geq 56 \end{cases} \qquad (5)$$

Through the formula above, we determine the surplus capacity of carriage, and its quantity is equal to service capacity. It should be worth noting that we don't discuss the route selection and optimization methods of terminal delivery in detail, the outcome of the shortest path was solved with the shortest path analysis in ArcGIS based on the principle of Dijkstra algorithm.

#### c: LOGISTICS FACTOR COST

Logistics factor cost refers to the summation of the workforce, material, and financial resources generated by the logistics activities such as loading, unloading, handling, and storage of goods in metro stations. It is a constant value and takes ground logistics factor cost for reference. The difference between the internal structure and space area of each metro station leads to the difference in logistics factor cost. Since the logistics delivery function is not implemented at present, we assume the cost of the logistics factor in the metro station.

### d: PASSENGER TRANSPORT IMPACT COST

When the function of freight is increased in the metro station, it may have a more significant impact on the existing passenger flow, which is passenger transport impact cost. In general, the walking speed of passengers in metro stations is negatively correlated with the available space in the station. After the walking area is reduced, the slower walking speed as a more significant impact on passengers, the boarding time will be delayed, the travel efficiency of the passengers is reduced, so passengers may choose other modes to get around. Finally, the income of the metro is shrinking. The calculation of passenger transport impact cost is shown in (6).

$$E_i = \frac{V_i T_i}{S_i} P_i \qquad (6)$$

where $V_i$ is the quantity of passenger flow in the $i$th metro station per unit time, $T_i$ is platform space occupied after mixed passenger and goods transportation, $S_i$ is the area of the $i$th metro station, $P_i$ is the average passenger fare.

### 2) WEIGHT CALIBRATION

The weight of four factors indicates its importance in the system. Therefore, the relationship between factors of the index should be comprehensively considered when determining the weight. The four factors mentioned above will affect the decision of candidate metro stations location without exception, while the degree of impact varies.

Therefore, the factors of each aspect should be considered comprehensively and the weight should be reasonably distributed according to the practical situation to achieve optimization effect.

According to the influence on location optimization, the weight of each factor is determined by ranking the countdown method, and four factors are arranged in descending order. We use a four-scale method (with values of 1, 2, 3, and 4) of the analytic hierarchy process (AHP) to evaluate the cost of factors. The apply for using the 1-4 scales method instead of 1-9 scales makes it easier for the experts to judge and avoid inconsistency problems [15].

Infrastructure cost is the primary expense of logistics delivery by MULS, then transport cost and logistics factor cost generate. Based on the concept of benefit first, we assign Infrastructure cost, transport cost, logistics factor cost, and passenger transport impact cost from 1 to 4 based on their impact cost, 1 represents the most important influencing factor, while 4 represents the least important factor. The weight value of each influencing factor is calculated by (7).

$$w_i = \frac{1/r_i}{\sum\limits_{i=1}^{4} 1/r_i} \qquad (7)$$

where $w_i$ is the normalization weight value of the $i$th influencing factor, $r_i$ is the $i$th influencing factor of ordinal assignment number.

### 3) DATA STANDARDIZATION

Four factors mentioned above need to be standardized before calculation. After the process of standardization, factors value with different dimensions can fall in the same direction, so that the effect on the dimension on the calculation result will be eliminated.

The Min-Max Normalization method is adopted in this paper since the maximum and minimum value of the four influencing factors in the article are known. The maximum value of a variable minus the minimum value is taken as the range. Then the observed value of a variable is divided by the range to obtain the standardized data. The Min-Max Normalization shown in (8), the data after the Min-Max Normalization turn into the value without unit, and the range is between 0 and 1, which can be multiplied by the weight and summed to calculate the total cost of location optimization.

$$L_i' = \frac{L_i - L_{\min}}{L_{\max} - L_{\min}} \qquad (8)$$

where $L_i'$ is the specific value after Data standardization, $L_i$ is the specific value of a variable, $L_{\max}$ is the maximum value of all variables, $L_{\min}$ is the maximum value of all variables.

### C. STRUCTURE OF MODEL

In TABLE 3, we explain the parameters of the asymmetric model.

