MULTI-OBJECTIVE OPTIMIZATION MODEL FOR PLANNING METRO-BASED UNDERGROUND LOGISTICS SYSTEM NETWORK: NANJING CASE STUDY

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ABSTRACT. Utilizing rail transit system for collaborative passenger-and-freight transport is a sustainable option to conquer urban congestion. This study proposes effective modeling and optimization techniques for planning a city-wide metro-based underground logistics system (M-ULS) network. Firstly, a novel metro prototype integrating retrofitted underground stations and newly-built capsule pipelines is designed to support automated inbound delivery from urban logistics gateways to in-city destinations. Based on four indicators (i.e. unity of freight flows, regional accessibility, environmental cost-saving, and order priority), an entropy-based fuzzy TOPSIS evaluation model is proposed to select appropriate origin-destination flows for underground freight transport. Then, a mixed integer programming model, with a well-matched solution framework combining multi-objective PSO algorithm and A* algorithm, are developed to optimize the location-allocation-routing (LAR) decisions of M-ULS network. Finally, real-world simulation based on Nanjing metro case is conducted for validation. The best facility configurations and flow assignments of the three-tier M-ULS network are reported in details. Results confirm that the proposed algorithm has good ability in providing high-quality Pareto-optimal LAR decisions. Moreover, the Nanjing M-ULS project shows strong economic feasibility while bringing millions of Yuan of annual external benefit to the society and environment.

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1. Introduction. Economic vitality of cities largely depends on the circulation efficiency of means of production and the holistic performance of urban supply chain. The urban logistics is defined as a series of commercial, household, and manufacturing freight transport activities aiming at creating temporal and spatial efficacy of things within city boundaries [29]. Hitherto, urban goods movement operates following a road-dominating mode. The high cost, low efficiency, and negative externalities caused by truck travels are pushing heavy burden on urban economy, society and environment [5, 6]. In Chinese megacities, for example, the direct operating cost of social logistics accounts for 13%-15% of the urban GDP, and 50% of the cost is attributed to the trucking and the manual work of last-mile delivery [34]. In addition, freight transport generates around 30%-60% of local transport-related pollution, and consumes approximately a quarter of the road traffic capacity [11]. Although there are several attempts to pursue the maximization of logistics efficiency, such as crowdsourcing [12], just-in-time logistics, and joint distribution [22], they produce little effect on the improvement of social logistics performance from the wholesale. Instead, the government has to devote excessive resources and expenditures (e.g., truck access restrictions and parking policies) to regulate urban logistics operations [35]. In addition, those innovative transport technologies such as electric vans (EVs) and parcel drones do not seem as satisfactory as they are thought. Based on our surveys, the EV initiatives sponsored by the local administration of Beijing, China, have last over a decade, whereas the overall rate of modal shift from gasoline trucks to EVs is still less than 10%. Moreover, the adoption of EVs may encounters barriers, such as the land occupation due to installing charging sites and the aggravating congestion and accidents [27]. Confined by loading capacity and powering, the applicability of parcel drones for the long-distance large-size cargo transport in downtown urban district is still limited at current stage [25].

As an important supplementary of urban supply chain, the concept of utilizing high-capacity pipelines for commercial logistics was first proposed in 1970s [19], named as the underground freight transportation system or the underground logistics system (ULS). In the early initiatives, ULS planning mostly focuses on building simple infrastructure that consists of numerous underground depots and tunnel segments to connect airports, seaports and other logistics centers for the point-to-point cargo transfer [13]. Representative systems are the automatic palletized flower tray shipping pipelines planned around the Amsterdam Schiphol Airport [30] and the underground container line planned at the Port of Houston [23]. As more ULS technical prototypes are proposed, the potential of utilizing ULS network for the extensive in-city delivery gradually arouses attention, and several pilot projects have been activated, such as the CargoCap system tested in German cities, the Pipejet system tested in Italian cities, and the Magway system planned in London metropolitan area. Existing literature has argued that the implementation of large-scale urban underground freight transport can generate huge direct economic incomes and save billions of annual external losses from the aspects of logistics cost, energy use, carbon emission, land occupation, and mobility [8]. Meanwhile, a robust underground logistics network can significantly enhance urban transport resilience and emergency ability against pandemic outbreak.

