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Location Selection of Metro-Based Distribution Nodes for Underground Logistics System with Bi-Level Programming Model

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Abstract: The main purpose of the study was to apply symmetry principles to general mathematical modeling based on a bi-level programming model in order to select the optimal nodes of the underground metro-based logistics system (M-ULS). The first step was to select the metro stations as alternative logistics distribution nodes based on the existing metro network. Secondly, given the requirements of suppliers and demanders, a bi-level programming model was built based on symmetry principles to minimize the total cost of logistics distribution nodes, including construction cost, transport cost, and fixed cost. The third objective was to use an efficient heuristic algorithm to solve the model to obtain the optimal location of the nodes of the logistics distribution. Lastly, Nanjing's Metro Line 2 was used as an example to validate the efficacy of the proposed model. The results of the case indicate that it is possible to deliver goods from logistics distribution nodes to demanders using the excess capacity of the metro, and the proposed bi-level programming model for M-ULS can be used to select suitable metro stations as distribution nodes and achieve the lowest cost on both the supply and demand sides of logistics while still ensuring the green and efficient transport of logistics services. References and suggestions for planning and selecting the location of logistics distribution nodes based on the metro network in the future can be found in this article.

Keywords: metro-based underground logistics system; distribution nodes; bi-level programming model; heuristic algorithm

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1. Introduction

The rapid development of the social economy has led to an approximate 16.5 times increase in China's total logistics volume compared to 20 years ago. The 2021 China Post Express industry report published by the State Post Bureau of China found that in 2021 China's express service companies completed a total of 108.30 billion business items, a year-on-year growth of 29.9%, and the urban business volume completed a total of 14.11 billion pieces, a year-on-year growth of 16.0% [1]. The demand for e-commerce and urban logistics has surged, so convenient and efficient logistics transportation mode has become a key factor in improving the service level of the logistics industry and the quality of life in the city. Currently, electric vehicles, motorcycles, and small vans have become the primary means of transportation. However, internal urban traffic congestion on the ground is increasing due to accelerated urbanization across China. The speed of transport and distribution of urban logistics could not be guaranteed. One implication is that a reduction in the pressure that urban logistics places on urban areas are highly desirable [2]. One way to mitigate these issues is to use the underground logistics system (ULS) to mitigate the negative impacts of ground transportation [3,4].

Urban underground space in China has grown rapidly in recent years, and the development of underground spaces such as underground and underground complexes is being widely built [5]. The metro system is an important and common component of urban underground transportation, and as such, it has the characteristics of accessibility, punctuality, convenience, economy, and high passenger carrying capacity of most major cities.

Integrating ULS into the modern subway system is seen as an attractive and innovative solution for improving the efficiency of urban logistics transportation and improving logistics reliability [6]. The underground metro logistics system (M-ULS) is based on the excess capacity of the metro system to deliver cargo, which is made up of suppliers, distribution nodes, and requesters; the sketch map is shown in Figure 1. During off-peak periods, the metro system often has a considerable excess capacity, which is used for freight delivery. This can, on the one hand, ensure the security and timeliness of logistics distribution. Conversely, it can improve the level of logistics service and customer satisfaction.

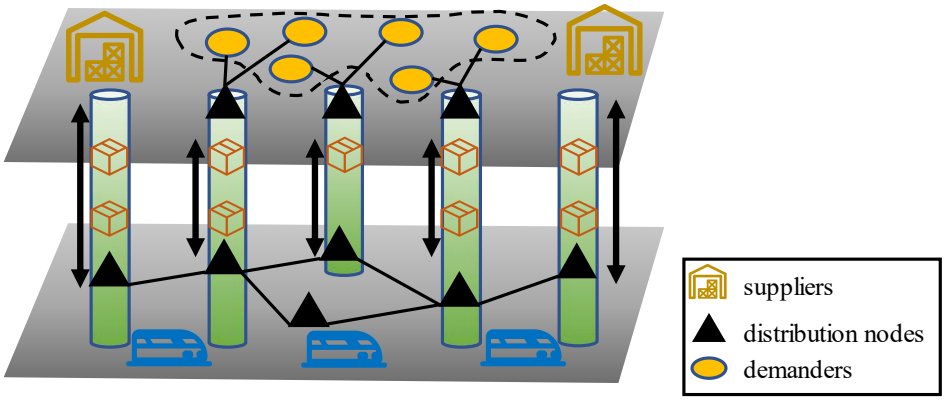

Figure 1. The sketch map of the metro-based underground logistics system.

The choice of the appropriate station as a logistics distribution node is very important in the underground logistics system based on the metro. The location of the system directly affects the total cost of the system and the level of service to customers [7].

