

Article

Optimization of Metro-Based Underground Logistics Network Based on Bi-Level Programming Model: A Case Study of Beijing

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Abstract

Characterized by zero-carbon, congestion-free, and high-capacity features, the utilization of metro systems for collaborative passenger-and-freight transport (the metro-based underground logistics system, M-ULS) has been recognized as a favorable alternative to facilitate automated freight transport in future megacities. This article constructs a three-echelon M-ULS network and establishes a multi-objective bilevel programming model, considering the interests of both government investment departments and transport enterprises. The overall goal of the study is to establish a transportation network with the lowest construction cost, lowest operating cost, and highest facility utilization rate, taking into account factors such as population density, transportation conditions, land resources, logistics demand, and metro station location, under given cost parameters and demand conditions. The upper-level model takes government investment as the main body and aims to minimize the total cost, establishing an optimization model for location selection allocation paths with capacity constraints; the lower-level model aims to minimize the generalized cost for freight enterprises by simulating the competition between traditional transportation and the M-ULS mode. In addition, a bi-level programming model solving framework was established, and a multi-stage precise heuristic hybrid algorithm based on adaptive immune clone selection algorithm (AICSA) and improved plant growth simulation algorithm (IPGSA) is designed for the upper-level model. Finally, taking the central urban area of Beijing as an example, four network scales are set up for numerical simulation research to verify the reliability and superiority of the model and algorithm. By analyzing and setting key indicators, an optimal network configuration scheme is proposed, providing a feasible path for cities to improve logistics efficiency and reduce the impact of logistics externalities under limited land resources, further strengthening the strategic role of subway logistics systems in urban sustainable development.

Keywords: metro-based underground logistics system (M-ULS); network planning; bi-level programming; multi-objective optimization; case study



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1. Introduction

Today's urban freight faces multiple challenges, not only to meet customers' personalized logistics service requirements and to alleviate the negative externality of freight, but also to seek more effective and safe logistics transportation methods during disasters. The concept of underground logistics systems provides new inspiration and opportunities for solving the urban freight dilemma [1]. A variety of technical prototypes have been proposed for ULS; however, it has some defects, such as high investment risk and difficult

construction, which makes project construction difficult to advance [2,3]. In contrast, a much cheaper alternative, the M-ULS, has been recognized as having better operation effect [4,5]. The initiatives of M-ULS aim to use existing or newly built urban metro systems to realize shared passenger-and-freight transport [6,7]. More and more cities have carried out the pilot work of metro freight transportation. Figure 1 shows the operation cases of Dresden, Sapporo, China, Beijing and Wuxi, respectively.



Figure 1. The case of metro freight operation.

Aiming at realizing wide-range, high-capacity underground freight transport, scholars have designed a variety of transportation organization modes, and carried out a great deal of research on network operation. The research focuses on multiple aspects, such as facility location selection, path optimization, and cargo flow allocation. Zhao et al. [8] and Zheng et al. [9], respectively, used the TOPSIS model and p-median model to study the site selection of metro stations for the M-ULS network. Zhao et al. [10] considered a combination optimization model for facility location and path selection and designed a greedy random adaptive search algorithm to solve the problem. Ren et al. [11] further expanded the network optimization problem. They designed a double-layer hub and spoke network for M-ULS and then, considering facility capacity constraints, proposed a location-allocation-routing combinatorial model with construction and operation costs objectives. On the basis of Ren et al. [11], respectively, considered the optimal network layout schemes based on deterministic requirements and fuzzy stochastic requirements, and compared the two schemes.

The above literature all starts with the perspective of environmental benefits in building M-ULS, and conducts optimization research with the goal of minimizing costs or

maximizing facility utilization. However, they only considered the structure and layout of the network from a static perspective and ignored the competitive relationship between M-ULS as a new transportation mode and traditional transportation modes; that is, they ignored the shipper's choice between the two modes.

Therefore, in the process of network optimization, this article considers the impact of shipper selection on network layout, and summarizes the main contributions of this study as follows:

- (1) We consider the holistic planning and optimization of an intermodal three-echelon M-ULS network concept that combines existing metro lines, newly built freight dedicated lines and underground pipelines for realizing city-wide underground goods movement. In addition, we emphasize not only the establishment and functional renovation of diverse fixed network facilities but also a variety of delivery modes from the freight station to the distribution terminal.
- (2) In order to evaluate the comprehensive benefits of M-ULS reasonably, we designed four evaluation indexes to evaluate the demand, traffic situation, distribution response requirements and logistics operation ability of each terminal distribution station, respectively. Then we comprehensively evaluated the site by E-TOSIS to determine the corresponding network scale under different comprehensive benefits.
- (3) Fully considering the competitive relationship between M-ULS and traditional transportation modes, we have established a multi-objective bilevel programming model with minimum government investment and minimum shipper's generalized cost, which provides a more systematic and comprehensive optimization method and solution algorithm for the location, distribution and path planning of integrated transportation networks and a decision-making scheme for determining the optimal network size with economic benefits.

2. Three-Echelon M-ULS Network Architecture

Urban underground comprehensive transportation network refers to the construction of a fast, clean, high-capacity, and networked urban passenger and freight comprehensive transportation rail transit network on fully enclosed lines using urban underground space. This network is built upon the backbone of the existing subway system and forms an interactive transportation network based on actual freight demand, integrating infrastructure layout and customer routing choices. The main concept of its network planning is to combine the city's existing logistics facilities with the subway network, establish corresponding logistics nodes according to regional logistics demand, balance the interests of both construction and operation parties, and carry out optimization of the transportation network structure as well as route planning between nodes. The structure characteristics of the urban underground comprehensive transportation network proposed in this article can be described using the paradigm of "four-level nodes and three-echelon networks". Four-level nodes include: large comprehensive logistics parks in the outskirts of the city, underground transfer stations, underground freight stations, and terminal points; three-echelon networks consist of rail transportation trunk lines, rail transportation branch lines, and terminal distribution lines. The network hierarchy is shown in Figure 2.

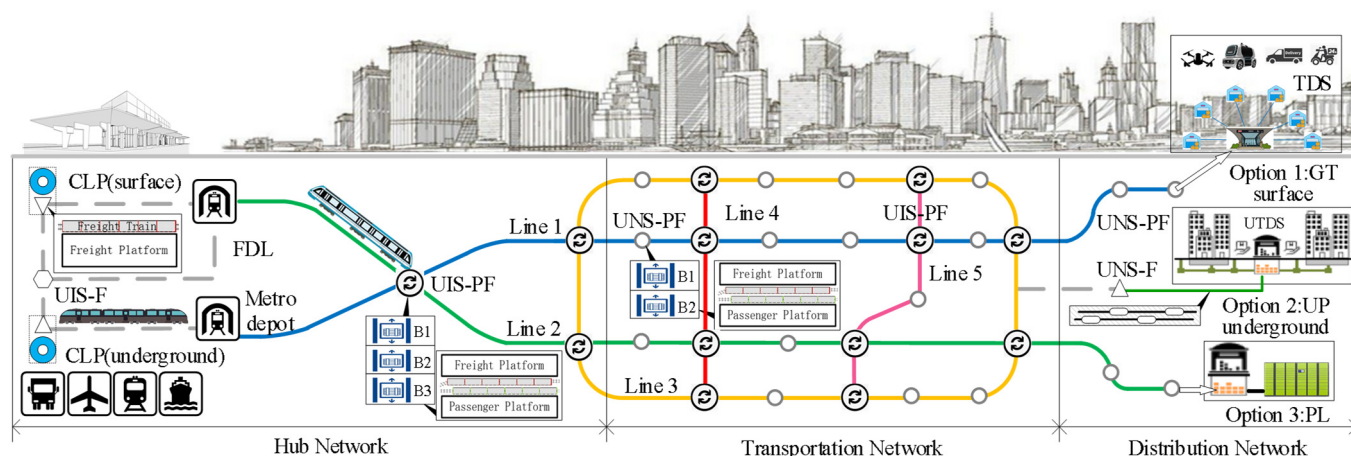


Figure 2. Schematic diagram of comprehensive transportation network structure.

The definition and function summary of the four-level nodes in the network are as follows:

(1) First-level node: Comprehensive Logistics Park (CLP)

The first-level node is the highest-level node of the urban logistics infrastructure network, connecting the logistics hub facilities inside and outside the city, and serving as the exchange point between trunk transportation and logistics within the city. Mainly responsible for the logistics distribution of cargo from other ports and the urban area and providing suitable underground transportation pallets or standardized units for the city's internal transfer centers, achieving functions such as sorting, packaging, temporary storage, and transportation. In addition to traditional logistics functions, the park should also set up a parking lot to provide a workplace for train scheduling, maintenance, departure, etc., so that freight trains can enter the underground network. Its location is mainly located at the end points of aviation, railways, highways, and integrated logistics warehouses on the outskirts of the city.

(2) Secondary node: Urban Underground Interchange Station (UIS)

The second-level node is an underground first-level node within the city that has independent freight platforms and transfer functions, connecting the CLP with the transportation terminal station. According to the nature of the stations, underground transfer stations can be divided into two categories: independent freight interchange stations (UIS-F) and integrated passenger and freight interchange stations (UIS-PF). The main task undertaken is to provide logistics operation chain services such as sorting and packaging, rapid transfer and distribution, and short-term storage.

(3) Third-level node: Urban Underground Non-transfer Station (UNS)

The third-level node is the terminal station for completing underground rail transportation, connecting with the terminal distribution station. The cargo is delivered to the user through underground capsule pipelines or other ground transportation methods at the station, completing the delivery. According to the nature of the stations, underground freight stations can be divided into two categories: Underground Non-transfer Station for Freight (UNS-F) and Underground Non-transfer Station for passenger and freight (UNS-PF). UNS-PF can be divided into independent freight platform stations and shared platform stations based on whether they have independent freight platforms.

(4) Fourth-level node: Terminal Delivery Station (TDS)

The fourth-level node is the lowest-level node of the urban logistics infrastructure network, directly connected to customers, and reasonably arranged in major demand areas

such as communities, universities, large commercial areas, and large public buildings according to a certain number of service population standards. Its main tasks include receiving and sending, tallying, storing, picking up, and delivering. In areas with appropriate conditions, underground terminal delivery stations (UTDS) should be set up in conjunction with underground pipe galleries to reduce traffic interference caused by road operations. Setting up traditional ground delivery stations (STDS) in unconditional areas is sufficient.

It is clarified that nodes are graded according to their functions. In the actual layout of the site, there may be overlaps between different levels of site locations, but this does not affect the level of the site. For example, a third-level UNS may also be a fourth-level TDS, so this station must have all the functions of underground transportation and distribution.

The definition and function summary of the three-echelon network are as follows:

(1) First tier: hub network

The primary hub network is connected by the main rail transportation line to large CLPs and UIs, responsible for the transportation of cargo inside and outside the city, as well as the allocation of cargo within the urban area. The cargo is packaged in the CLP and transported by the main transportation line to the UI, achieving the exchange of cargo inside and outside the city; cargo between different urban areas is collected through UI, achieving the exchange of cargo between urban areas.

(2) Second tier: transportation network

The cargo packaged through the UI is directly allocated to the carrying trains and transported by the rail transport branch line to the destination station. Loose packages have been pre-classified and pre-packaged at the final destination distribution station or UI, and cargo in the secondary transportation network does not require secondary packaging.

(3) Third tier: distribution network

Cargo transported to UNS can be delivered to customers in two ways. One method is to lift cargo from underground networks to the ground and deliver them through Ground Transportation (GT) tools or Parcel Lockers (PL); Another method is to transport cargo directly from UNS to UTDS through short distance, small diameter underground capsule pipelines (UP).

According to Figure 2, the comprehensive transportation network proposed in this paper has independent freight stations and transfer stations. Therefore, compared to the metro transportation network proposed by other scholars, this network is not simply using existing urban rail transit infrastructure to carry out urban freight value-added services without interfering with urban passenger transportation. Instead, freight transportation also has a certain degree of autonomy. In terms of infrastructure construction and use, passenger transportation and freight transportation have both special independence and deep sharing.

The specialized independence of freight transportation is reflected in:

- (1) Independent freight stations can be set up in locations with high demand for freight transportation.
- (2) Freight dedicated tracks can be laid or freight dedicated lines (FDL) can be opened between stations with frequent freight traffic.
- (3) Freight dedicated time slots can be set on tracks shared by passengers and freight based on the volume of passenger and freight transportation.

The deep sharing of passenger and freight transportation is reflected in:

- (1) Urban metro stations can strengthen the comprehensive transportation function of passengers and freight (shared stations).

- (2) Shared underground mainline tracks for passenger and freight transportation (shared tracks).
- (3) A combination of passenger and freight trains operated during low peak passenger traffic (shared trains).

3. Problem Description

To achieve the construction of the three-echelon M-ULS network, the objectives and considerations of the model are summarized as follows. The overall goal of the model is to establish a multi-objective bi-level programming model with the lowest construction cost, lowest operating cost, and highest facility utilization under established cost parameters and requirements, taking into account the capacity constraints of underground facilities and shipper preferences as well as the factors of population density, traffic conditions, land resources, logistics demand and metro station (MS) location.