Despite huge demand and business perspective, the high cost of underground construction and maintenance greatly hinders the stakeholders’ awareness for developing ULS [7]. Currently, several inter-cities dedicated ULS lines have been
substantially funded, such as the CST system in Switzerland [36] and the CargoSpeed system in USA [37]. However, the initiatives of developing ULS network within urban regions have not aroused sufficient investment interest so far. Different from the former, a newly-built urban ULS project has to undergo long-term period before it shapes sizeable benefit [7]. By contrast, another underground freight transport concept with much less investment shows stronger feasibility, that is, to dually utilize the existing metro systems for collaborative passenger-and-freight transport, hereinafter named as the M-ULS. Available literature maintains that the surplus transport capacity of metro can be fully exploited to support large-scale underground goods movement [26]. In addition, a wide-spread M-ULS network has significant social-environmental benefit and service capability which are equivalent to those of the dedicated ULS [17].

The embryo of M-ULS concept first appeared in some European cities (e.g., Zurich, Paris, Amsterdam and Dresden), where the old-fashioned tram and light rail lines were retrofitted to transport homogeneous commodities from suburban factories to in-city stores [28, 3]. Most of the ongoing M-ULS systems were designed by placing individual freight units inside the original passenger carriage or compartmenting specific carriage for units loading and unloading. Dampier and Marinov [10] investigated the profitability and external benefits of using one metro line to transport cargo pallets from airport to the downtown of Newcastle upon Tyne district. Behiri et al. [2] proposed a hybrid mixed integer programming (MIP) and discrete event simulation technique to address the dual passenger-freight timetabling and train scheduling issues of single metro line. Zheng et al. [32] stated that most of the interviewed commuters approved to split carriage room for placing freight units during off-peak hours, and such collaborative passenger-and-freight transport pattern could save one-third of the delivery cost. Zhao et al. [33] proposed a hybrid TOPSIS and MIP approach to locate freight stations in the Shanghai metro network based on a “circular and radial” structure. The MIP model and meta-heuristic algorithm were developed by Dong et al. [9] for the location-allocation decision-making in the simplified Nanjing metro network with two intersecting lines. Hu et al. [15] maintained that the service performance of M-ULS could be largely improved through incorporating logistics function into the design of conventional metro passenger stations, tunnels and trains.

The majority effort of M-ULS network research were mainly devoted to plan freight transport path on the simple metro lines by following small-batch distribution and manual in-station handling ideas. By reviewing the state-of-the-art of worldwide M-ULS practice and literature, one can notice that the focus of previous relevant studies was mostly put on monotonous decision, small-size, single-stage, and single objective M-ULS network planning problems, whereas the holistic planning and global layout optimization of a large-scale M-ULS network were neglected, especially when the system planning horizon is emphasized on more complex metro facilities (such as transfer stations) and higher requirements of whole-process automated underground logistics to realize fully-automated, city-wide underground freight transport in urban district. As far as we know, no literature has tackled the large-scale discrete combinatorial decisions (with number of decisions and constraints over 100 million) of M-ULS network with hybrid evaluation and optimization procedures. Given that the current knowledge of M-ULS network planning lag far behind its project practice, there is an urgent need to explore the effective operations research technique for relevant decision-making.
To bridge the gap, this study deals with the problem of planning a city-wide underground freight transport infrastructure network where the existing metro lines are retrofitted to support hub-level parcel transport and the capsule pipelines are newly established for the spoke-level distribution from metro stations to customer destinations. The detached operation model proposed by Hu et al. [15] is referred as the planning basis of M-ULS network. This study has the following novelties.

- We consider a three-tier M-ULS network that connects metro freight stations with a variety of small-diameter local pipelines to realize nearly 100% door-to-door automated movement of urban delivery orders. The modeling and optimization method for a more comprehensive decision portfolio of M-ULS network layout that includes node location, customer allocation, and flow routing, are proposed.