In summary, the main contributions of this paper are as follows:

(1) This paper proposes a new bi-level programming model from the supplier and demander perspectives to select optimal nodes from alternative logistics distribution nodes;
(2) We programmed a heuristic algorithm in MATLAB to solve the logistic distribution node location selection model;
(3) Case analysis proves the practicality and feasibility of the proposed model and the efficacy of the methods adopted.

The rest of this paper is organized as follows. Section 2 introduces related work from M-ULS. The third section introduces the search methods, which include model assumption, objective function, and parameter tuning. Then, in Section 4, Nanjing's Metro Line 2 is used as a case study, the optimal logistics distribution nodes are calculated and selected, and insightful analysis and discussion of the results are presented. Section 5 concludes with a summary of the main results and a proposal for the limitation of this study.

2. Literature Review

The modern urban ULS is seen as a vital means of addressing the negative impacts of ground transportation, providing efficient solutions for the delivery of goods in congested urban areas. Numerous innovative concepts and technologies have been proposed, such as applications of drones, package lockers, and mobile depots in local logistics distribution and the development of last-mile delivery [8–11]; electric vehicles (EVs) and urban cluster centers (UCC) in third party logistics operations [12,13]; and buses, taxis, and cargo-bikes in crowd-sourced and shared logistics [14,15]. Most of these measures, however, either rely heavily on roads and labor (e.g., EVs) or suffer from poor system capacity and applicability (e.g., drones and cargo bikes), and there is a consensus that all of the behaviors of road transport use are difficult to substantially ameliorate the negative externalities of freight transport [16]. ULS has important implications for alleviating urban traffic congestion and

promoting urban sustainability [17], and the M-ULS is an important way to solve urban traffic problems with unique benefits [6,18–21].

Currently, the relevant research on M-ULS stays in the theoretical research stage, mainly focusing on system concept and planning, traffic organization, and network operation [22]. Sun et al. proposed an entropy-based fuzzy TOPSIS evaluation model and combined the multi-objective PSO algorithm and A* algorithm, which were developed to optimize the location-allocation-routing (LAR) decisions of the M-ULS network [18]. The feasibility of using the metro system for freight transport is being investigated, and three models of collaborative transport of passengers and goods are proposed by Amsterdam [23]. Dampier and Marinov discussed the feasibility of using a metropolitan rail network to transport goods directly to a city center from surrounding businesses and used the Tyne and Wear metro system as an example of this [24]. Cochrane et al. investigated that passenger train cars were used for the overnight loading of specialized garbage containers in the New York subway system [25]. Kelly and Marinov proposed a new interior design for subway trains, which were used to deliver goods to city centers from surrounding companies [26]. Serafini et al. discussed the feasibility of using the metro to transport e-commerce based on the preferences of the public [27]. Hu et al. proposed innovative concepts for M-ULS prototypes, which made use of knowledge from engineering practice, emergent initiatives, the literature, and experts' views [28].

From the point of view of node layout planning, Masson et al. proposed a mathematical model and adaptive search of large neighborhoods to solve a two-level transportation problem [29]. Dong et al. proposed a set of mixed-integer programming models for solving the optimal node's location allocation (LAP) problem in the M-ULS network. A hybrid algorithm was then designed with a combination of E-TOPSIS, the exact algorithm, and the heuristic algorithm for solving the mixed-integer programming model [6]. Zhao et al. evaluated the importance of each metro station using the TOPSIS model and determined the candidate metro distribution hubs for the location model. Then, considering logistics demand, the final metro distribution hubs were determined from the candidate metro distribution hubs [30]. For example, He et al. constructed a 0–1 mixed integer programming model to minimize the total logistics cost that includes construction, fixed costs, and distribution costs and used the Bat-inspired improved algorithm to find the optimal solution [7]. Zheng et al. adopted the Voronoi diagram to optimize the locations of candidate metro stations and to re-derive the scope of logistics services by adding weighted terms, and the Nanjing subway was selected as a case study to validate the efficacy of the method developed [31].

Screening the previous literature work on M-ULS feasibility and layout planning suggests that further research into feasibility is still needed, and researchers are testing the use of urban metro freight as an effective supplement to the underground logistics transport mode from different perspectives. In the area of node layout planning, researchers propose the optimization model of location selection of logistics nodes by considering different factors for different scales and complexity of the metro network. In contrast to previous studies, however, this paper proposes a bi-level programming model to determine the optimal layout of logistics distribution nodes and minimize the total cost of the provider and requesters in M-ULS. Metro line 2 in Nanjing was chosen as a case study to test the efficacy of the model.

3. Bi-Level Programming Model for M-ULS

3.1. Model Assumptions

In order to ensure that the real abstract problem was transformed into a mathematical model, certain assumptions were made as follows:

- The same distribution node can undertake the logistics requirements of different demanders;

- The competition and influence between the new and old logistic distribution nodes were not considered. M-ULS goods were undertaken only by new logistics distribution nodes;
- The distance and maximum cargo volume from each logistics distribution node to different demanders were known;
- The construction cost of logistics distribution nodes and the cost of managing goods were known.