**TABLE 3.** Parametric description of improved *P*-median model.

| Parameters | Description |
|---|---|
| $C$ | Total system cost of logistics delivery |
| $C_{ij}$ | Total cost from $i$th metro station to $j$th demand point |
| $R_i$ | Infrastructure cost of $i$th candidate metro station |
| $D_{ij}$ | Transport cost from $i$th station to $j$th demand point |
| $L_i$ | Logistics factor cost of the $i$th station |
| $E_i$ | Passenger transport impact cost of $i$th station |
| $w_1, w_2, w_3, w_4$ | Weight value of each influencing factor |
| $M$ | The set of metro station, $M = \{1, 2, \cdots, m\}$ |
| $N$ | The set of demand point, $N = \{1, 2, \cdots, n\}$ |
| $P$ | The number of selected delivery center, $P < m$ |
| $x_i$ | The choice of the $i$th metro station as delivery center, $i \in M$ |
| $y_{ij}$ | The choice of $j$th demand point served by $i$th delivery center |

The structure of the improved p-median model is as follows. Equation (9) and (10) are objective functions ensuring the total system cost of logistics delivery by MULS to be minimum.

$$C_{ij} = w_1 R_i + w_2 D_{ij} + w_3 L_i + w_4 E_i, \quad (i \in M, j \in N) \qquad (9)$$

$$\min C = \min \sum_{i \in M, j \in N} y_{ij} C_{ij} \qquad (10)$$

From (11) to (15) are constraints. Equation (11) meets each demand point is served by only one delivery center; (12) sets the total number of metro stations which can be selected for establishing the delivery center as $P$; (13) ensures that each delivery center has demand point. Eqation (14) and (15) indicate the choice of the metro station as the delivery centers and if demand point is served by the selected delivery center, if true marked as 1 otherwise marked as 0.

$$\sum_{j \in N} y_{ij} = 1, \quad i \in M \tag{11}$$

$$\sum_{i \in M} x_i = P \tag{12}$$

$$x_i \geq y_{ij}, \quad i \in M, j \in N \tag{13}$$

$$x_i \in \{0, 1\}, \quad i \in M \tag{14}$$

$$y_{ij} \in \{0, 1\}, \quad i \in M, j \in N \tag{15}$$

The improved p-median model needs to solve how to select the appropriate delivery center location and assign the demand point to the corresponding delivery nodes. So, we will introduce an effective solution algorithm in Section IV.

## IV. VORONOI DIAGRAM

First of all, we should determine the minimum number of metro stations used for underground logistics delivery nodes. The determination depends on the logistics demand of the selected area and capacity available of the candidate metro stations. The minimum number of metro stations $k$ can be calculated by (16).

$$k = \frac{\sum W}{(S_i)_{\text{ave}}} \tag{16}$$

where $\sum W$ is the total demand in the research area, $(S_i)_{\text{ave}}$ is the average service capacity of candidate metro stations.

The improved *p*-median model is solved by the Voronoi diagram. Vaidya and Kumar [16] proposed a mathematical formulation of two variants and a heuristic approach based on Voronoi diagrams and a binary linear program to solve the continuous multiple obnoxious facility location problems. Drezner *et al.* [17] introduced a bi-level Voronoi diagram-based metaheuristic to solve the large-scale multi-depot vehicle routing problems (MDVRPs).

The idea of the Voronoi diagram is to partition the plane into polygons such that all the points inside a polygon are closest to one of the communities [18]. The vertices of these polygons are equally distant to at least three communities (and closest to them) or at least two communities if the Voronoi vertex is on the edge of the feasible region. The vertices of the feasible region are also Voronoi vertices that are at the minimum distance to at least one community. Therefore, the best location for the facility is on one of these vertices. The specific algorithm design flow chart is shown in FIGURE 5.
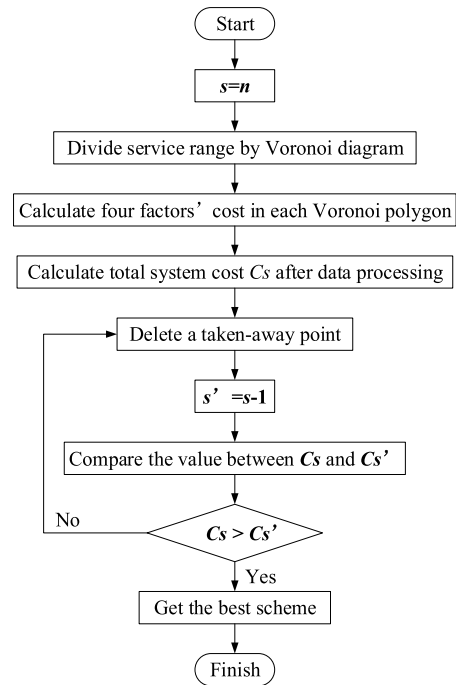