- A novel two-stage mathematical model for M-ULS network planning is proposed. In the first stage, the service scope of M-ULS network determined via an Entropy-TOPSIS-Fuzzy evaluation method. In the second stage, M-ULS network layout is optimized from a Pareto front perspective by means of integrating the objectives of minimal network construction cost, minimal operating cost, and maximal system utilization jointly.

- An improved multi-objective particle swarm optimization algorithm is developed to solve model with good performance. Validity of the proposed algorithm and model have been testified in the Nanjing metro case using real-life data.

The remainders of this paper are organized as follows. Section 2 describes the network planning problem and the applied case profile. In Section 3, a two-stage mathematical programming model is described. Section 4 presents the solution method. In Section 5, simulation results of Nanjing M-ULS network schemes are discussed. Finally, Section 6 summarize the findings and points out future research directions.

2. System design and problem statement. The M-ULS network is planned to incorporate the distribution process of business-to-customer (B2C) orders from suburban logistics parks and warehouses (LPWs) to in-city customer destinations. Figure 1 depicts the decisions and facility relationships with regard to the considered three-tier M-ULS network design (3EM-ULSNd) problem. Therein, the first-tier of M-ULS network is composed by six sorts of facilities [15], namely, LPWs, access railways, freight terminuses, non-transfer freight stations (NFSs), interchange freight stations (IFSs), and metro line segments. The second-tier of M-ULS network consists of NFSs, capsule pipeline segments (CPs), spoke underground depots (UDs), as well as satellites and demand clusters (SCs). The third-tier M-ULS network refers to the ground delivery paths from UDs to SCs.

The transport process of M-ULS network is described as follows. At first, parcel orders demanded by different SCs are sorted, palletized and loaded at LPW. The freight trains, which have similar technical specifications with the passenger metro trains, carry orders from LPW to the nearest metro station (known as freight terminus), then drive into the metro network. The freight terminus is defined as a specific metro station that has direct connection with one or more LPWs. The overground or subterranean railway section should be built in-between. Freight trains and passenger trains depart from the terminus alternatively. Two train echelons share the same rail tracks and keep safe distance during underground trips. When arriving at the scheduled NFS, freight trains pass through track switches and docks at the independent freight platforms for loading and unloading within the stipulated time.
After that, the train waits for the timely-adjusted schedule, leave the platforms and move to the next NFS along metro line. If the scheduled NFS locates on other metro line, the corresponding orders would experience an underground in-station transfer at IFS beforehand. When arrives at passenger station, freight train stops at the passenger platform for the same duration as passenger train does (about 30 to 60 seconds). Such procedures repeat until it reaches terminus. Note that the original passenger interchanges can be retrofitted to equip with the functions of NFS and IFS simultaneously. The freight handling capacity at NFS and the freight transfer capacity at IFS are both limited.

At NFS, units are unloaded from the train to the freight station platform of NFS automatically. The in-station conveyor belt system and shaft system are used for freight carrying, moving and transfer. Necessary logistics work, including sorting, unpacking, storage, stacking, tally and assembly, are paid to handle the freight container units turn into a series of deliverable parcels that are well sorted and checked. The in-station logistics activities could be highly-automated by installing various modules (e.g., conveyor system, moving/stacking robots, radio frequency identification devices, and automatic storage/retrieval system) in the unoccupied underground space of metro station. Well-processed orders are distributed to UD facilities via the local CP networks which are built to connect each NFS with its affiliated UDs. When orders reach UDs, they are directed to the ground and finally delivered to nearby customer destinations with a very short road trip.

The objectives of 3EM-ULSND problem are to minimize the system construction cost and operating cost while maximizing other performance such as the external
benefit and utilization level. Specifically, M-ULS network planning involves the following six parts of combinatorial decisions: (i) to evaluate whether the customer orders are suitable for underground transport and determine the service scope of M-ULS; (ii) to locate NFSs among metro station set; (iii) to locate UDs among SC set; (iv) to allocate SCs to UDs; (v) to assign the transport path of orders in the underground network; (vi) to determine the layout of local CP network.