3.2. Upper-Level Model Construction

The goal of building the Upper-Level programming model was to help providers design an optimal location scheme of logistics distribution nodes with the lowest total cost and the highest quality of service under fixed investment cost.

3.2.1. Variables Definition

The relevant variables of the Upper-Level programming model are defined in Table 1.

Table 1. The definition of Upper-Level Model variables.

Parameters	Definition
l	the number of suppliers
n	the number of alternative logistics distribution nodes
m	the number of demanders
x_{ki}	the volume of the goods from supplier k to logistics distribution node i
p_{ki}	the unit transportation cost of goods from supplier k to logistics distribution node i
d_{ki}	the distance from supplier k to logistics distribution node i
x_{ij}	The volume of the goods from logistics distribution node i to demander j
p_{ij}	the unit transportation cost of goods from logistics distribution node i to demander j
d_{ij}	the distance from logistics distribution node i to demander j
f_i	the fixed construction cost of the logistics distribution node i
c_i	the management and storage cost of logistics distribution node i
B	the total investment budget of the logistics distribution nodes, set to 20 million yuan
S_i	the maximum capacity of the logistics distribution node i
A_k	the maximum supply capacity of the supplier k
Decision Variables	**Definition**
Z_i	1 when the logistics distribution node i is selected, or 0 otherwise.
Y_j	1 when the requirement of demander j is selected, or 0 otherwise

3.2.2. Objective Function

The mathematical formulation of the Upper-Level programming model for the logistics distribution node is defined by the objective function as Equation (1), and it is an objective function designed to minimize the sum cost from the point of view of the decision makers. This includes the cost of transport from supplier to logistics distribution nodes; the cost of delivering logistics distribution nodes to demanders; and the cost of constructing, managing, and storing logistics distribution nodes [32].

$$U : \min F = \sum_{k=1}^{l}\sum_{i=1}^{n} x_{ki}p_{ki}d_{ki}Z_i + \sum_{i=1}^{n}\sum_{j=1}^{m} x_{ij}p_{ij}d_{ij}Y_j + \sum_{i=1}^{n} f_iZ_i + \sum_{k=1}^{l}\sum_{i=1}^{n} c_ix_{ki} \tag{1}$$

3.2.3. Constraints

The constraints for the Upper-Level programming model are summarized below:

$$\sum_{i=1}^{n} f_iZ_i \leq B \tag{2}$$

$$\sum_{k=1}^{l} x_{ki} \leq S_i i = 1, 2, \ldots, n \tag{3}$$

$$\sum_{i=1}^{n} x_{ki} \leq A_k k = 1, 2, \ldots, l \tag{4}$$

$$Z_i \in \{0, 1\}, \forall i \tag{5}$$

$$Y_j \in \{0, 1\}, \forall j \tag{6}$$

Equation (2) represents the construction cost of the logistics distribution node does not exceed the budget;

Equation (3) guarantees that the accumulation of goods in the logistics distribution node i will not exceed its capacity;

Equation (4) ensures that the volume of goods supplied by the supplier to the logistics distribution node does not exceed its maximum capacity;

Equations (5) and (6) define the binary decision variables.

3.3. Lower-Level Model Construction

When applying the principle of symmetry, the Lower-Level programming model is symmetrical with the Upper-Level programming model. The goal of building the Lower-Level programming model was to minimize the cost of the requestors. The model reflects demanders' selection behavior for logistics distribution nodes and provides a scientific basis for determining the location and scale of logistics distribution nodes.

3.3.1. Variables Definition

The relevant variables of the Lower-Level programming model are defined in Table 2:

Table 2. The definition of Lower-Level Model variables.

Parameters	Definition
u_{ij}	the minimum cost for demander j to select the logistics distribution node i
n	the number of alternative logistics distribution nodes
m	the number of demanders
x_{ij}	the volume of goods from logistics distribution node i to demander j
W_j	the sum requirements of demander j
S_i	the maximum capacity of the logistics distribution node i
ε	Enough small positive numbers, set to 0.1
M	Enough big positive numbers, set to 800
β	The correction coefficient, set to 1 [33]
v_i	The utility coefficient of distribution node i
Decision Variables	**Definition**
Z_i	1 when the logistics distribution node i is selected, or 0 otherwise.