To facilitate modeling, the following assumptions are respected:

- (1) All CLPs are connected to at least one metro line.
- (2) The FDL tunnel is a single hole with two-tracks and is laid directly below the ground road.
- (3) All metro interchange stations support freight transfer by default.
- (4) Only considering the capacity limitations of stations, without considering the capacity limitations of freight flow in the local railway network.
- (5) The capacity-related parameters of M-ULS network facilities are homogeneous, that is, (i) all UNSs and UISs have the same handling and inventory capacity; (ii) all UISs have the same transfer capacity; (iii) all FDLs and UPs have the same transport capacity; (iv) regardless of capacity limitations of freight in the metro tunnel.
- (6) Goods passing through UTDS must be transported through M-ULS networks.
- (7) There is a waiting time for downloading and scheduling, and additional storage costs are required when goods are transported through M-ULS.
- (8) The shipper chooses the transportation method with the minimum cost between M-ULS and traditional road transportation methods.

Based on the above assumptions, this model aims to optimize four sorts of decisions:

- (1) Network scale: Determine the number of UTDS at a certain level of expected benefits.
- (2) Location selection: Determine the location of UNS for the second-tier network.
- (3) Allocation: Determine the subordinate relationship between UNS and TDS.
- (4) Path: For the third-tier network, determine the UP between the UNS and UTDS; for the second-tier network, determine the FDL between UNS-F and existing metro lines; for freight demand, determine the cargo transportation route from CLP to the TDS in the three-echelon network.
- (5) Shipper's Choice: Choose the transport mode with the lowest generalized cost between M-ULS network and traditional road transport mode.

4. Model Development

In order to solve the above problems, a multi-stage and multi-objective bi-level programming model is established. Using the bi-level programming model interactive iterative relationship between top-down decision control and bottom-up response feedback in the hierarchical relationship, the interests of both government investment departments and cargo shippers can be taken into account at the same time. The model design inspiration is summarized as follows.

The decision-makers of the upper-level model are government construction departments. The upper-level model aims to optimize the system, taking into account factors such as urban logistics demand, population density, transportation conditions, land resources,

environmental protection, and metro station location. It optimizes the location, capacity configuration, cargo flow allocation, and transportation paths between logistics nodes at different levels of the city. In order to achieve sustainable development of the integrated transportation network, it is necessary to determine the network scale based on the expected environmental benefits; that is, to screen and determine the shared urban logistics needs based on the comprehensive improvement of urban traffic conditions, ground resources, and other environmental benefits of the integrated transportation network, then minimize the total cost of network construction and operation while ensuring the corresponding logistics needs. In addition, as a high investment operating system, it is significant to impose certain penalties on the comprehensive transportation network when the network construction capacity exceeds the actual usage capacity to avoid the situation of excess network transportation capacity.

The decision-maker of the lower-level model is the shipper. The lower-level model assumes that all shippers will choose the transport mode with the minimum transportation cost between M-ULS mode and traditional road transport mode, that is, the objective function is to minimize the transportation cost of shippers given the M-ULS transportation network. The objective function of the lower-level model is also a constraint condition of the global model. Through the interaction and iteration between the upper and lower-level models, the transportation network layout form that maximizes the interests of both parties is sought.

The following notations in Table 1 are utilized for mathematical equations.

Table 1. Explanation of Mathematical equation notations.

Symbol	Definition
Indices	
I	set of TDSs, including set of UTDSs I_1 and set of STDSs I_2 , $i \in [1, I]$
J	set of UNSs, including virtual UNS-F J_1 and existing metro station $J_2 = I_1$, $j \in [1, J]$
R	set of UISs, $r \in [1, R] \subseteq J$
K	set of CLPs, $k \in [1, K]$
S	set of urban road segments, $s \in [1, S]$
P	set of metro line segments between any two adjacent stations, $p \in [1, P]$
$A(j)$	set of TDSs covered by UNS j
$B(i)$	set of UNSs covering TDS i
Parameters	
d_{ik}	freight demand between CLP k and TDS i
c_a	unit penalty cost for low operation of UIS or UNS
c_b	unit construction cost of underground freight dedicated line
c_c	fixed cost of constructing UIS-F or UNS-F
c_d	unit construction cost of UP
c_e	fixed cost of constructing UTDS
c_f	fixed cost of converting metro stations into UIS-PF or UNS-PF
c_p	unit cost of cargo transport on underground sections
c_j	unit cost of cargo loading and unloading
c_s	unit cost of cargo transport on ground road sections
c_r	unit transfer cost of cargo
c_m	unit storage cost of cargo
c_w	unit cost of cargo waiting time
w_{ik}	Waiting time of cargo
cap_s	freight dedicated line transportation capacity

Table 1. Cont.

Symbol	Definition
cap_j	operation and storage capacity of UIS or UNS
cap_r	transfer capacity of UIS
E_s	Euclidean length of segment s
E_p	Euclidean length of segment p
E_{ik}	Euclidean length between CLP k and TDS i
E'_{ik}	minimum Euclidean length between CLP k and TDS i along the ground road
E_{ij}	Euclidean length between UNS j and TDS i
E_j^{max}	maximum coverage radius of UNS j
μ	minimum load rate without penalty for UNS or UIS
Decision	binary variable, equals to 1 if station j is activated as UNS; 0, otherwise.
X_j	Include X'_j and X''_j . If virtual UNS-F $j(j \in J_1)$ is activated as UNS $X'_j = 1$; otherwise, $X'_j = 0$
	If existing metro station $j(j \in J_2)$ is activated as UNS, $X''_j = 1$; otherwise, $X''_j = 0$
Z_s	binary variable, equals to 1 if laying a freight dedicated line below the urban road segments s
W_{ik}^j	binary variable, equals to 1 if d_{ik} is transported to UNS j ; 0, otherwise
U_{ik}^p	binary variable, equals to 1 if d_{ik} is transported by segment p ; 0, otherwise
V_{ik}^s	binary variable, equals to 1 if d_{ik} is transported by underground freight dedicated segment s ; 0, otherwise
H_{ik}^s	binary variable, equals to 1 if d_{ik} is transported by ground road segment s ; 0, otherwise
T_{ik}^r	binary variable, equals to 1 if d_{ik} is transported to UIS r ; 0, otherwise
S_{ij}	binary variable, equals to 1 if TDS i is allocated to UNS j ; 0, otherwise
L_{ik}	binary variable, equals to 1 if d_{ik} chooses M-ULS transportation; 0, otherwise

4.1. First Stage: Network Scale Decision

To evaluate the benefits generated by the M-ULS network, research data were systematically collected and screened using the expert scoring method. A set of indicators was subsequently developed based on the principles of scientific rigor, systematic structure, operational feasibility, and dynamic adaptability. This framework ensures a comprehensive representation of the economic, social, and environmental benefits of M-ULS while maintaining data accessibility.

Four indicators were ultimately constructed to assess the following dimensions: freight demand level, traffic congestion status, freight demand responsiveness, and land resource utilization at transportation origins and destinations. Given the widespread adoption of new environmentally friendly vehicles in urban distribution, pollution emission factors associated with traditional trucks were not considered in this study. For analytical convenience, the network coverage area was evenly divided into multiple spatial units, with one TDS established per unit, indexed by i .

(1) Freight demand

M-ULS networks not only need to consider the external effects of the system but also need to consider their own benefits. Building an underground direct operation network in areas with high and concentrated freight demand can help the system generate economies of scale. Indicator D_i represents the concentration of freight at TDS i , as shown in Equation (1). The larger D_i indicates the more concentrated freight demand at TDS i . ρ is correction coefficient for the indicator, taken as [0.1, 0.45] based on the empirical range [12].

$$D_i = \sum_{k \in K} E_{ik} \cdot (d_{ik})^\rho \quad (1)$$

(2) Regional accessibility

According to the degree to which the efficiency of ground distribution is affected by road conditions, priority should be given to underground transportation of goods in congested areas, which is beneficial for improving traffic mobility. The regional accessibility index is characterized by the time road response function proposed by Masson et al. [13] as shown in Equation (2).

$$A_i = \sum_{k \in K} \frac{E'_{ik}}{v \cdot t_{ik}} \left\| \frac{E_{ik}}{E'_{ik}} \right\|^{\varphi_i} \quad (2)$$

where φ_i is the daily average congestion index of region of TDS i ; v is the average speed of the trucks without congestion; E'_{ik} and t_{ik} represent the minimum transport distance and average transport time of the freight flow from the CLP k to the TDS i , respectively.

(3) Demand responsiveness

The advantage of M-ULS transportation network lies in its punctuality and rapidity, and the transport time is not limited by urban roads. Therefore, metro freight should give priority to the logistics demand with high requirements on freight timeliness and transport period. Demand responsiveness is reflected by the freight volume of the distribution station and the time function P_i , as shown in Equation (3).

$$P_i = \sum_{k \in K} d_{ik} \cdot \left(\frac{L_{\max} - \mu_{ik}}{L_{\max} - L_{\min}} \cdot \omega_{ik} \right)^{\vartheta} \quad (3)$$

where μ_{ik} is the demand response time window, which satisfies the maximum-minimum response time limit of $L_{\min} < \mu_{ik} < L_{\max}$; ω_{ik} is the waiting time for limited transport, and ϑ is the response time correction coefficient, taken as [0.5, 1.0].

(4) Logistics land utilization rate

Assuming that logistics demand is directly proportional to population density, define U_i as the ratio of the land area of TDS i to the regional population density, shown in Equation (4), where δ is the correction coefficient, which represents the ratio of unplanned land to the total area of the region. The smaller the U_i is, the more prominent the contradiction between the logistics working space and the logistics demand of the distribution TDS i is, and the ability to expand the logistics land in the future is also very small.

$$U_i = \left(\frac{u_i^l}{u_i^e} \right)^{1-\delta} \quad (4)$$

Among the four indicators mentioned above, the correction coefficient can also be used to reflect policy-related factors. For instance, if the government plans to establish a large-scale logistics base at a particular demand node, this policy orientation can be represented by increasing the correction coefficient. This approach offers a quantitative means to support future government decision-making. However, since the MULS network is a hypothetical case and no relevant policy influence factors were collected, a quantitative analysis of such policy impacts was not conducted in the subsequent case study.

We use the four observation indicators mentioned above to adjust the network size of M-ULS using the E-TOPSIS method. E-TOPSIS combines the entropy weight method (Entropy) and TOPSIS method. Firstly, determine the weight of each observation indicator by calculating the information entropy of each observation indicator. Then, rank to achieve the evaluation of each TDS by calculating the distance between each comprehensive evaluation indicator and the best and worst indicators. The process of constructing the E-TOPSIS model for screening TDS is described below.

Construct the original evaluation matrix $Z = [z_{ij}]$, z_{ij} represents the evaluation value of the TDS i ($i = 1, 2, \dots, n$) on the evaluation index z_j ($j = 1, 2, 3, 4$). Take the maximum and minimum values of each evaluation index and record them as $z_{\max(j)}$ and $z_{\min(j)}$, respectively.

Convert the minimal index into the maximal index by Equation (5).

$$\bar{z}_{ij} = z_{\max(j)} - z_{ij} \quad (5)$$

Using the evaluation matrix $\bar{Z}$, construct a dimensionless standardized discriminant matrix $X = [x_{ij}]$, x_{ij} represents the standardized observation value of TDS i about index x_j ($j = 1, 2, 3, 4$). The calculation process of x_{ij} is shown in Equation (6).

$$x_{ij} = \frac{z_{ij} - z_{\min(j)}}{z_{\max(j)} - z_{\min(j)}} \quad (6)$$

Calculate the proportion of the standardized observation value of the TDS i to the index j , as shown in Equation (7).

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^n x_{ij}}, (j = 1, 2, \dots, m) \quad (7)$$

Calculate the entropy value of the index j , as shown in Equation (8). If $P_{ij} = 0$, define $P_{ij} \ln P_{ij} = 0$.

$$E_j = -\frac{1}{\ln n} \sum_{i=1}^n P_{ij} \ln P_{ij} \quad (8)$$

Calculate the difference coefficient of the index j , as shown in Equation (9).

$$G_j = 1 - E_j \quad (9)$$

Calculate the normalized index weight coefficient, as shown in Equation (10).

$$w_j = \frac{G_j}{\sum_{j=1}^m G_j} \quad (10)$$

Calculate the positive ideal solution and negative ideal solution of each index, and record them as $X^+ = (x_j^+) = (x_1^+, x_2^+, x_3^+, x_4^+)$ and $X^- = (x_j^-) = (x_1^-, x_2^-, x_3^-, x_4^-)$, respectively. Calculate the weight distance between each distribution station and the positive and negative ideal solutions using Euclidean distance, as shown in Equations (11) and (12).

$$D_i^+ = \sqrt{\sum_{j=1}^4 w_j (x_j^+ - x_{ij})^2} \quad (11)$$

$$D_i^- = \sqrt{\sum_{j=1}^4 w_j (x_j^- - x_{ij})^2} \quad (12)$$

Calculate the relative closeness between each TDS i and the optimal solution, as shown in Equation (13).

$$\lambda_i = D_i^- / (D_i^- + D_i^+) \quad (13)$$

Sort λ_i , calculate the environmental benefits of constructing the corresponding TDS i as M-ULS network terminal until the cumulative environmental benefits reach the preset target, then the selected TDS can determine the M-ULS network scale. In addition, the construction scale can also be determined by the percentage $\bar{\lambda}$ of network size set by decision-makers. Ranking in the top percent $\bar{\lambda}$ TDS i will be included in the comprehensive

transportation network operation scope ($i \in I$). If TDS i is determined to be UTDS, then $i \in I_1 \subseteq I$.