**FIGURE 5.** Flow chart for the process of voronoi diagram.

The specific steps of the *p*-median model location optimization solution method based on the Voronoi diagram as follows:

*Step 1:* Suppose the number of currently selected candidate metro stations $s = n$, all candidate metro stations are chosen. Use all candidate metro stations to be the growth point to generate the Voronoi diagram based on the influence range characteristics of the Voronoi diagram, and determine the service scope of each metro station.

*Step 2:* The cost within the polygon range of each Voronoi diagram are calculated respectively according to the formula, and the total expense $Cs$ under this condition is obtained by summation after data weight calibration and standardization.

*Step 3:* Determine a take-away point from the current candidate metro stations, which meets the following requirements: when the point is deleted, the demand point originally within the scope of the Voronoi diagram is served by the remaining points, and the total logistics cost is the minimum compared with deleting other points.

*Step 4:* Order $s' = s - 1$, compare the value of total system cost between $Cs$ and $Cs'$, if $Cs \leq Cs'$, switch to step 3, otherwise get the scheme with the minimum system cost, the algorithm ends.

After the process of location optimization, the service scope of the optimized nodes needs to be calculated. Compared with the general Voronoi diagram, the weighted Voronoi diagram takes into account the service-ability and path influencing factors of the growth point. Since the weight of each point is different, the division of service scope is more accurate.

The service capacity of delivery nodes and the density of network around nodes directly affect the delivery efficiency.

**TABLE 4.** The value of distance in program and transport cost.

| Number | S1 | S2 | S3 | S4 |
|---|---|---|---|---|
| $T_i$ | 3184.9 | 2708.5 | 4953.4 | 4711 |
| $W_i$ | 1.8 | 1.4 | 1.4 | 1.3 |
| $D_{ij}$ | 300.973 | 199.075 | 364.075 | 321.526 |
| Number | S5 | S6 | S7 | S8 |
| $T_i$ | 3387.2 | 2835.8 | 5698.5 | 3484.3 |
| $W_i$ | 1.5 | 1.7 | 1.2 | 1.8 |
| $D_{ij}$ | 266.742 | 253.095 | 359.006 | 329.266 |
| Number | S9 | S10 | S11 | S12 |
| $T_i$ | 4649.6 | 7616.9 | 4516.7 | 6688.5 |
| $W_i$ | 1.6 | 1.7 | 1.4 | 1.3 |
| $D_{ij}$ | 390.566 | 679.808 | 331.977 | 456.490 |

Notes: $T_i$: Total Distance in program (Unit: m); $S_i$: Service capacity(Unit: ton/d); $D_{ij}$: Transport cost (Unit: yuan/d).

**TABLE 5.** The value of passenger transport impact cost.

| Number | S1 | S2 | S3 | S4 |
|---|---|---|---|---|
| $E_i$ | 55.9 | 184.7 | 97.0 | 73.0 |
| Number | S5 | S6 | S7 | S8 |
| $E_i$ | 72.8 | 116.7 | 69.9 | 65.7 |
| Number | S9 | S10 | S11 | S12 |
| $E_i$ | 68.0 | 42.4 | 53.8 | 51.6 |

Notes: $E_i$, Passenger transport impact cost (Unit: yuan).