3.3.2. Objective Function

In the Lower-Level programming model, the demand function Equation (7) is usually in the form of an exponential function [34], and its inverse function is introduced to describe the impact of logistics requirements on the location of logistics distribution nodes. The objective function is Equation (8) as follows:

$$\begin{aligned} x_{ij} &= Q_{ij}(u_{ij}) = A_w \exp(u_{ij}/B_w) \\ A_w &= \exp(v_i Z_i/\beta) \\ B_w &= \beta \end{aligned} \tag{7}$$

$$L : \min T = \sum_{i=1}^{n} \sum_{j=1}^{m} \int_0^{x_{ij}} Q^{-1}(\omega) d\omega \tag{8}$$

$$Q^{-1}(\cdot) = \beta \ln x_{ij} - v_i Z_i \tag{9}$$

3.3.3. Constraints

The constraints for Lower-Level programming model are summarized below:

$$\sum_{i=1}^{n} x_{ij} \geq W_j \; \forall j = 1, 2, \cdots, m \tag{10}$$

$$\sum_{j=1}^{m} x_{ij} \leq S_i \; \forall i = 1, 2, \ldots, n \tag{11}$$

$$Q^{-1}(x_{ij}) \geq 0 \tag{12}$$

$$\varepsilon Z_i \leq x_{ij} \leq M Z_i \tag{13}$$

$$x_{ij} \geq 0 \tag{14}$$

Equation (10) represents the requirement of demander *j* can be satisfied in any case;

Equation (11) ensures that the accumulation of goods at logistics distribution node *i* will not exceed its capacity;

Equation (12) shows that the minimum cost to demander *j* of selecting logistics distribution node *i* is nonzero;

Equations (13) and (14) specify the extent of the volume of goods from logistics distribution node *i* to demander *j*.

3.4. Model Calculation

For solving the layout models of logistics distribution nodes presented in the previous section, in this paper, we adopted a heuristic algorithm with relatively fast convergence and optimality. The basic rules of the algorithm are:

Based on the analysis of the Lower-Level programming model, the decision variable Z_i ensures that Equation (13) satisfies the condition in all cases. Hence, Equation (13) is transformed to the following form to yield the reaction function.

$$x_{ij} = M Z_i - e_{ij} i = 1, 2, \cdots, n \; j = 1, 2, \ldots, m \tag{15}$$

where e_{ij} is the slack variable.

The transport volume x^*_{ij} can be obtained from the alternative logistics distribution nodes to the demanders in equilibrium by computing the Lower-Level programming model. We then substituted x^*_{ij} into Equation (15) in order to compute the slack variable e^*_{ij}.

The reaction function is simultaneous:

$$x^*_{ij} = M Z_i - e^*_{ij} i = 1, 2, \cdots, n \; j = 1, 2, \ldots, m \tag{16}$$

Given the two steps above, Equation (16) is substituted into the Upper-Level programming model, and the optimal solution is found. The volume of goods allocated by the alternative logistics distribution nodes can then be obtained by re-computing the Lower-Level programming model.

The calculation process of the logistics distribution nodes selection is as follows:

Step 1: In the Lower-Level programming model, the inverse of the demand function is transformed into a non-linear polynomial:

$$\begin{aligned} L : \min T &= \sum_{i=1}^{n} \sum_{j=1}^{m} \int_0^{x_{ij}} Q^{-1}(\omega) d\omega = \sum_{i=1}^{n} \sum_{j=1}^{m} \int_0^{x_{ij}} \beta \ln \omega - v_i Z_i d\omega \\ &= \sum_{i=1}^{n} \sum_{j=1}^{m} \left[x_{ij} \left(\beta \ln x_{ij} - v_i Z_i \right) - \beta \right] \end{aligned} \tag{17}$$

Define z_i^k = (Z_1, Z_2, Z_3, Z_4, Z_5, Z_6, Z_7, Z_8, Z_9), when the logistics distribution node *i* is selected, Z_i = 1; otherwise, Z_i = 0, and *k* is a counter;

Step2: Model initialization and setting z_i^0 = (1,1,1,1,1,1,1,1), k = 0;

Step3: z_i^k is substituted into the Lower-Level programming model to solve the volume of the goods allocated x_{ij}^k by each node of the alternative logistics distribution;

Step4: x_{ij}^k is substituted into the Upper-Level programming model in order to solve for the location of the new logistics distribution node z_i^{k+1}, and the objective function of the Upper-Level programming model is *min F*, so the corresponding total cost for the $k + 1$ time is F^{k+1}.

Step5: Verify outcomes. If $F^{k+1} - F^k \leq \alpha$ are not satisfied, let $k = k + 1$ and replace it in Step3. The iteration is complete until the result is stable, α for iterative accuracy is set to 0.1 [33].

The specific calculation steps are shown in Figure 2.