4.2. Second Stage: Upper-Level Model

The upper-level model is based on the network construction points selected in first stage, combined with the existing metro operation network, to complete the network planning of M-ULS with the minimum construction cost. The upper-level model can be standardized as a Capacity Constrained Location-Allocation Routing Problem (CLARP) [14].

The upper-level model with multi-objective model aims at determining the initial network. The first objective f_1 is to minimize the total construction cost for UNSs, FDLs and UPs. The second objective function f_2 is the minimum total operating cost of the M-ULS network, including the operating costs at UNSs, the transfer costs at UISSs, and the transport costs in underground path. The third objective function f_3 is to minimize the total penalty cost due to low-load operations of UNSs and UISSs. The objective functions of each part are shown in Equations (14)–(16).

$$f_1 = c_c \sum_{j \in J_1} X'_j + c_f \sum_{j \in J_2} X''_j + c_b \sum_{s \in S} \sum_{i \in I} \sum_{k \in K} Z_s E_s \left\lceil \frac{d_{ik} V_{ik}^s}{cap_s} \right\rceil + c_d \sum_{i \in I_1} \sum_{j \in J} E_{ij} X_j \quad (14)$$

$$f_2 = \sum_{r \in R} \sum_{i \in I} \sum_{k \in K} L_{ik} d_{ik} T_{ik}^r c_r + \sum_{j \in J} \sum_{i \in I} \sum_{k \in K} L_{ik} d_{ik} S_{ij} W_{ik}^j c_j + c_p \left(\sum_{p \in P} \sum_{i \in I} \sum_{k \in K} L_{ik} d_{ik} U_{ik}^p E_p + \sum_{s \in S} \sum_{i \in I} \sum_{k \in K} L_{ik} d_{ik} V_{ik}^s E_s + \sum_{i \in I_1} \sum_{j \in J} \sum_{k \in K} L_{ik} E_{ij} W_{ik}^j \right) \quad (15)$$

$$f_3 = \sum_{j \in J} \max \{ \mu \cdot cap_j - \sum_{i \in I} \sum_{k \in K} d_{ik} W_{ik}^j L_{ik}, 0 \} \cdot c_a \quad (16)$$

The model subjects to:

$$\sum_{i \in A(j)} \sum_{k \in K} d_{ik} W_{ik}^j S_{ij} \leq cap_j, \forall j \in J \quad (17)$$

$$\sum_{i \in I} \sum_{k \in K} d_{ik} T_{ik}^r \leq cap_r \quad (18)$$

$$\sum_{j \in B(i)} S_{ij} = 1, \forall i \in I \quad (19)$$

$$\sum_{i \in A(j)} S_{ij} \geq 2, \forall j \in J \quad (20)$$

$$E_{ij} S_{ij} \leq E_j^{max}, \forall i \in A(j), j \in B(i) \quad (21)$$

$$W_{ik}^j \leq X_j, T_{ik}^r \leq X_r, U_{ik}^p \leq X_p, V_{ik}^s \leq X_s, \forall i \in I, j \in J, r \in R, k \in K, p \in P, s \in S \quad (22)$$

$$S_{ij} \leq X_j, \forall i \in I, j \in J \quad (23)$$

$$V_{ik}^s \leq Z_s, \forall i \in I, k \in K, s \in S \quad (24)$$

$$\sum_{s \in S} V_{ik}^s + \sum_{p \in P} U_{ik}^p \geq 1, \forall i \in I, k \in K \quad (25)$$

$$V_{ik}^s + H_{ik}^s = 1, \forall i \in I, k \in K, s \in S \quad (26)$$

$$L_{ik} \leq W_{ik}^j, \forall i \in I, k \in K, j \in J \quad (27)$$

Constraints (17) and (18) ensure that the operation and storage capacity of UIS or UNS and transfer capacity of UIS shall not exceed the capacity limit cap_j and cap_r , respectively. Constraint (19) ensures that any TDS i can only be served by a unique UNS j . Constraint (20) states that any UNS j needs to serve at least two TDSs. Constraint (21) ensures that the distance between any UNS j and the TDS i it serves cannot exceed the maximum coverage radius. Constraint (22) and (23) state that if UNS j is not built, it will not generate underground transport and will not have allocated TDSs. Constraint (24) ensures that there

is no underground cargo flow passing through the section s when there is no dedicated freight line under the section. Constraint (25) indicates that if the cargo flow is transported through the M-ULS network, it will go through at least one section of metro line or FDLs. Constraint (26) ensures that the cargo flow can only be transported by FDLs or road when passing through any section s . Constraint (27) indicates that when the shipper chooses M-ULS network transportation, it must go through a UNS for operation.

4.3. Third Stage: Lower-Level Model

The lower-level model simulates the competition between the M-ULS and traditional freight modes. M-ULS further intensifies the “decentralization” trend in traditional logistics hub competition. This implies that, alongside the large logistics hubs surrounding cities, intra-city distribution centers will be replaced by individual transfer stations. By integrating with these stations, M-ULS enables “pre-positioned inventory” and “micro-scale” operations, which significantly reduce transfer times compared to traditional freight. Furthermore, the extensive accessibility of metro rail transit ensures more reliable on-time delivery. Nevertheless, M-ULS presents certain drawbacks relative to conventional logistics, such as multiple transfers between stations due to the absence of direct routes, additional waiting times imposed by constrained operating schedules, and excessive transportation mileage resulting from limited route availability. To better quantify the competitive dynamics, we have developed the following lower-level model to compute the generalized costs.

The decision-maker of the lower-level model is the shipper. This section assumes that all shippers will choose the mode with the minimum generalized transport cost between M-ULS and traditional freight mode; that is, the objective function is to minimize the generalized transportation cost of shippers given the M-ULS transportation network. Record the network nodes and road segments allocated for demand d_{ik} in the upper-level model as path L . The decision variables follow the L_{ik} in the upper-level model, when shipper's demand d_{ik} selects M-ULS, $L_{ik} = 1$, when traditional freight mode is selected, $L_{ik} = 0$. The objective function is shown in Equation (28).

$$\min f_4 = L_{ik}c_{m-uls} + (1 - L_{ik})c_{road} \quad (28)$$

where c_{m-uls} represents the generalized cost of M-ULS; c_{road} represents generalized cost of traditional road transport. The calculation methods of the above two expenses are listed as follows.

(1) The generalized cost of M-ULS: c_{m-uls}

c_{m-uls} includes the loading and unloading cost, underground transport costs, storage cost, and transfer cost. The first two costs mentioned above are consistent with the upper-level model, but the transfer cost differs significantly from it. According to the investigation results of the shipper's behavior preference, the number of transfers will affect the shipper's selection. Therefore, the piecewise penalty function of transfer cost is designed, as shown in Equation (29). The penalty function stipulates that the shipper will not accept the M-ULS when the total number of transfers in transport is more than two.

$$c_{rp} = \begin{cases} +\infty, & \sum_{r \in R} T_{ik}^r > 2 \quad \forall i \in I, k \in K \\ 1, & \sum_{r \in R} T_{ik}^r \leq 2 \quad \forall i \in I, k \in K \end{cases} \quad (29)$$

In addition, because the network planning only considers the spatial transfer to meet the freight demand but does not consider the transit time of each load of cargo, which is one of the generalized costs that cannot be ignored in the actual operation situation, this section increases the unit storage cost of cargo in the generalized cost of M-ULS transportation to

replace the time cost caused by M-ULS freight scheduling, in order to achieve an objective balance in the generalized costs of the two modes. Finally, the generalized cost description of M-ULS transportation is shown in Equation (30).

$$c_{m-uls} = \sum_{p \in P} d_{ik} U_{ik}^p E_p c_p + \sum_{s \in S} d_{ik} V_{ik}^s E_s c_s + c_{rp} \sum_{r \in R} d_{ik} T_{ik}^r c_r + \sum_{j \in J} d_{ik} S_{ij} W_{ik}^j (c_j + c_m), \forall i \in I, k \in K \quad (30)$$

(2) The generalized cost of traditional road transport: c_{road}

c_{road} includes the transport cost of trucks and the waiting time cost of transport. The transport cost is related to the transport distance, and the waiting time cost is the sum of the congestion cost during the transportation period and the waiting cost for restricted transport caused by urban freight policies, taking the average of each freight survey period. The generalized cost of traditional road transportation is shown in Equation (31).

$$c_{road} = E'_{ik} c_s + c_w W_{ik}, \forall i \in I, k \in K \quad (31)$$

The lower model has no other constraints except the decision variable $L_{ik} \in \{0, 1\}$.

4.4. Global Model and Complexity Analysis

In order to make the cost unit of the objective function consistent, the network construction cost is depreciated by the average life method for introducing depreciation coefficient γ . The complete bilevel programming model is shown as follows.

$$\begin{aligned} \min F &= \gamma \cdot f_1 + f_2 + f_3 \\ &= \gamma \cdot \{c_c \sum_{j \in J_1} X_j' + c_f \sum_{j \in J_2} X_j'' + c_b \sum_{s \in S} \sum_{i \in I} \sum_{k \in K} Z_s E_s \left\lceil \frac{d_{ik} V_{ik}^s}{cap_s} \right\rceil + \\ &\quad c_d \sum_{i \in I_1} \sum_{j \in J} E_{ij} X_j\} + L_{ik} (\sum_{p \in P} \sum_{i \in I} \sum_{k \in K} d_{ik} U_{ik}^p E_p c_p + \\ &\quad \sum_{s \in S} \sum_{i \in I} \sum_{k \in K} d_{ik} V_{ik}^s E_s c_s + \sum_{r \in R} \sum_{i \in I} \sum_{k \in K} d_{ik} T_{ik}^r c_r + \sum_{j \in J} \sum_{i \in I} \sum_{k \in K} d_{ik} S_{ij} W_{ik}^j c_j) + \\ &\quad \sum_{j \in J} \max \left\{ \mu \cdot cap_j - \sum_{i \in I} \sum_{k \in K} d_{ik} W_{ik}^j L_{ik}, 0 \right\} \cdot c_a \\ \text{s.t.} &\begin{cases} \text{Constraints (17) to (27)} \\ \text{--- the follower ---} \\ \min f_4 = L_{ik} c_{m-uls} + (1 - L_{ik}) c_{road} \\ \text{s.t. } L_{ik} \in \{0, 1\} \end{cases} \end{aligned}$$

The model is a mixed integer linear programming model, which includes 10 decision variables, 24 input parameters and 11 related core constraints. The complexity of the model will increase exponentially with the expansion of the initial network construction scale. The complexity of the model will increase exponentially with the expansion of the initial network construction scale (Network scale refers to I: the number of TDS; J + R: the number of metro stations and interchange stations; K: the number of CLP). In addition, the dynamic interaction between the upper and lower models makes the solution of the model more complicated. Firstly, the upper model determines the node construction (X_j), pipe gallery laying (Z_s) and site allocation (S_{ij}) of the network according to the demand d_{ik} , and determines the optimal network structure. Then the path L of demand d_{ik} , including network nodes (W_{ik}^j, T_{ik}^r) and road sections (V_{ik}^s, U_{ik}^p), is transferred to the lower model (Equations (29) and (30)). The objective function of the lower-level model (Equation (28)) is also the constraint condition of the whole model. The shippers' choice result L_{ik} will adjust the construction scheme and routing scheme of the upper model and then input the new scheme into the lower model to solve the adjusted shippers' choice result L_{ik} . After a series of iterations until all the constraints are satisfied, the lower model solution L_{ik} is

input to the upper-level objective function (Equation (15)), and the optimal network layout and path planning scheme of the model are output. In order to express the complexity of this model more clearly, the number of decision variables and key constraints in the global model is counted, as shown in Table 2.

Table 2. Number of Model Decision Variables and Key Constraints.