**TABLE 6.** The value of four factors after standardization.

| Number | $R_i$ | $D_{ij}$ | $L_i$ | $E_i$ |
|---|---|---|---|---|
| S1 | 1 | 0.1 | 1 | 0.1 |
| S2 | 0.52 | 0 | 0.73 | 1 |
| S3 | 0.38 | 0.46 | 0.82 | 0.39 |
| S4 | 0.38 | 0.41 | 0.82 | 0.22 |
| S5 | 0.14 | 0.14 | 0.73 | 0.21 |
| S6 | 0.24 | 0.03 | 0.64 | 0.52 |
| S7 | 0.48 | 0.61 | 0.64 | 0.19 |
| S8 | 0.14 | 0.16 | 0.36 | 0.17 |
| S9 | 0.62 | 0.4 | 0.45 | 0.18 |
| S10 | 0.1 | 1 | 0 | 0 |
| S11 | 0 | 0.37 | 0.18 | 0.08 |
| S12 | 0.48 | 0.81 | 0.27 | 0.07 |

Notes: $R_i$: Infrastructure cost; $D_{ij}$: Transport cost; $L_i$: Logistics factor cost; $E_i$: Passenger transport impact cost.

These weighting factors are used to calculate the weight of each node, the calculation formula is found in (17).

$$QZ_i = \frac{W_i}{\overline{W}} + \frac{J_i}{\overline{J}} \qquad (17)$$

where $QZ_i$ is the weighting factor of delivery node, $W_i$ and $J_i$ are service capacity as well as density of network around node $i$, $\overline{W}$ and $\overline{J}$ are the average service capacity and density of network.

Then, the weighted Voronoi diagram is generated by taking each delivery node as the growth point, the weighted Voronoi polygon corresponding to each node is updated service scope.

## V. RESULTS OF ANALYSIS

### A. OPTIMIZATION PROCESS

The location optimization process of candidate metro stations as follows:

*Step 1:* Determine the number of underground logistics delivery nodes. The number of metro stations that need to be used as logistics delivery nodes in the range of study is 8 calculate by (16).

*Step 2:* Determine the minimum transport costs. First, we use the network analyst tool in ArcGIS to find the shortest path. FIGURE 6 shows the process of finding the shortest route. The green line in FIGURE 6 represents the path selection process of the marking method. The green points represent the decision nodes in the program, and the blue point represents the destination.

By using the labeling method, we obtain the shortest path from candidate metro stations to the demand points within each polygon range of the Voronoi diagram. Then, we assume the goods which meet the metro's surplus capacity were sent to demand points, and the standard cost of ground logistics delivery is 0.35 yuan/ton/km. So, the total distance of the shortest path and the minimum transport cost are shown in Tab.4.

*Step 3:* The determination of passenger transport impact cost for each metro station. We assume the average passenger fare $P_i$ is 5 yuan. The calculation results are shown in TABLE 5.

*Step 4:* Calibrate the weights and normalize the data.. According to (7), we calculate the weight of factors $w_1, w_2, w_3, w_4$ are 0.48, 0.24, 0.16, and 0.12, respectively. From the parameters and previous steps, we determine the value of four factors mentioned in SECTION III. Before beginning the circulation in the program, we should use the Min-Max normalization method to standardize the data of influencing factors and obtain the result in TABLE 6.

*Step 5:* Cycle the system and solve the model. In the process of the systemic circulation, if the total cost of a system is the smallest after the node is deleted, it means that the point increases the system cost. It is necessary to remove the points which raise the cost of the objective function and calculate the total cost of the system. Only one can be deleted in each cycle, and if the system cost in the next cycle is higher than the previous cycle, the circulation will be terminated. In addition, it can be seen from (16) that 8 stations are needed as delivery nodes, at least, so we will cycle up to four times.

*Step 6:* Redraw the service scope. The logistics service capacity, road network density, and weighting factors of the optimized metro stations are shown in TABLE 7. Then, the service scope after optimization is divided by the weighted Voronoi diagram.