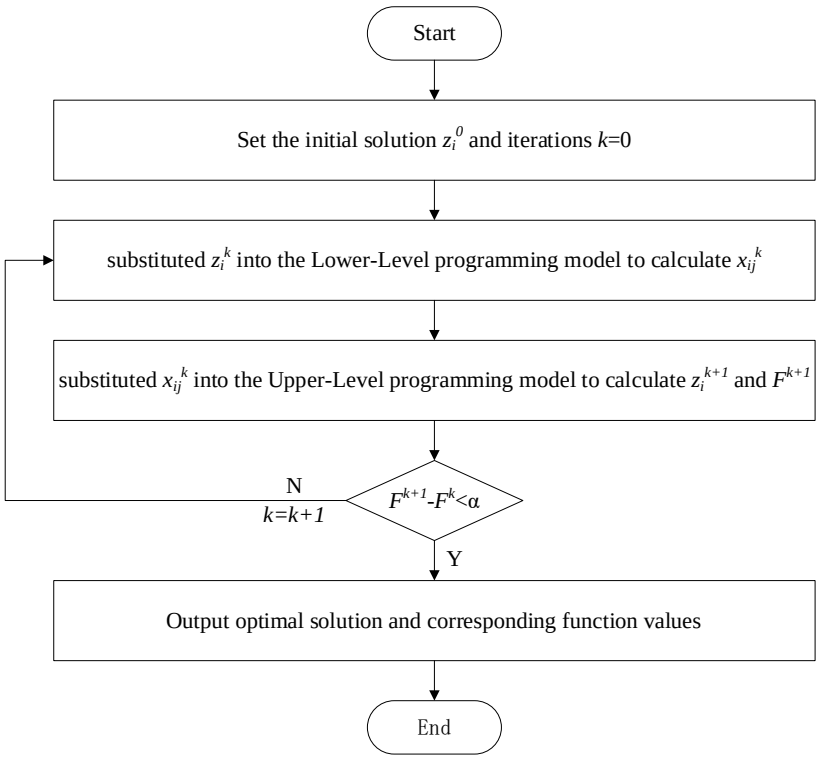

Figure 2. Flow chart of calculating bi-level programming model.

4. Case Study: Logistics Distribution Nodes Selection Based on Nanjing Metro Network

In order to test the effectiveness and practicality of the model, Nanjing's Metro Line 2 was selected as a case study that selects optimal logistics distribution nodes [35].

Metro Line 2 bisects the east–west axis of Nanjing's main urban area, with an overall length of 37.93 km. The spatial distribution of Metro Line 2 stations and the logistics park within the study area is shown in Figure 3.

This line has 26 stations. By taking into account the influences of geographic location, development, and cost, nine stations were selected as alternative logistics distribution nodes, which include Jingtianlu station (No.1), Xianlinzhongxin station (No.2), Zhonglingjie station (No.3), Muxuyuan station (No.4), Xinjiekou station (No.5), Mochouhu station (No.6), Xinglongdajie station (No.7), Yuantong station (No.8) and Youfangqiao station (No.9), as shown in Figure 3. The basic information on alternative logistics distribution nodes is shown in Table 3.

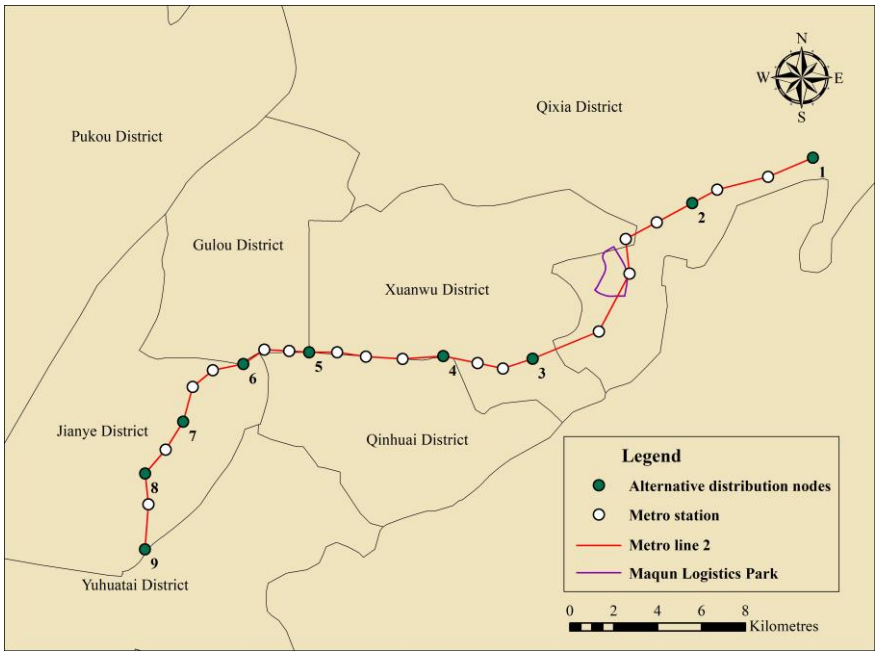

Figure 3. The spatial distribution of metro line 2 stations, alternative distribution nodes, and logistics park.