Decision Variables or Constraints	Maximum Quantity Expression
X_j (binary variable)	$I + J$
Z_s (binary variable)	S
W_{ik}^j (binary variable)	$I \cdot K \cdot J$
$U_{ik}^p, V_{ik}^s, H_{ik}^s$ (binary variable)	$I \cdot K \cdot P + 2 \cdot I \cdot K \cdot S$
T_{ik}^r (binary variable)	$I \cdot K \cdot R$
S_{ij} (binary variable)	$I \cdot J$
L_{ik} (binary variable)	$I \cdot K$
constraints (17) and (18)	$I^2 \cdot K + I^2 \cdot K \cdot R$
constraints (19) to (21)	$3 \cdot I^2 \cdot K$
constraints (22) to (27)	$I \cdot K \cdot (2 \cdot P + 4 \cdot S + R + 2 \cdot J) + I^2$

5. Solution Method

5.1. Algorithm Framework

The bi-level programming model established in this article is a non-convex optimization problem with optimization problems included in the constraint conditions and a two-layer linkage structure, which has been proven to be a typical NP hard problem [15]. The change in the site selection and path planning decision of the upper model will affect the decision of the shipper, and the decision of the shipper's choice will affect the decision made by the government investment department in the upper model. In view of this game relationship, this section sets that the upper-level decision makers have priority over the lower-level decision makers; that is, the government investment department first comprehensively considers the urban environmental benefits, investment and construction costs and other factors to formulate the network path and cargo flow distribution plan; then the shipper chooses a transport scheme with lower generalized cost according to the upper planning and its current traditional transport mode; finally, the result is passed up for dynamic adjustment. The overall solution of the model is summarized as follows:

Firstly, the investment department of the upper government formulates the network planning and design scheme;

Secondly, the lower shipper makes a choice on the transportation scheme;

Thirdly, the shipper feeds back the selection result to the government investment department, and the government investment department adjusts the planning scheme according to the selection result;

Finally, repeat step 2 and step 3, and iterate with the upper-level goal as the overall goal of the whole model until the iteration termination condition is met. The overall algorithm framework is shown in Figure 3.

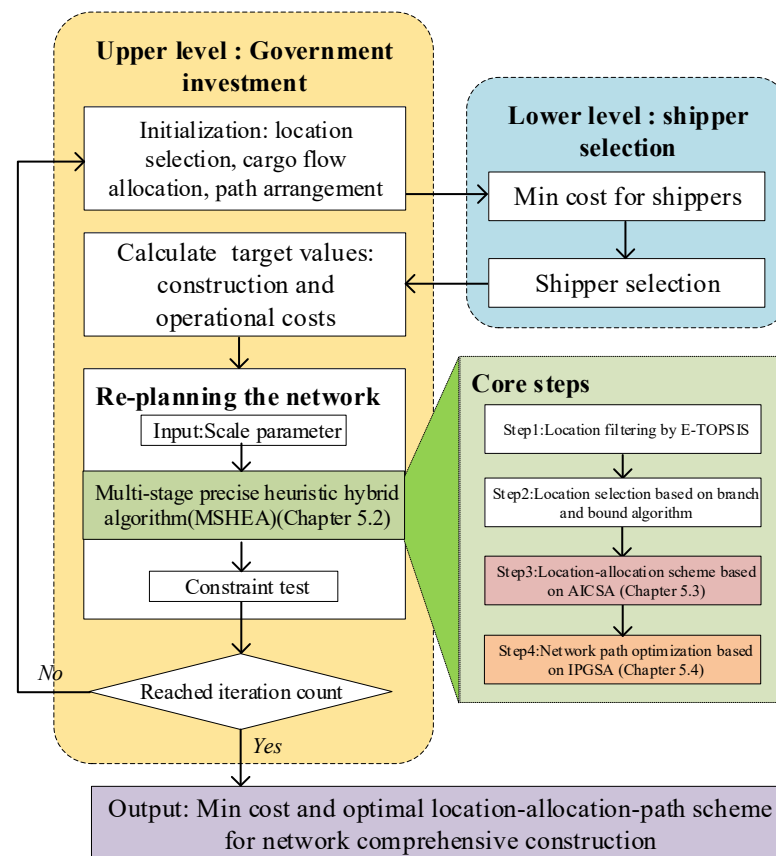


Figure 3. Flow chart of M-ULS transportation network optimization algorithm.

5.2. Design of MSHEA Algorithm

As shown in Figure 3, The difficulty of solving the model focuses on step 1, solving the CLARP model. Numerous studies have shown that CLARP has NP-Hard computational complexity [16], and it is difficult to find an algorithm with polynomial time complexity. The optimization model constructed in this study fundamentally belongs to an NP-hard problem, which means that as the problem's scale expands, its solution space grows exponentially, rendering it computationally infeasible to find an exact optimal solution within polynomial time. This complexity characteristic dictates that any single optimization algorithm struggles to achieve a satisfactory balance between solving efficiency and solution quality. For instance, exact algorithms can guarantee global optimality but suffer from excessively long computation times, making them unsuitable for large-scale practical cases; whereas purely heuristic algorithms offer rapid computation speeds but cannot ensure global optimality and may even converge to local optima [17]. Therefore, we design a multi-stage algorithm combining heuristic with exact algorithm (MSHEA) in order to improve the computational efficiency and quality of the solution.

We divide the problem to be solved into three stages based on network planning: location selection, allocation, and path planning. By selecting the most suitable precise algorithm or heuristic algorithm in stages and combining iterative optimization, we expect to improve the accuracy and optimization efficiency of the algorithm. The core steps of MSHEA algorithm are summarized as follows:

- (1) Step 1: Determine the initial scale of the M-ULS network according to the comprehensive environmental benefits, comprehensively evaluate the A_i , P_i , U_i and D_i indicators of each TDS, screen out the initial network nodes with the expected scale by E-TOPSIS method, and transmit the screening results to the next stage.

- (2) Step 2: The branch-and-bound algorithm is adopted to obtain the exact solution of the set coverage model satisfying the constraints (19) to (21), and determine the location of the UNS-F, then output optimization result to the next stage.
- (3) Step 3: Based on the improved adaptive immune clone selection algorithm (AICSA), randomly generate the location-allocation scheme of UNS-PF and the remaining unassigned TDS. The allocation decision follows the constraints (17), (18), (22) and (23), and the shortest path of goods flow in the network is determined on the premise of satisfying the constraints (24) to (26).
- (4) Step 4: Optimize the path between UNS and UTDS by using the improved plant growth simulation algorithm (IPGSA). After obtaining the optimal path layout under the location-allocation scheme, enter the bi-level programming master model again and carry out a new round of optimization until it reaches the termination condition.

In this framework, the branch-and-bound algorithm functions as both a “benchmark verifier” and a “local refiner.” Rather than being applied to the entire problem, it performs intensive searches within promising sub-regions of the solution space identified by meta-heuristic algorithms. This process verifies and secures the exact optimal solution in each region, thereby guaranteeing the high quality of the final solution. Meanwhile, AICSA and IPGSA act as efficient “global explorers,” each specialized in tackling the subproblems they are best suited for: site allocation and path optimization, respectively. Leveraging their strong global search capability and tendency to escape local optima, these algorithms rapidly scan the vast solution space and locate promising areas containing high-quality solutions. The effectiveness of this dual-role strategy is validated through case studies in Section 6.1.

5.3. Solving the Problem of Location-Allocation Optimization Based on AICSA

Immune clonal algorithm is a heuristic optimization algorithm that simulates the selection process of human immune clones. In the immune cloning algorithm, the individuals in the solution space are called antibodies. The core idea is to improve the number of outstanding individuals in the population through continuous cloning, mutation and selection operations [18]. By increasing the number of excellent individuals in the population, the algorithm can maintain a high global search ability, better explore the solution space, and have a higher possibility of finding the global optimal solution. However, it also has some shortcomings, such as slow convergence speed and that it is easy to fall into local optimal solution [19]. In order to improve the defects of the immune cloning algorithm, we introduce a clonal amplification operator and adaptive mutation probability operator and put forward an adaptive immune cloning algorithm (AICSA) to keep more high-quality antibodies and adjust their mutation probability adaptively according to their response ability, thus improving the efficiency and stability of algorithm search. The working mechanisms of the two operators are summarized as follows.

(1) Clonal amplification operator

The purpose of a cloning amplification operator is to amplify more high-quality antibodies. The principle is to determine the number of amplified antibodies according to their ability to respond to antigens, which means that the number of cloned antibodies is directly proportional to their affinity. The calculation method of clonal amplification operator is shown in Equation (32).

$$N_k(i) = \left\lceil N_c \cdot \frac{f(S_k(i))}{\sum_{j=1}^m f(S_k(j))} \right\rceil \quad (32)$$

where $N_k(i)$ is the number of amplified clones of the first antibody in the generation population k ; N_c is the total antibody value after cloning; $f(S_k(i))$ is the fitness (objective function value) of the antibody i in the generation population k .

(2) Adaptive mutation probability operator

The design intention of the adaptive mutation probability operator is to dynamically adjust the mutation probability of the algorithm in different stages and perform adaptive mutation operations on each antibody that meets the mutation rate in the global scope. The principle is that at the beginning of the algorithm, the space of the problem is fully searched with high mutation probability to maintain the diversity of the population; when the algorithm enters the convergence stage, the mutation probability changes adaptively according to its fitness value and affinity to ensure the mutation probability decreases with the number of iterations to reduce the oscillation phenomenon caused by the high mutation probability in the early stage. The calculation method of adaptive mutation probability is shown in Equation (33).

$$m^{(k+1)} = (1 - \frac{f_{\text{mean}}^{(k)} - f_{\text{bad}}}{f_{\text{best}} - f_{\text{bad}}})m^{(k)} \quad (33)$$

where $m^{(k+1)}$ and $m^{(k)}$, respectively, represent the mutation probabilities used in the $k + 1$ and k cycle steps; $f_{\text{mean}}^{(k)}$ is the average value of fitness at the current stage; f_{best} and f_{bad} represent the optimal value and the worst value of fitness, respectively.

Regard S_k and S_0 as the k generation population of antibody and initial population, respectively, $S_k(i)$ as the antibody i in the generation population k . Regard Z_k as the clonal population produced by the k generation antibody, and $Z_k(i)$ as the clone of the antibody i in the k generation population. Regard Y_k as a new population produced by mutating the k generation clonal population, $Y_k(i)$ as the variant i in the k generation population, and $Y_k \cup Z_k$ as the antibody population for immune selection of the k generation. Antibodies are represented by double-queue binary codes and randomly generated from the feasible solution space. When the metro station is selected as the UNS, the value in queue one is 1; when the TDS is assigned to the corresponding UNS, the value in queue two is 1. The flowchart of the AICSA algorithm is shown in Figure 4, and the framework of the AICSA algorithm is shown in Algorithm 1.

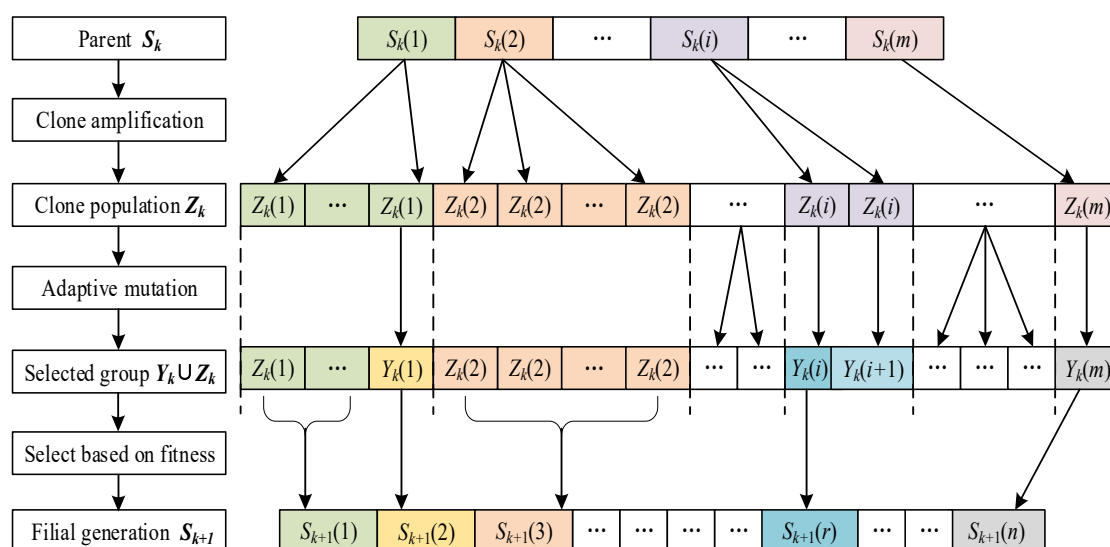


Figure 4. AICSA Algorithm Process.