### B. OPTIMIZATION RESULTS

As we can see from TABLE 8, the total cost of the first four times is reduced after deleting one candidate metro station. Still, the minimum system cost after the fifth cycle is higher than the fourth cycle result, so we terminate the cycle. 8 points are obtained, and the outcome of the cycle is marked in red. With the foundation of meeting the demand, the total cost of the system before the optimization is 3.397, and it
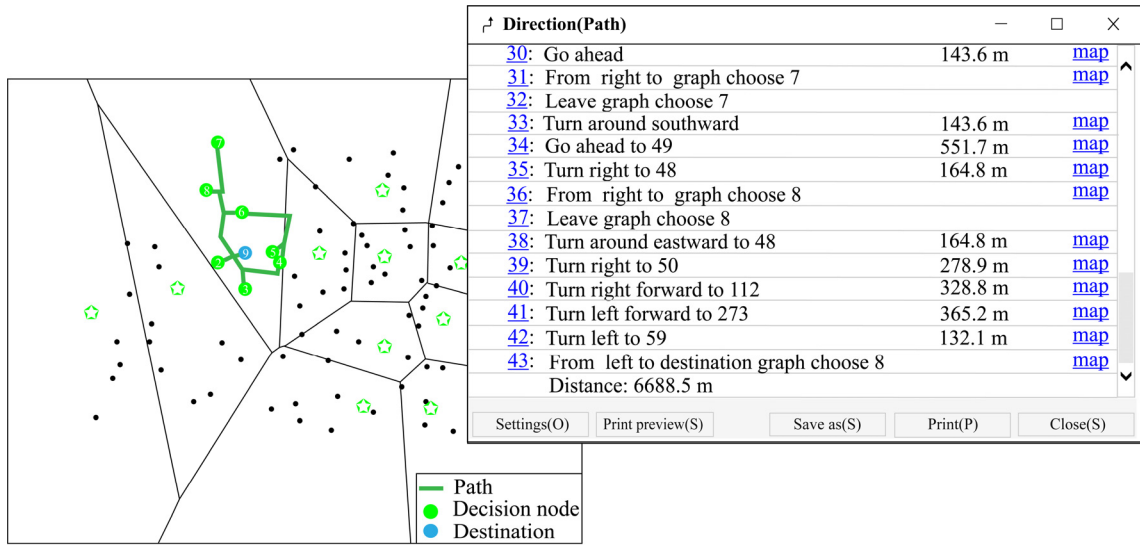
**FIGURE 6.** The process of solution to find the shortest path.

**TABLE 7.** The result of circulation in program.

| Number | $W_i$ | $J_i$ | $QZ_i$ |
|--------|-------|-------|--------|
| S3 | 1.4 | 13029.4 | 1.755 |
| S4 | 1.3 | 16532 | 1.914 |
| S6 | 1.7 | 14903 | 2.071 |
| S8 | 1.8 | 18949.9 | 2.359 |
| S9 | 1.6 | 13777.9 | 1.934 |
| S10 | 1.7 | 14097.7 | 2.02 |
| S11 | 1.4 | 16955.3 | 2.006 |
| S12 | 1.3 | 16950.9 | 1.941 |

Notes: $J_i$: Network density(Unit: 1/m); $QZ_i$: Weighting factor.

**TABLE 8.** The result of circulation in program.

| Cycles | 1 | 2 | 3 | 4 | 5 |
|--------|---|---|---|---|---|
| $P_D$ | S5 | S1 | S7 | S2 | S4 |
| $C$ | 3.957 | 3.534 | 3.082 | 2.519 | 2.657 |

Notes: $P_D$: The node should be deleted; $C$: The total system cost after deleting $P_D$.

decreases to 2.519 after the optimization when 8 points are used for logistics delivery, which is reduced by 33. 27% from the total cost of the system. The result shows that the optimization process can obviously reduce the total cost of logistics delivery, which proves the feasibility of optimization method.

In conclusion, the candidate metro stations that can be used as logistics delivery nodes by MULS are **S3, S4, S6, S8, S9, S10, S11, and S12**.