Table 3. The Basic Information of Alternative Logistics Distribution Nodes.

Node Number	Station	Station Coordinate	Station Scale (m^2)
1	Jingtianlu	118.9714802, 32.11826558	5162
2	Xianlinzhongxin	118.9253611, 32.10087312	5111
3	Zhonglingjie	118.8643526, 32.04134058	10,455
4	Muxuyuan	118.8302058, 32.04237866	11,015.5
5	Xinjiekou	118.7789346, 32.04386025	39,508.27
6	Mochouhu	118.7537415, 32.03933986	12,745
7	Xinglongdajie	118.7307263, 32.0173144	12,377
8	Yuantong	118.716248, 31.9975094	12,982.12
9	Youfangqiao	118.7161628, 31.96848578	5686

The impact of each alternative logistics distribution node on the transportation cost of delivered goods, construction costs, unit storage, and management costs should be taken into account in order to achieve the ultimate objective of the lowest total cost. The unit transport cost from the alternative logistics distribution nodes to the demanders is shown in Table 4. Table 5 shows the distance from each alternative logistics distribution node to the demanders. The capacity, utility coefficient, and cost of alternative logistics distribution nodes are shown in Table 6. In addition, considering the residential groups, geographical conditions, economic conditions, and ground transportation in the vicinity of metro line 2; combined with the actual situation in Nanjing, China, 1 provider and 19 requesters were also selected. The Maqun logistics park is responsible for the provision of goods; it is located in the middle section of Metro Line 2 and covers an area of 45,000 km^2. Provider details are shown in Table 7.

Table 4. The Unit Transportation Cost from Alternative Logistics Distribution Nodes to Demanders (yuan/km/ton).

Demander Number	Node Number								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	8	8	8.5	9	10	10.5	11	11	10.5
2	7	8	8.5	9.5	10	10.5	11	11.5	10.5
3	8	7.5	8.5	9.5	11	11	11	10.5	10
4	8	6	8	9.5	10.5	10.5	11.5	11	10
5	7	7.5	9	10	11	11	11	10.5	10
6	7	7.5	10	10	11	12	11	10	9.5
7	8	7	10	10	11	12	10.5	10	9.5
8	8	7	10	10.5	11	11	10.5	9.5	9
9	7	7	10	10.5	11	11	10.5	9	9.5
10	8	8	11	11	10.5	10.5	10	9.5	8.5
11	8.5	8	11	11	11	10.5	10	9.5	8.5
12	9	8.5	11	11	11	10	10	9	8
13	8	8	10	10.5	11	10	10	9	8
14	9	8.5	11	11	11	10	10	9	8
15	9.5	8	10.5	11	10	9.5	9	8.5	8.5
16	10	8.5	10.5	10.5	10	9	8.5	8	8
17	10	9	10	9	9.5	8.5	7.5	7	7
18	11	9.5	8.5	8	8	8	7	7	7
19	10	10	8	8	8	8	7.5	7	7

Table 5. The Distance from Alternative Logistics Distribution Nodes to Demanders (km).

Demander Number	Node Number								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	34	38	21	18	10	7.5	4.3	3	6.6
2	35	39	22	19	10	7.4	3.4	1.5	6.4
3	36	40	22	19	6	3.3	2.3	5.5	8.9
4	36	41	23	20	8.4	5.4	1.5	3.5	8.4
5	30	34	14	11	4.8	1.7	2.8	6.5	10
6	29	32	12	10	3.4	1.2	4.3	8.1	12
7	30	33	13	11	4.2	1.7	5	8.8	12
8	30	32	11	9.8	2.3	3.7	7.9	12	15
9	27	31	11	9	1.9	2.2	6.1	9.9	13
10	24	28	7	5.6	4	6.7	11	15	17
11	23	27	6.8	4.8	3.4	6.1	10	14	16
12	21	25	4.3	1.1	6.2	8.6	13	17	18
13	29	27	6.2	7.6	5.7	8	13	17	19
14	20	23	3.3	2.6	6.7	9.1	13	17	19
15	17	21	5.3	5	9.9	12	15	19	19
16	14	18	5	7.6	13	16	19	22	24
17	2.4	14	13	18	18	20	34	38	39
18	1	13	18	21	25	27	33	37	38
19	3.7	7	17	20	24	26	32	36	37

Table 6. Description of Related Information for Alternative Logistics Distribution Nodes.

Items		The Maximum Loading Capacity	The Utility Coefficient	Default Investment Fees	Unit Storage and Management Fees
Symbol		S_i	v_i	f_i	c_i
Unit		10,000 tons	/	10,000 yuan	yuan/ton
Logistics Distribution Nodes Number	1	60	1.2	200	1
	2	60	2	100	1
	3	120	3	150	0.85
	4	150	1.5	250	0.8
	5	200	2	250	0.65
	6	150	1.3	250	0.75
	7	150	1.5	250	0.75
	8	100	2	200	0.8
	9	60	2	150	0.9

Table 7. Description of Related Information for Supplier.