Algorithm 1: AICSA for location-allocation optimization problem

Input:	initial set of location-allocation decision (Antibody) $S \leftarrow S_0$, MaxIter,
	initial mutation probability ϑ
Output:	optimal location-allocation decision S^*

```

1:  for Iter = 1:MaxIter do
2:       $Z \leftarrow \emptyset, Y \leftarrow \emptyset$ 
3:      for  $i = 1:\text{length}(S)$  do
4:          calculate  $f(S_i)$ ;  $F \leftarrow F + f(S_i)$ ; update  $f_{best}, f_{bad}, f_{mean}, S^*$ 
5:      end for
6:      for  $i = 1:\text{length}(S)$  do
7:           $N_i \leftarrow \text{int}(\text{length}(S) \times (f(S_i)/F))$  // (clonal amplification operator)
8:          for  $i = 1:N_i$  do
9:               $Z \leftarrow \text{Append}(Z, S_i)$  // form a clonal population
10:         end for
11:     end for
12:      $\vartheta \leftarrow (1 - (f_{mean} - f_{bad}) / (f_{best} - f_{bad})) * \vartheta$  // (adaptive mutation
probability operator)
13:     for  $i = 1:\text{length}(Z)$  do
14:         if  $\text{random}[0, 1] < \vartheta$  then
15:              $Y_i \leftarrow \text{GeneExchangeMutation}(Z_i)$ ;  $Y \leftarrow \text{Append}(Y, Y_i)$  // form a
mutant population
16:         else
17:              $Y \leftarrow \text{Append}(Y, Z_i)$ 
18:         end if
19:     end for
20:      $Y \leftarrow \text{sorted}(Y_i, \text{key} = f(Y_i))$  // sorting antibodies according to
fitness value
21:      $Y_{top} \leftarrow Y[\text{int}(0.3 \times \text{length}(Y))]; Y_{bottom} \leftarrow Y[\text{int}(0.7 \times \text{length}(Y))]$ 
22:      $S \leftarrow Y_{top} + Y_{bottom}$  // replace the last 30% antibody with the first 30%
antibody of fitness function
23: end for
24: Return:  $S^*$ 

```

5.4. Solving the Problem of Path Optimization Based on IPGSA

The Plant Growth Simulation Algorithm (PGSA) was first proposed by Chinese scholar Li Tong [20] in 2005. It is an intelligent optimization algorithm inspired by the mechanism of plant phototropism (the concentration theory of morphogens). This algorithm takes the phototropism of plants as the mechanism, regards the feasible region as the growth environment of plants, calculates the concentration of plant morphogens based on the changes in the objective functions of each feasible solution, and simulates the dynamic mechanism of plant phototropism growth in order to form a search mechanism for rapid growth towards the global optimal solution. Li Tong et al. [21] have demonstrated that simulated plant growth algorithms have stronger accuracy, stability, and global search ability in solving path optimization compared to ant colony algorithms and simulated annealing algorithms. In addition, the continuous growth of plant growth points in the solution space in this algorithm gives it the ability to evolve in network form, which is more closely related to the construction timing and dynamic optimization process of M-ULS. However, in large-scale, complex problems, PGSA has the defects of falling into local optimization and being difficult to terminate automatically. Therefore, in this section, we design the new growing point limiting operator and the new growing point removing

operator to improve the above two defects of the algorithm, respectively, and propose the improved plant growth simulation algorithm (IPGSA). The working mechanisms of the two operators are summarized as follows.

(1) New growing point limiting operator

The PGSA algorithm controls the probability that the growing point will receive the priority growth opportunity according to the concentration of morphogens. The large-scale optimization problem has a large growth space, and more growable points will be added in each growth process, which will reduce the probability of selecting high-quality growth points and increase the number and time of each optimization. The principle of this operator is that before selecting the next growth point, the objective function value of each growth point is calculated and sorted, and only the top k growth points are selected, and the rest of the growth points are excluded to limit the number of growth points participating in the optimization. On the one hand, this operator can greatly reduce the scale of the set of growing points and accelerate the convergence speed of the algorithm; on the other hand, it is helpful to keep high-quality growth points and jump out of local optimal solutions.

(2) New growing point removal operator

The original PGSA algorithm traverses the growth space until there is no growth point [22], so it lacks an effective termination mechanism, which often leads to the global optimal solution in the optimization process, but the algorithm cannot be terminated in time. Therefore, we designed a new growing point removal operator to improve the problem that PGSA lacks an effective termination mechanism. The core step is to pre-eliminate the growing points whose function value in the newly added growing point set is worse than the worst value in the growing point set and then add the remaining newly added growing points into the growing point set for iterative optimization. The advantages of this method include two aspects: first, it reduces the chance that inferior growable points are selected, thus ensuring the quality of the whole set; secondly, the scale of the set of growing points can be further reduced, and it will become an empty set termination algorithm after a limited amount of non-aggressive culling, thus providing an effective algorithm termination mechanism to improve the computational efficiency of the algorithm.

Based on the optimization results of location-allocation in the previous stage, this section assumes that the TDSs covered by a UNS m correspond to an initial Steiner point set $S_m = (S_{1,m}, S_{2,m}, \dots, S_{n,m})$, and the path optimization problem can be briefly summarized as: in a given network node set S_m , calculate other Steiner points and connect all Steiner points to form Steiner Minimal Trees (SMT). The objective function is shown in Equation (34).

$$\min F = \sum_{j=1}^n \sum_{i=1}^n \omega_{ij} \|S_{i,m} - S_{j,m}\| \quad (34)$$

where ω_{ij} represents the connectivity between two Steiner points, and when $S_{i,m}$ is connected with $S_{j,m}$, $\omega_{ij} = 1$; $\|S_{i,m} - S_{j,m}\|$ denotes the Euclidean distance between two connected Steiner points.

Record the concentration of morph corresponding to each Steiner point as $P_m = (P_{1,m}, P_{2,m}, \dots, P_{n,m})$. The calculation method of $P_{i,m}$ is shown in Equation (35), and $P_{1,m} + \dots + P_{n,m} = 1$, where $f(S_{i,m})$ is the sum of the Euclidean distances of the sides adjacent to $S_{i,m}$.

$$P_{m,i} = \frac{f(S_{m,i})}{\sum_{i=1}^n f(S_{m,i})} \quad (35)$$

The framework of IPGSA algorithm is shown in Algorithm 2

Algorithm 2: IPGSA for path optimization problem

```

Input:  set of growing point  $X$ , step length  $s$ , angle of rotation  $\theta$ , maximum growth times  $t$ 
Output: minimum cost  $F_{min}$ , the minimum network path with set of Steiner point  $S_m$ 
1:      Generating SMT topology structure of point  $S_m$  by Prim Algorithm
2:       $F_{min} \leftarrow f(S_m)$ ;  $f_{bad} \leftarrow f_{bad}(S_{i,m})$ 
3:      while growth <  $t$  do
4:          growth ++; calculate the morphogen concentration  $P_m = (P_{1,m}, \dots, P_{n,m})$  to each point in the set  $X$ 
5:           $P_{i+1,m} \leftarrow P_{i+1,m} + P_{i,m}$ 
6:          if  $P_{i,m} < \text{random}[0,1] < P_{i+1,m}$  then// randomly select the next growing point
7:               $X_{i(0),m} \leftarrow S_{i,m}$ 
8:              search and generate new growable points  $X_{i(j),m}$  in the feasible region with  $s$  and  $\theta$ 
9:              if  $f(X_{i(j),m}) > f_{bad}$  then// (new growing point removal operator)
10:                  $X \leftarrow \text{append}(X, X_{i(j),m})$ 
11:             end if
12:         end if
13:         if  $X \neq \emptyset$  then
14:              $X = \text{sorted}(X_{i(j),m}, \text{key} = f(X_{i(j),m}))$ 
15:             Update global worst value  $f_{bad}$ 
16:             if  $\text{length}(X) > k$  then
17:                  $X = X(1:k)$  // only the top  $k$  are retained (new growing point limiting operator)
18:             else
19:                  $X = X(1 : \text{length}(X) * 0.8)$  // only the top 80% are retained (limiting operator)
20:             end if
21:             if  $F_{new} < F_{min}$  then // update the  $F_{min}$  and the corresponding growable point  $X$ 
22:                  $F_{min} \leftarrow F_{new}$ ;  $S_m \leftarrow \text{append}(S_m, X)$ 
23:             end if
24:         else
25:             break
26:         end if
27:     end while
28:     Return:  $F_{min}, S_m$ 

```

6. Case Study

In this section, we verify the effectiveness of the model and algorithm in the actual case through calculation experiments, and program it in MATLAB R2019b software. All experiments were carried out on a personal Windows 10 computer (Intel (R) Core (TM) i7-9700k CPU @ 3.60 ghz RAM 8.00 G). Before the empirical simulation, we first test the accuracy and stability of the algorithm through a set of examples, then introduce the planning background and data set of the case and finally discuss the optimal layout scheme of M-ULS network in different expected scenarios.

6.1. Validity Test of the Algorithm

The validity of the algorithm is tested by using the data provided by reference [12]. By comparing the optimization results of AICSA and IPGSA with CPLEX and the improved multi-objective co-evolution algorithm (MoCC) proposed by reference [12], the efficiency and accuracy of this algorithm are tested. When the scale of the example is large, the longest solution time of CPLEX is limited to 3600s, and the lowest total cost is taken as Lower Bound (LB). Table 3 shows the comparison results.

Table 3. Comparison of small-scale optimization results examples.

Case	Count of Facilities		Solution	Obj.cost (USD 10 ³)	CPU Time (s)	Gap with CPLEX (%)
1	CLP	1	CPLEX	32.5	337	—
	MS	10	MoCC	32.5	9.2	0
	TDS	20	AICSA and IPGSA	32.5	14.3	0
2	CLP	2	CPLEX	128.3	1546	—
	MS	18	MoCC	129.1	28.5	0.62
	TDS	60	AICSA and IPGSA	128.9	40.2	0.47
3	CLP	3	CPLEX	288.9	3600	—
	UNS	30	MoCC	292.7	60.9	1.32
	TDS	12	AICSA and IPGSA	290.1	90.3	0.42
4	CLP	3	CPLEX	306.1	3600	—
	MS	32	MoCC	311.3	64.2	1.70
	TDS	130	AICSA and IPGSA	309.2	97.9	1.01

Table 3 shows that the heuristic algorithm designed in this paper can obtain a more accurate optimal solution in a reasonable CPU time, and the calculation time is much less than that of CPLEX. For example, CPLEX takes 337 s and 1546 s to find the optimal solution of case 1 and case 2, respectively, while this algorithm only takes 14 s and 40 s. When the network scale is larger than case 3, the computational consumption of CPLEX increases rapidly, and it cannot converge due to overtime, which has no great influence on the two heuristic algorithms. The heuristic algorithm can still obtain the optimal solution or feasible solution in a short time, and the gap is not more than 2%. Compared with the MoCC algorithm, this algorithm is slightly inferior to the MoCC algorithm in time, but the calculation time is still within the acceptable range, and the calculation accuracy is improved by 52.1% on average, which is of great significance to large-scale network construction. In summary, the algorithm in this paper has good accuracy and reliability.

6.2. Case Background and Parameter Settings

As one of the nine major mega cities in China, Beijing has a permanent population of 21.843 million as of the end of 2022, with a daily demand for express delivery exceeding 8 million items. However, due to the constraints of urban transportation resources, the development of the logistics industry is severely constrained, and there is an urgent need for a sustainable freight transportation method. Recently, the feasibility of the Beijing underground logistics system network project led by the local government is under discussion. It is proposed to establish an underground logistics distribution trunk system by using a facility service ring. This means that the emerging mode of “metro freight” is expected to develop rapidly in Beijing. Based on the document *Beijing Logistics Special Plan (2020)*, we conducted relevant data research on the six central districts in Beijing, to optimize and simulate the comprehensive transportation network using the bilevel programming model and corresponding algorithm. The Plan gives the location of nine CLPs and requires that TDSs be set up close to other service facilities such as supermarkets, convenience stores, office buildings, community service centers and shopping malls. From nearly 320,000 POI data of six central districts obtained from Amap, we screened out 226,000 points that meet the requirements of setting terminal distribution stations and obtained 702 distribution stations of six central districts through grid clustering, so that all distribution stations were

placed in the center of the grid and avoided roads, lakes, cultural relics and other points. At the same time, 28 metro lines (including lines under construction) and 314 metro stations (including 103 transfer stations) were obtained. Considering the relationship between the existing demand and the logistics center, only six logistics centers near the core area are enabled in the optimization simulation, and the shortest laying path connecting to the existing metro network is planned, which is marked by gray line segments. The location distribution of the above facilities is shown in Figure 5.