In addition, we determine the service scope of delivery nodes according to the weighted Voronoi diagram. Combined with the collected data, the service scope of each logistics delivery node is obtained by the weighted Voronoi diagram generation algorithm.
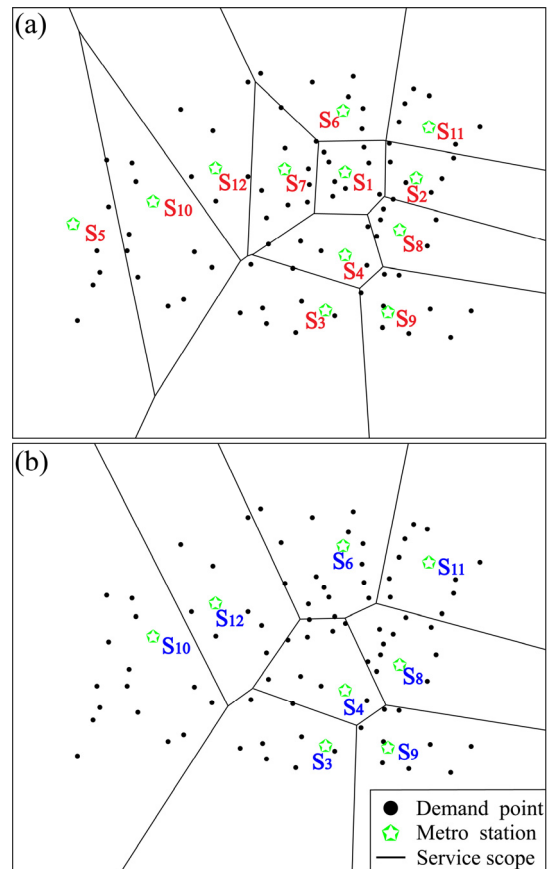


**FIGURE 7.** (a) The service scope before optimization, station number marked in red is candidate metro stations; (b) the service scope after redrawing, 8 metro stations chosen to be delivery nodes are marked in blue.

Compared with the difference between FIGURE 7(a) and FIGURE 7(b), we find two significant characteristics of deleted stations except for station S5.

First, station S1, S2 are multi-line transfer stations. The number of station exit is 21 and 6, respectively. Station S1 has the maximum exit number of Nanjing metro and the largest scale of metro stations in Asia. Station S2 and S7 are second slightly to Station S1 in range.

Moreover, station S1, S2, S7 are located in the central business district of Nanjing, the primary type of land usage is commercial and business facilities, and the number of traffic flow of the three metro stations mentioned is at the forefront of Nanjing metro station.

According to the characteristics mentioned above, we can preliminarily obtain the following results:

- In urban areas, metro stations near residential areas are more likely to be chosen as underground logistics delivery nodes, followed by stations near commercial areas.
- Multi-line transfer stations are less likely to be selected as the logistics delivery nodes. On the one hand, transfer stations have a more complicated structure, which needs more workforce and material resources to handle and transport the goods. On the other hand, the transfer station has a large passenger flow, and the flow lasts for a long time. So, there is little time for goods delivery, and the capacity and efficiency could be reduced.
- Although the number of nodes is reduced after location optimization, the total service scope remains unchanged, and the division of service area of each node is more well-distributed, which improves the delivery efficiency.

## VI. CONCLUSION

This paper proposed an improved p-median model to minimize the total cost of MULS and used the Voronoi diagram to optimize the location of metro stations in the study area. The service capacity and network density were used as a weighted term to build the weighted Voronoi diagram and calculate the service scope of 8 optimized nodes.

According to the qualitative and quantitative feasibility analysis, the use of the metro for logistics delivery from the view of system compatibility and surplus capacity is feasible. More than 85.22% of interviewees support logistics delivery by the metro. It should be noted that a serious concern of interviewees is nonstandard goods loading may lead to safety threats to passengers. The optimization results show that the total cost of MULS is reduced by 33. 27%. The service scope distribution of 8 optimized logistics nodes is more uniform. In addition, we also draw some preliminary results about the location characteristics of delivery nodes in the process of optimization. For instance, optimized locations preference the residential areas and single-line metro stations.

Besides the above contributions, this study still has several limitations. First, the complexity of the selected metro network is not enough. A more complex network with more stations and lines will be chosen to verify the rationality of results and explore more uncertainty problems. Additionally, the research on the optimization of the ground terminal delivery route is not involved. Since the choice of route may affect the timeliness of delivery and satisfaction of clients,

the problem of the optimal route for terminal delivery will be studied in the future.

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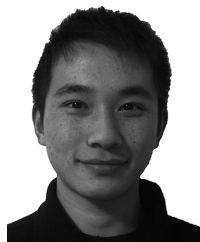
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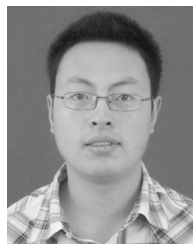


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