Items	The Supply Capacity		The Volume from Supplier to Logistics Distribution Nodes	The Distance from Supplier to Logistics Distribution Nodes	The Unit Transportation Costs from Supplier to Logistics Distribution Nodes
Symbol	A_k		x_{ki}	d_{ki}	p_{ki}
Unit	10,000 tons		10,000 tons	km	yuan/km/ton
Values	600		/	/	/
	Logistics Distribution Nodes Number	1	50	10.2	5.5
		2	60	5.4	6
		3	50	6.6	7
		4	65	10	6.5
		5	100	14.8	6.5
		6	66	17.4	6
		7	55	21.5	5.5
		8	60	24.1	5.5
		9	45	28.4	5

Calculation Results and Discussion

Table 8 and Figure 4 can be used to see the iterative process of solving the model; we conclude that the selection of logistics distribution nodes is more prone to node reduction. The total cost at the beginning of the model iteration decreases rapidly as the number of iterations increases. Since the number of logistics distribution nodes is decreasing and the model quickly selects unfavorable nodes with too high a transport cost to each requester.

Table 8. Iterative Process of Model Solving.

Iterations	Goods Volume of Logistics Distribution Nodes x_{ij}	Location of Logistics Distribution Nodes zi
1	(15,40,20,35,72,50,47,35,0)	(1,1,1,1,1,1,1,1,0)
2	(0,40,45,40,82,50,47,35,0)	(0,1,1,1,1,1,1,1,0)
3	(0,55,40,30,82,50,45,35,0)	(0,1,1,1,1,1,1,1,0)
4	(35,40,35,51,0,66,52,60,0)	(1,1,0,1,1,1,1,1,0)
5	(35,40,35,25,92,0,52,60,0)	(1,1,0,1,1,1,1,1,0)
...	...	...
135	(0,55,0,65,87,50,47,35,0)	(0,1,0,1,1,1,1,1,0)
136	(0,55,0,65,87,50,47,35,0)	(0,1,0,1,1,1,1,1,0)

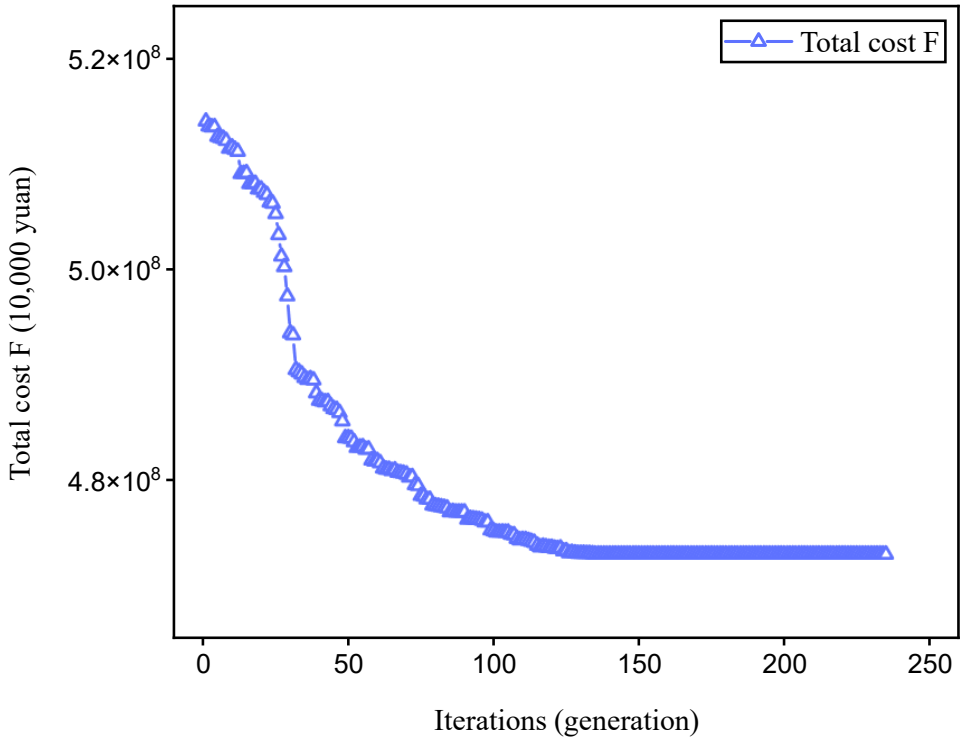

Figure 4. The iterative process of solving the model.