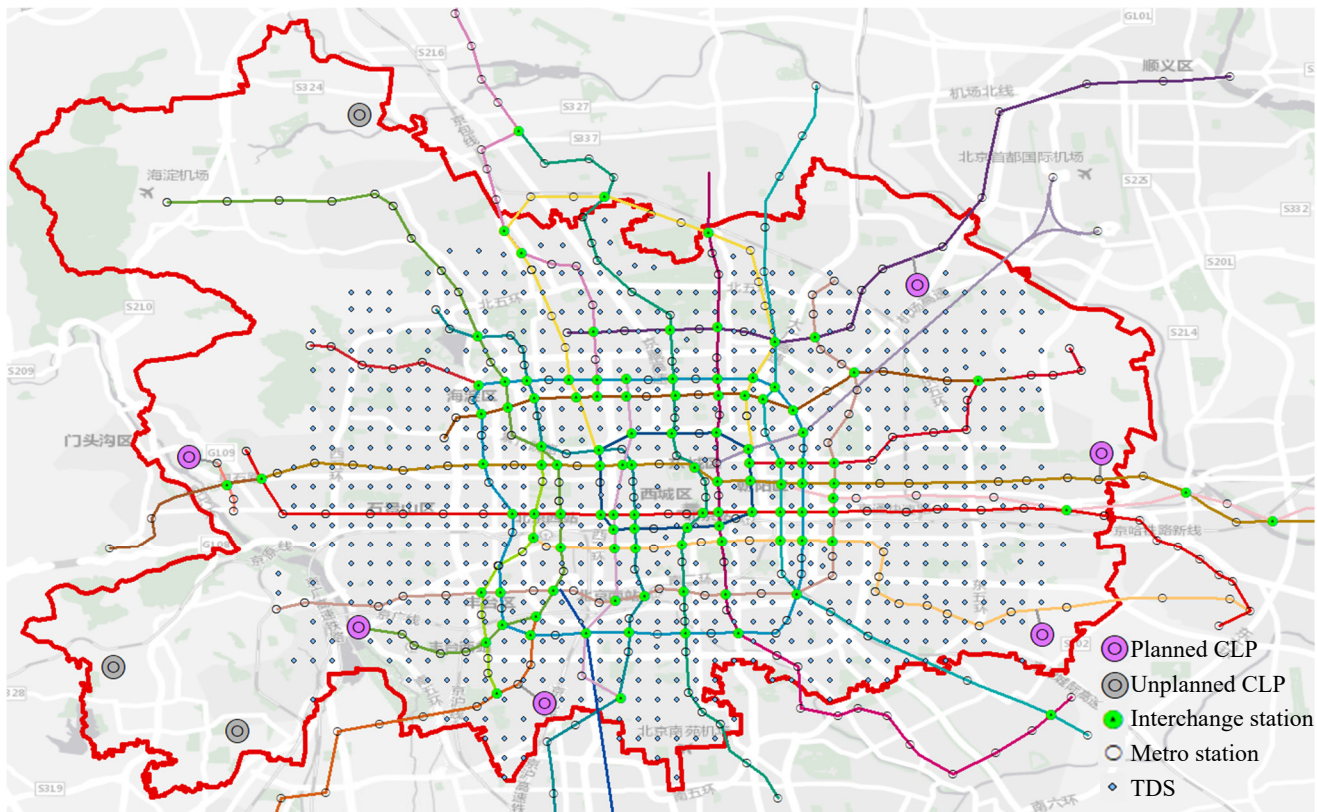


Figure 5. Distribution Map of M-ULS Infrastructure Location in the Central Urban Area of Beijing.

According to the *Statistical Bulletin on the Development of Beijing Postal Industry in 2022*, the per capita delivery business in Beijing is 1.36 parcels/day. Combined with *Beijing Census Yearbook 2020*, the freight demand is allocated to each CLP and TDS in Figure 5 according to the population of the region and street, and the cargo flow relationship between CLP and TDS is determined in a random way to obtain the data of d_{ik} . The simulation parameters of other models are listed in Table 4, in which some data are taken from references [5,23,24] and some data are taken from investigation or empirical values. The waiting time of cargo in traditional road transportation is the average of the survey results. The congestion index of each region is obtained through the website of Beijing Municipal Transportation Commission. The index of logistics land use rate was replaced by regional population density. The network scale is adjusted by changing the network scale percentage $\bar{\lambda} = [40\%, 60\%, 80\%, 100\%]$ in the first stage. The number of underground distribution sites shall be configured according to the top 20% of the network scale in each scenario. For the convenience of calculation, when the distance between the distribution station and the metro station is less than 500 m, the distribution station is set at the metro station; when it exceeds 500 m, the distance of the newly laid FDL or UP shall be calculated as the minimum distance between two points.

Table 4. Model Simulation Parameter Values.

Parameter	Value	Parameter	Value
c_a	USD 0.5 per parcel	c_r	USD 0.1 per parcel
c_b	USD 120 million per km	c_m	USD 0.06 per parcel
c_c	USD 80 million per station	c_w	USD 0.2 per h
c_d	USD 20 million per km	cap_s	0.15 million parcels per day
c_e	USD 40 million per station	cap_j	0.2 million parcels per day
c_f	USD 20 million per station	cap_r	0.6 million parcels per day
c_p	USD 0.002 per parcel km	μ	60%
c_j	USD 0.08 per parcel	E_j^{max}	1.5 km
c_s	USD 0.004 per parcel km	γ	1/365/100

The setting of algorithm parameters is arranged as follows. The total number of iterations of the bilevel programming model sets as 100; the initial population and iteration times of AICSA algorithm are both 200, and the initial mutation probability $m^{(0)}$ sets as 0.85. The maximum growth times t of IPGSA algorithm is set to 100; the step size s is set to 0.05, the rotation angle θ is set to 90, and the maximum number k in the set of growing points is set to 20.

6.3. Optimization Results and Discussion

(1) Performance of AICSA in Site Selection and Allocation Solution in case

We used the E-TOPSIS method to score and rank 702 TDS, in which $\max \lambda_i = 0.979$ and $\min \lambda_i = 0.038$. Before solving the model, we first tested the performance of the two improved intelligent algorithms. According to the scenario assumption of network scale, the improved AICSA algorithm and the traditional ICSA algorithm are used to solve the location-allocation optimization problem for four scenarios repeatedly 10 times to show the differences between the two algorithms. The results are shown in Table 5. In Table 5, we present the best solution value obtained in column “BestV”, indicate “AvgV” as the average value after both algorithms’ ten runs.

Table 5. Comparison of the differences between the AICSA and the ICSA.

λ	AICSA			ICSA		
	BestV	AvgV	Iterations of BestV	BestV	AvgV	Iterations of BestV
40%	978.70	978.70	48	978.70	978.70	61
60%	1613.90	1613.90	96	1620.86	1628.86	137
80%	2171.80	2187.12	111	2196.46	2260.94	200
100%	3152.82	3160.62	184	3208.74	3309.26	200

Note: The unit of BestV and AvgV is USD 10^3 per day.

According to Table 5, when $\bar{\lambda} = 40\%$, the two algorithms can converge to the minimum target value of 978.70 USD 103 per day every time, and AICSA algorithm is slightly better than ICSA algorithm in convergence speed. However, with the expansion of network scale, the optimization effect of the AICSA algorithm is significantly improved. From the convergence, the AICSA algorithm can converge within the specified number of iterations, but the ICSA algorithm cannot converge within the specified iterations after $\bar{\lambda} = 80\%$. From the calculation results, after $\bar{\lambda} = 80\%$, the difference of optimization accuracy of the algorithm in each scenario is 0.43%, 1.12% and 1.74% respectively, that is, with the expansion of network scale, the optimization accuracy of the AICSA algorithm is higher.

The above results show that the AICSA algorithm is superior to the ICSC algorithm in convergence speed and calculation accuracy, and the convergence speed is more significant.

(2) Performance of IPGSA in Path Planning Solution in case

Figure 6 presents the calculation results of UPs laying between one UNS and its affiliated UTDSs randomly selected under the scenario of $\bar{\lambda} = 100\%$. Figure 6a presents the coordinate information of the facilities, and Figure 6b presents the optimal pipeline laying result by using the IPGSA algorithm after adding Steiner growth point. Table 6 gives the coordinates of the facilities in Figure 6a,b.

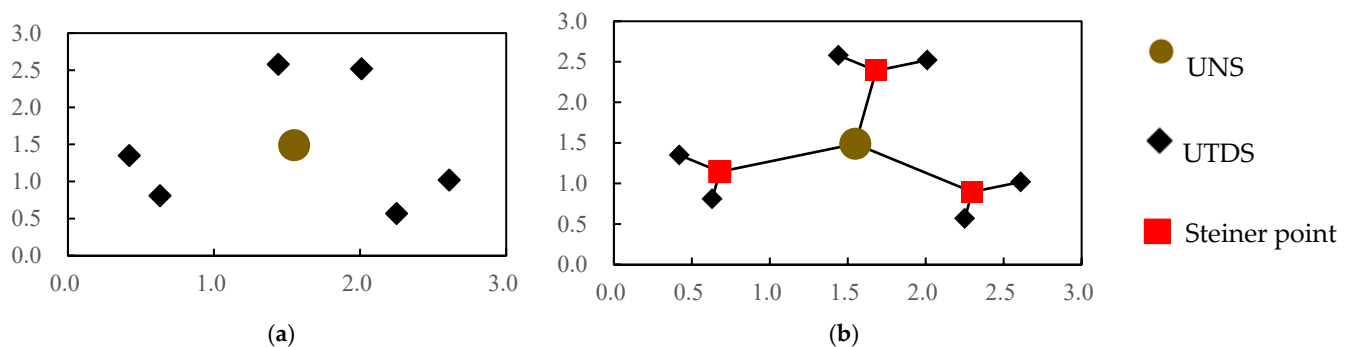


Figure 6. Example of optimization results for the pipelines laying between UNS and UTDC. (a) Site Distribution Figure. (b) Optimization Results.

Table 6. Point coordinate values in Figure 6.

Point	X	Y	Point	X	Y
UNS	1.50	1.50	UTDS 5	2.25	0.57
UTDS 1	0.42	1.35	UTDS 6	2.61	1.02
UTDS 2	0.63	0.81	Steiner point 1	0.68	1.14
UTDS 3	1.44	2.58	Steiner point 2	1.68	2.39
UTDS 4	2.01	2.52	Steiner point 3	2.30	0.90

Note: For the convenience of display, UTDS coordinates are converted from the UNS as the center datum.

Figure 7 takes the optimization case in Figure 6 as an example to show the differences between IPGSA and PGSA. After the 45th growth, the set of growing points of IPGSA became empty, and obtained the best value of 1.81, while the PGSA was forced to stop after the 100th growth to obtain the optimal value of 1.91. Therefore, the IPGSA is superior to the traditional PGSA in efficiency and accuracy, and the advantage in efficiency is more significant.

(3) Pareto fronts of the optimized in different scale scenarios

The above algorithm is nested into the bilevel programming solution process, and the optimal calculation results of the case of Beijing are shown as follows.

Figure 8 presents the Pareto fronts of the optimized in four different scale scenarios, the size of the sphere reflects the carrier's selection rate in this state and projects the three-dimensional point coordinates onto the coordinate plane. As seen from the X–Y plane, the objective of construction cost f_1 and the objective of operation cost f_2 are roughly in the opposite trend. It seems that the objective of penalty cost f_3 is not directly related to the f_1 and f_2 , but it is closely related to the carrier selection rate. The higher the carrier selection rate, the lower the penalty cost of the network, which indirectly shows that it is meaningful to consider the game relationship between government investment and carrier mode selection. However, this phenomenon is not absolute, from the highlighted points S1 and S2. The disparity in the choice of carriers between these two points is not significant,

but there is a noticeable difference in the cost of f_3 . We compared and analyzed the network planning information of the above two points, as shown in Table 7, and explained the causes of the above scenarios as follows.

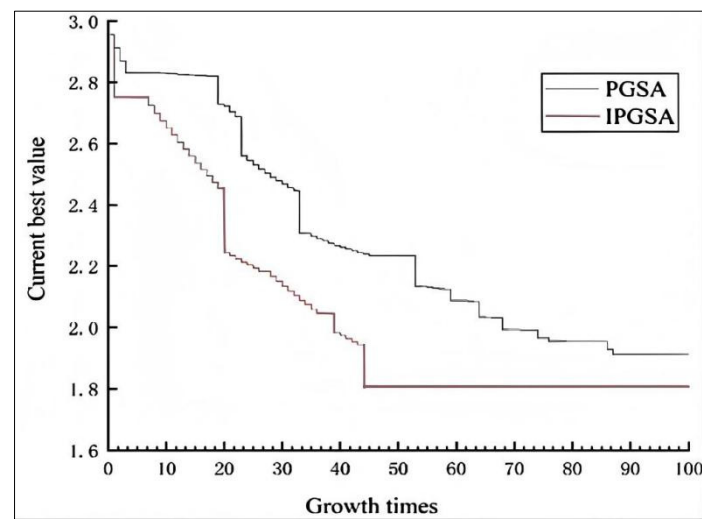


Figure 7. Improvement efficiency of IPGSA algorithm.

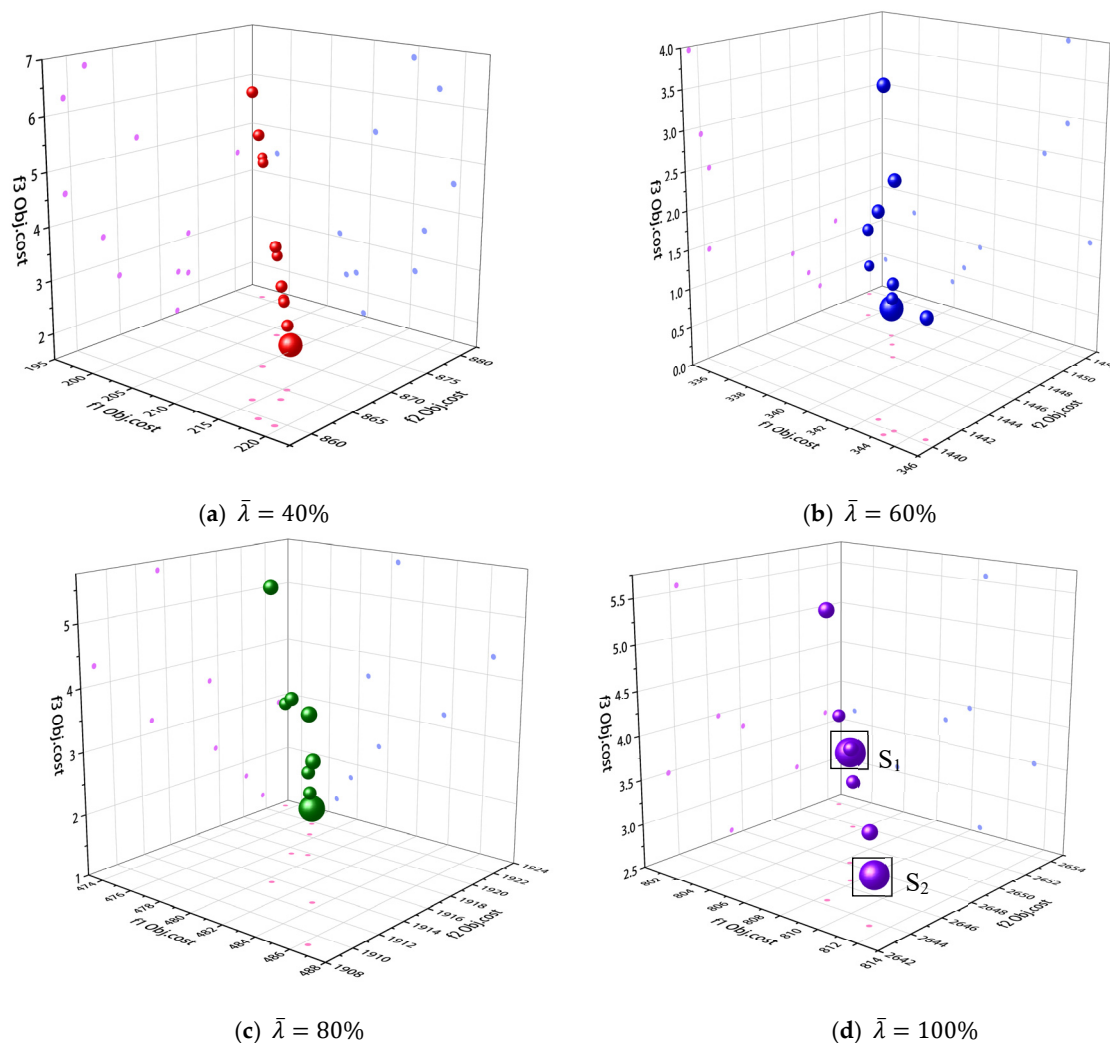
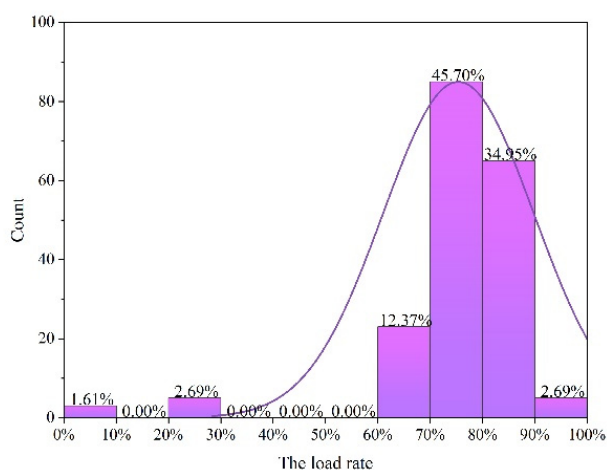
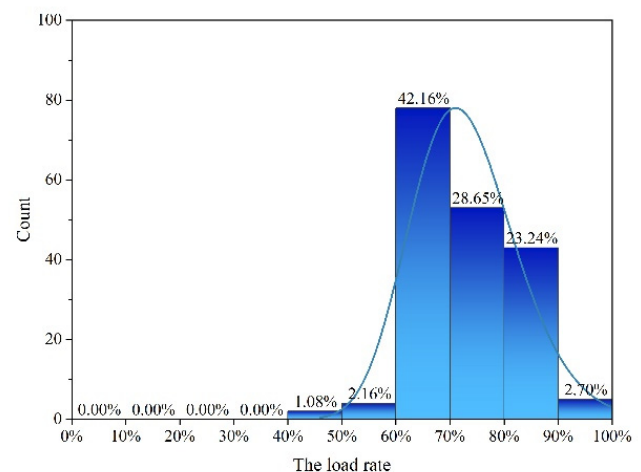


Figure 8. Pareto solution sets of four optimal network sizes.

Table 7. Main parameters of network construction in different scenarios.

λ	Number of TDS/UTDS	Number of UIS/UIS-F	Number of UNS/UNS-F	f_1 Obj.cost (USD 10^3 per Day)	FDL Length (km)	UP Length (km)	Ave. Coverage Radius of UNS (km)
40%	280/56	17/0	71/19	209.50	15.64	31.49	1.34
60%	421/84	20/2	88/35	339.90	29.90	53.91	1.43
80%	561/112	25/6	104/48	476.56	48.3	64.93	1.21
100%	702/140	37/8	149/90	808.40	106.23	77.96	1.03

Compared scenarios with S1 and S2, UIS-F is added, and a FDL is set up to connect with it in scenario S2. This route reduces the transport mileage and transfer times from CLP-3 to UNSs-79~81, so the operating cost is also reduced. In scenario S1, however, only one UNS-F is built, and the transport is completed by using the existing network, so the transportation mileage is slightly longer, and the operating cost is slightly higher. In addition, we compare the site load in two situations in detail, as shown in Figure 9. The station load ratio shows an extremely unbalanced phenomenon in scenario S1, while in scenario S2, it is more balanced, and the load rate is concentrated near the minimum load rate without penalty. Therefore, the objective f_3 of S1 is higher. We adjust μ (the minimum load rate without penalty) to 70%, this situation is reversed, the objective f_3 of S1 is USD 57.88×10^3 per day and S2 is USD 67.31×10^3 per day.

**(a) Scenario S1****(b) Scenario S2****Figure 9.** Comparison of site load in Scenarios S1 and S2.

(4) Network optimization scheme with the highest carrier selection rate

We select the scenario with the highest carrier selection rate under each optimal solution to carry out the next analysis. Table 8 lists the network construction parameters in different scenarios, and Table 9 lists the network operation parameters in different scenarios. Figure 10 shows the optimal network layout scheme in different scenarios.

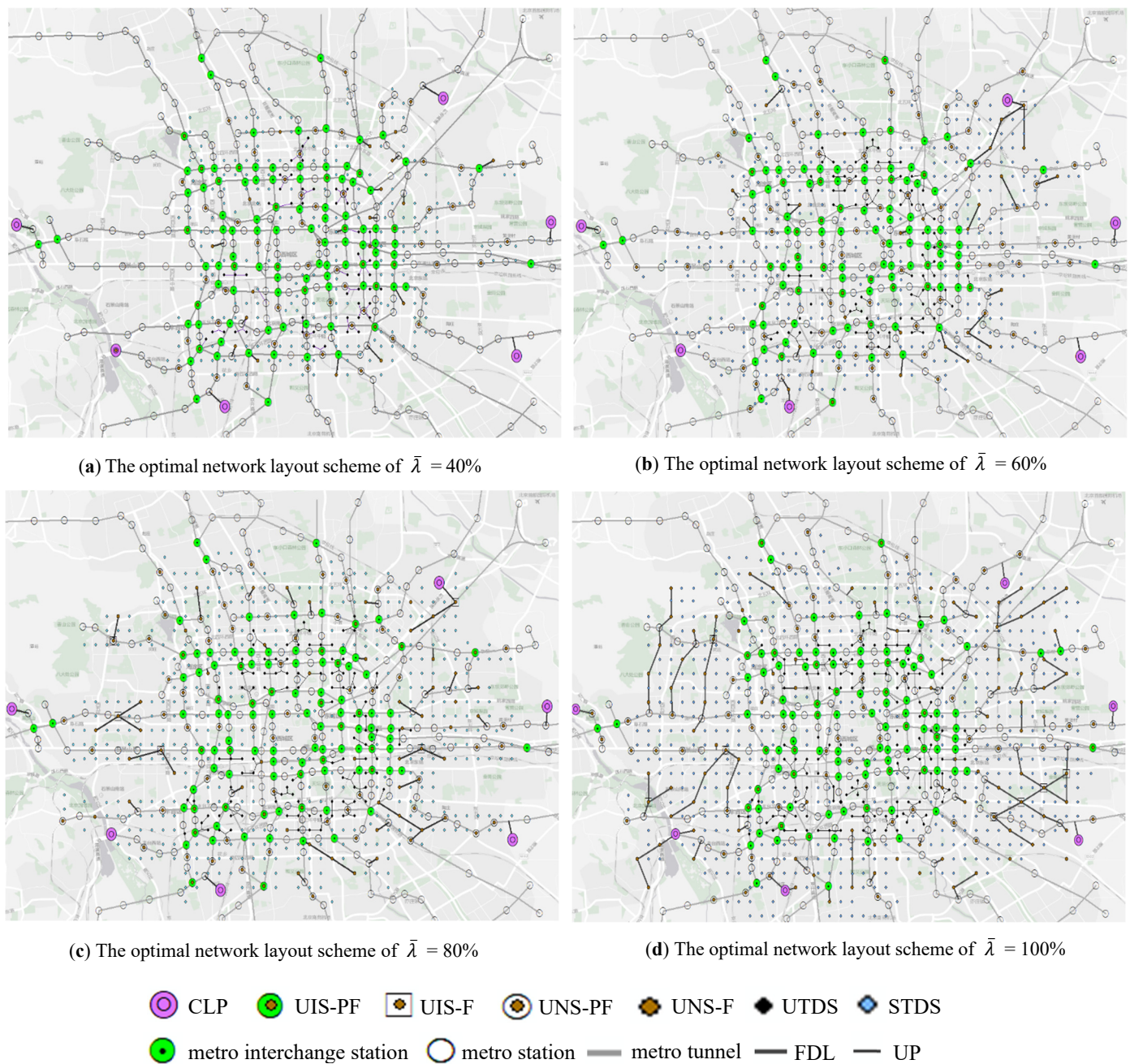


Figure 10. Optimal Network Layout Scheme.

Table 8. Main parameters of network operations in different scenarios.

λ	Number of TDS/UTDS	Number of UIS/UIS-F	Number of UNS/UNS-F	f_1 Obj.cost (10 ³ USD per day)	FDL Length (km)	UP Length (km)	Ave. Coverage Radius of UNS (km)
40%	280/56	17/0	71/19	209.52	15.64	31.49	1.34
60%	421/84	20/2	88/35	339.91	29.90	53.91	1.43
80%	561/112	25/6	104/48	476.56	48.3	64.93	1.21
100%	702/140	37/8	149/90	808.42	106.23	77.96	1.03

Table 9. Main parameters of network operation in different scenarios.

λ	f_2 Obj.cost (10 ³ USD per Day)	f_2 Obj.cost (10 ³ USD per Day)	ALR (%)	TF (Million Parcels)	TTC (USD 10 ³ per Day)	SR (%)	AUT (km per Parcel)	ATOC (USD per Parcel km)
40%	872.1	1.56	86.85	4.18	125.34	59.89	19.37	0.0108
60%	1447.96	0.38	93.25	6.87	206.02	76.59	20.42	0.0104
80%	1921.7	1.28	90.64	9.59	239.8	80.23	19.34	0.0104
100%	2648.16	3.78	82.76	12.07	318.84	83.34	21.32	0.0100

Note: ALR: Average load rate of the facilities; TF: Total freight; TTC: Total transfer cost; SR: Shipper selection rate; AUT: Average underground transportation distance of each cargo; ATOC: Average transport operating cost.

The total number of UNS and UIS in each scenario is 88, 108, 129 and 186, respectively, and the length of FDL is 47.13 km, 83.81 km, 113.23 km and 184.19 km, respectively. The average coverage radius of UNS fluctuates within 1.03 km~1.43 km. The total freight of the M-ULS network has increased from 4.18 million parcels to 12.07 million parcels per day. The total transfer cost increased from USD 125.34×10^3 to USD 318.84×10^3 per day. There is obvious scale effect in network operation, and the average operating cost is reduced from USD 0.0108 per parcel km to USD 0.0100 per parcel km. The selection rate of carriers also increased from 69.89% to 85.34%.