On the other hand, when the number of logistic distribution nodes is six and the iterations are 135th generation, the cost of construction and operation of logistics distribution nodes starts to level off and eventually reaches the minimum. The location of the logistic distribution node after the 135th iteration is $z_i^{135} = z_i^{136}$ = (0,1,0,1,1,1,1,1,0). Thus, the optimal logistics distribution node is whichever satisfies the demands of each requester and minimizes the cost of M-ULS. Lastly, z_2, z_4, z_5, z_6, z_7, and z_8 were chosen as the nodes of the optimal logistics distribution among the nine alternative nodes, and the corresponding stations are Xianlinzhongxin station, Muxuyuan station, Xinjiekou station, Mochouhu station, Xinglongdajie station and Yuantong station, as shown in Figure 5. The total cost of the project amounts to 473,012,580 yuan. Similarly, Table 9 shows that the volume of goods allocated by each node of the optimal logistics distribution is 550,000, 650,000, 870,000, 500,000, 470,000, and 350,000 tonnes, respectively. This can be seen in Table 9; the logistics load capacity of some of the logistics distribution nodes is much larger than that of the others. This is mainly due to the fact that these nodes have a significant operating cost advantage; although their construction cost is higher than the other nodes, the lower unit cost of freight and storage still makes them better than other alternative nodes.

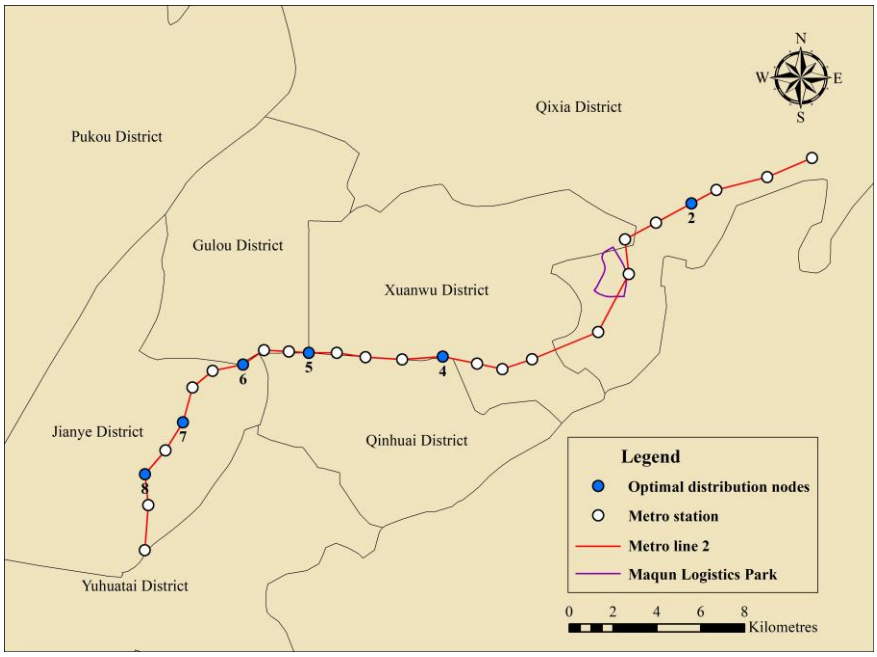

Figure 5. The iterative process of solving the model.

Table 9. The Optimal Logistics Distribution Nodes in M-ULS.

Node Number	Optimal Logistics Distribution Node	Goods Delivered Volume/10,000 tons
2	Xianlinzhongxin station	55
4	Muxuyuan station	65
5	Xinjiekou station	87
6	Mochouhu station	50
7	Xinglongdajie station	47
8	Yuntong station	35

5. Conclusions

In this paper, we innovatively considered using the metro's excess capacity to perform logistics transport by selecting suitable metro station points to act as distribution nodes in order to achieve more economical and efficient freight transport. Based on the symmetry principle, this paper constructed a novel bi-level programming model in which the objective function takes into account the minimum total investment cost of logistics operation of logistics suppliers and the minimum cost of personal services on the demand side of logistics. The location model of the logistics distribution nodes with the lowest total cost was then built, using the fmincon function in MATLAB software to solve the model results in the optimal model output. Finally, by using Nanjing's Metro Line 2 as a case study for selecting optimal logistics distribution nodes, the results of the case indicate that it is possible to deliver goods from logistics distribution nodes to demanders using the excess capacity of the metro, and the proposed bi-level programming model for M-ULS can be used to select suitable metro stations as distribution nodes and achieve the lowest cost on both the supply and demand sides of logistics while still ensuring the green and efficient transport of logistics services.

There are, however, several limitations to the present study. The first step was to select a single metro line. Further investigation of the complex metro system with multiple lines is required to further verify the applicability and reliability of the model. Secondly, this paper did not consider the competitive relationship between the new and old logistics distribution nodes. Competitiveness can have some impact on the service level of logistics distribution nodes. Thus, there is also a need to focus on this problem in the future.

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