(5) Analysis of Optimal Network Configuration Scale

There is an increasing marginal cost in the network, as shown in Table 10. With the expansion of network scale, the total cost rose from USD 1083.16×10^3 to USD 3460.34×10^3 , and the average freight first decreased and then increased, when $\lambda = 60\%$, the minimum average freight is USD 0.0128 per parcel km. For each new unit traffic volume, the total cost increment will increase from USD 0.0119 to USD 0.0148. For an increase of 1% of the carrier's selection rate, the total cost will increase from USD 42.22×10^3 to USD 341.09×10^3 , an increase of nearly seven times. And when the network reaches the maximum scale, the average load rate of all facilities is 82.76%, which is the lowest in all scenarios; however, when $\bar{\lambda} = 60\%$, the average load rate reaches the highest (93.25%). We compare the key indicators in different scenarios, as shown in Figure 11 (the data in the figure is standardized). Obviously, there is an optimal configuration scale of the network, which means that if the network scale reaches a certain level, the cost of increasing the unit benefit will increase more and more, and the utilization rate of the network will also decline.

Table 10. Marginal Cost of Network Expansion.

λ	TC (USD 10 ³ pre Day)	TF (million Parcel km)	AF (USD per Parcel km)	SR (%)	MC== $\Delta TC/\Delta TF$	MSC= $\Delta TC/\Delta SR$
40%	1083.16	80.93	0.0134	59.89	—	—
60%	1788.24	140.24	0.0128	76.59	0.0119	42.22
80%	2399.54	185.51	0.0130	80.23	0.0135	167.94
100%	3460.34	257.41	0.0134	83.34	0.0148	341.09

Note: TC: Total Cost; TF: Total Freight; AF: Average Freight; SR: Shipper Selection Rate; MC: marginal cost; MSC: Marginal Selection cost.

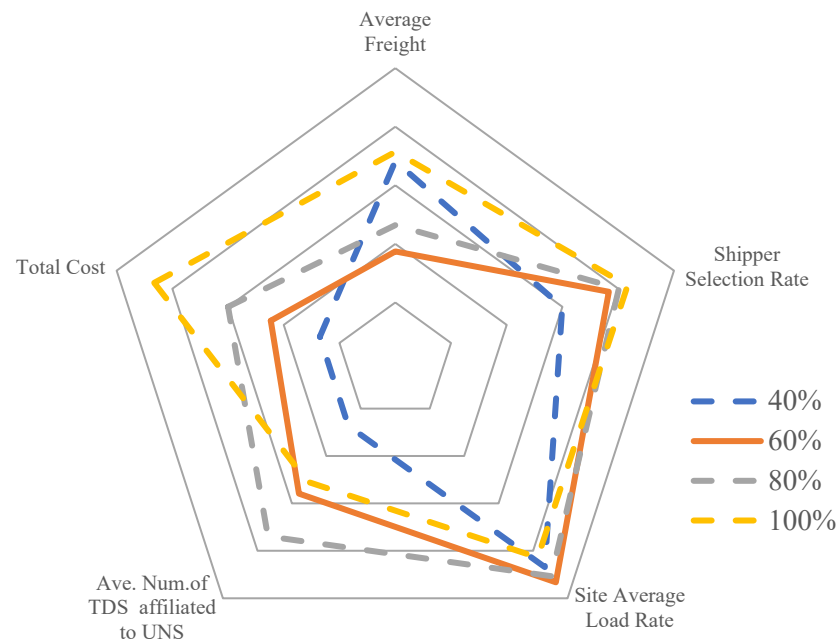


Figure 11. Comparison of Key Indicators under Different Scenarios.

In addition, we also measure the benefits of freight transportation in four network scales to alleviate traffic congestion, to further evaluate the economy of different network scales. Due to the excessive number of stations, we select stations along Line 6 with high load rate as local exhibitions, as shown in Figure 12. The benefit B_j of relieving traffic congestion at each station is defined as shown in Equation (36), where TFV and UFV, respectively, represent the total freight volume around the station and the underground traffic volume of the station, and φ_j is the congestion index of the station j , which is used to reflect the urgency of underground logistics to relieve traffic congestion in this area. As shown in Figure 12, under the scale of $\bar{\lambda} = 60\%$, the cumulative effect of the network on the main congested areas has exceeded 50%. If the network scale continues to increase, the mitigation rate of the network on the non-congested areas will be improved, while the mitigation effect on the congested areas will be almost saturated. This phenomenon shows that the M-ULS network has made outstanding contributions to improving the urban traffic environment to a certain extent, and the contribution will decline with the expansion of the network scale.

$$B_j = \frac{TFV - UFV}{TFV} \cdot \varphi_j \quad (36)$$

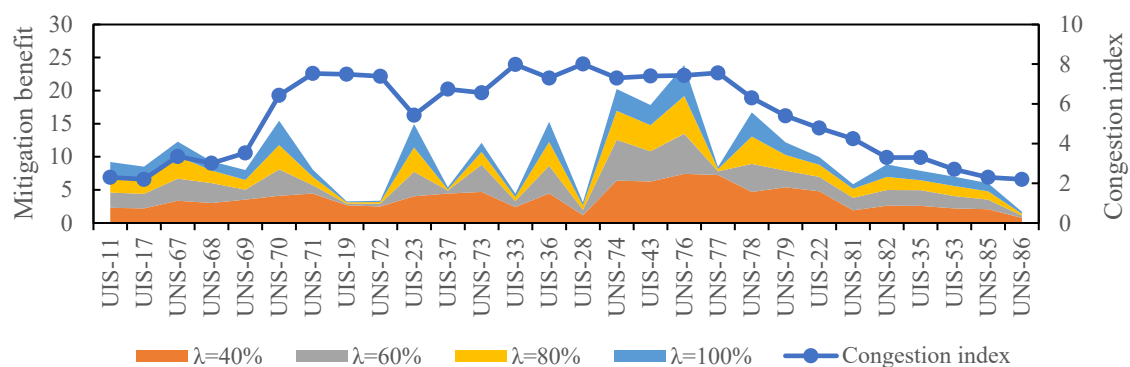


Figure 12. Cumulative benefits of traffic congestion mitigation in different scenarios. (Taking stations along Line 6 as examples).

Comprehensive Table 10 and Figures 11 and 12, the second scenario ($\bar{\lambda} = 60\%$) has the best network economic benefits. Under this scale, the utilization rate of network sites is the highest, the average cost of network construction and operation is the lowest, and the number of freight station service and distribution sites is also higher. In addition, the marginal cost of improving unit traffic volume and carrier's selection rate is also the smallest compared with the $\lambda = 40\%$ scenario.

Therefore, we choose the optimal scenario of network economic benefits as an example to show its general situation of operation, which is arranged as follows. The network consists of 108 freight stations (including 18 UIS-PFs, 2 UIS-Fs, 53 UNS-PFs and 35 UNS-Fs), serving 421 TDSs (including 84 UTDSs and 337 STDs). There are 59 freight stations serving more than 5 TDSs, among which the number of TDS attached to stations UIS-8, UIS-12 and UIS-17 is the largest, reaching 9. UNS-19 has the largest number of UTD (the total number is 5) and the longest underground pipeline (the total mileage is 2.13 km). In terms of station freight volume (excluding transshipment volume), there are 36 freight stations with a handling capacity of more than 100,000 parcels, of which UIS-8 has the largest handling capacity and is almost saturated, reaching 197,339 parcels; Most of the other freight stations have a workload of 50,000~100,000 parcels, and a few have a workload of less than 150,000 parcels, of which UNS-32 is the least, with 11,342 parcels. 70.87% of the interchange stations in the network undertake the cargo transshipment, with the maximum transshipment volume of 457,351 parcels and the minimum 7302 parcels. Among the UISs, UIS-4 station has a freight volume of 474,504 parcels, including 425,801 parcels, with the highest transfer rate of 89.73%; the transfer capacity of other transfer stations is about 50%, and the transfer rate of UIS-20 is the smallest, accounting for 42.72%. In terms of line freight volume, Metro Line 6 connects two CLPs, and the maximum freight volume reaches 1,037,174 parcels; Metro Line 16 followed, reaches 932,521 parcels; Metro Line 10 (loop line) has the highest transshipment capacity, with 783,468 parcels. The average freight volume of FDL is 94,501 parcels, of which the highest freight volume is FDL 1 (137,537 parcels) and the lowest freight volume is FDL 10 (53,709 parcels). The average freight volume of each section of UPs is 24,731 parcels, which range from 12,806 to 45,378 parcels.

(6) Sensitivity analysis of maximum coverage radius parameter

To test the influence of the parameter of maximum coverage radius E_j^{max} on the model, this section takes $\bar{\lambda} = 60\%$ network scale as an example, for E_j^{max} set five control experiments of 0.5, 1.0, 2.0, 2.5, and 3.0, Comparing with $E_j^{max} = 1.5$, a box plot was used to demonstrate the distribution of solution sets for the daily total cost of the network and carrier selection rate obtained using the bilevel programming algorithm for each group of experiments, as shown in Figure 13.

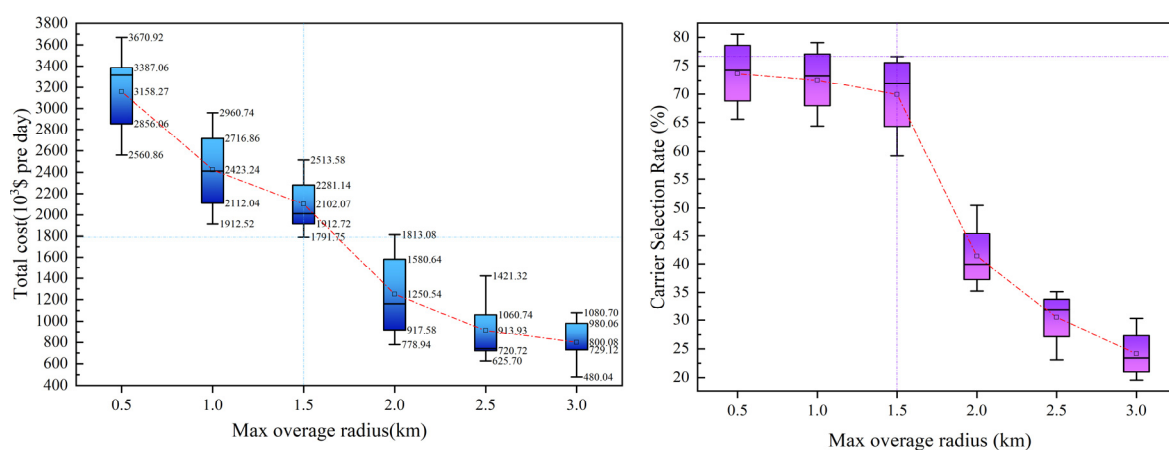


Figure 13. The impact of maximum coverage radius on total cost and carrier selection rate.

In Figure 13, The optimal solution corresponding to the settings for this chapter ($\bar{\lambda} = 60\%$, $E_j^{max} = 1.5$) has been marked with reference lines. As shown, with the increase in network coverage radius, the total cost of the network decreases uniformly, while the carrier selection rate fluctuates less in the range of $E_j^{max} = 0.5$ to $E_j^{max} = 1.5$. When $E_j^{max} > 1.5$, there is a significant decrease. Therefore, the sensitivity analysis results can indicate that the model in this chapter is set to $E_j^{max} = 1.5$ is relatively economically reasonable, and the model and algorithm are reliable in responding to subtle changes in constraints and can effectively adjust to the optimal solution.

7. Conclusions

This paper designs a three-echelon network structure for M-ULS, establishes a multi-objective bilevel programming model and designs a multi-stage accurate-heuristic hybrid algorithm framework for network optimization. Firstly, we used an E-TOPSIS model to screen terminal delivery stations to determine the network scale in different scenarios by setting up four key indicators. Then, considering the interests of both government and carriers, respectively, establish the upper model of location-allocation-path combination optimization based on capacity constraints (CLARP) and the lower model based on carrier's generalized minimum cost. In the process of solving the model, fully considering the dynamic game relationship between the upper and lower levels, we constructed a multi-stage solution algorithm framework by combining the branch-and-bound accurate algorithm and the heuristic algorithm based on AICSA and IPGSA. Finally, taking the six central districts of Beijing as a case study, the optimization results of network configuration in different scenarios were analyzed, and $\bar{\lambda} = 60\%$, was selected as the optimal scale of network construction through key evaluation indicators.

The calculation results show that the AICSA and IPGSA have better accuracy and higher convergence speed. As far as operating cost is concerned, there is obvious scale effect. With the expansion of the network, the average operating cost has dropped from USD 0.0108 per parcel km to USD 0.0100 per parcel km. As far as the total cost is concerned, the marginal cost of the network is increasing. When the network scale reaches a certain level, if it continues to expand the network scale, the cost of increasing the unit benefit will be larger and larger, and the utilization rate of the network will decline.

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