Nanjing is one of the largest logistics hub city of the East China. The throughput of postal delivery orders and online express parcels in Nanjing have exceeded one billion pieces since 2019 [38]. The total business volume of urban logistics was nearly three trillion Yuan. Surging B2C demand causes huge pressure to the traffic mobility and significantly damaging urban ecology. It is estimated that the annual external losses due to congestion and light goods vehicle (LGV) emissions in Nanjing have exceeded ten billion Yuan, approximately 40% of which attributes to goods movement. To ease the situation, local administrators have to exert strict access restriction policies by specifying that 90% of the LGVs travel in and out downtown areas are only permitted during night-time.

The Nanjing metro system is one of the most advanced urban rail transit systems in China. At present, the whole metro network is 378 km, with 10 lines and 174 stations that are mostly built underground. Considering the high accessibility, we chose the Nanjing metro network as the benchmarking case for M-ULS planning. Figure 2 depicts the geographic information of the studied area. Therein, a total of 488 km² urban district and 5.8 million residents are divided into 440 plots of land based on the population density. Each plot represents a SC. Four major logistics gateways of Nanjing are selected as the LPWs. For modelling convenience, we have adjusted the coordinates of LPWs to overlap with the coordinates of the nearby metro terminuses. In line with the Nanjing logistics data given in the previous work, we determined the demand of each urban resident that is transported by M-ULS as 0.7 parcels per-day (namely $30cm \times 30cm \times 30cm$ in size). The orders of each resident are randomly delivered from one of the LPWs. The orders are accumulated to each SC, forming a numerical matrix with a scale of $4 \times 440$.

The benchmarking metro network for M-ULS planning covers four Nanjing metro lines. We have slightly modified the geographical position of metro facilities and added several virtual stations based on GIS data, aiming at improving the closeness between SCs and the metro network. A total of 82 metro stations are considered as the potential location of NFSs, and seven passenger interchanges are considered to support underground freight transfer by default. In order to clarify the modelling boundaries, a set of assumptions and specifications are proposed as follows.

- Each NFS is connected to its affiliated UD via a point-to-point CP segment. Any deviation of CP length owes to geographical factors (e.g., gradient and geological barriers) is ignored.
- Only the inbound urban logistics flows are considered in the considered problem. Other logistics flows of M-ULS (such as reverse flows and intra-city flows) can be modelled and optimized following a similar idea.
- No direct link exists between the NFSs and the SCs that are not selected as UDs. No cost is needed for retrofitting passenger interchange as IFS.
- Each SC is allocated to unique UD, and each UD is allocated to unique NFS.
- Not all the urban delivery orders have to be transported by M-ULS network. However, the system should absorb customers’ demand as much as possible according to the predefined capacity.
Transport capacity of the metro line $s$ is not consumed by the orders that are transferred from other lines to line $s$.

3. **Model development.** In this section, model formulations of the 3EM-ULSND problem are explicated. The holistic modeling process is divided into two stages. In the Stage (I), we propose an E-TOPSIS-F model to decide whether the delivery orders of each SC are transported by M-ULS or LGVs. In the Stage (II), a multi-objective nonlinear MIP model is established to characterize the location-allocation-routing (LAR) decisions of M-ULS network.

3.1. **Stage (I): The entropy-TOPSIS model with fuzzy triangular numbers (E-TOPSIS-F).** The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), firstly put forward by Hwang and Yoon [16], is a soft operations research approach to settle the multi-attributes decision-making issues under finite alternatives. The idea of TOPSIS is to calculate spacial gaps between the closeness degree of each alternative and the most preferred one to the system attributes being assessed. However, the TOPSIS relies much on subjective rating. It is often difficult to assign rating to each alternative reasonably. To eliminate subjective biases, the concepts of fuzzy set and entropy weight are integrated into the body of TOPSIS.
Therein, the relative importance of attributes is assigned using fuzzy numbers (e.g., triangular fuzzy interval values), so that the uncertain information on decisions can be represented. Moreover, the mechanism of Shannon’s information entropy helps decision makers to measure the contrast intensities of multiple criteria and locate the objective differences in a convenient way [4]. In this study, the E-TOPSIS-F model is used to evaluate the contribution of delivery orders to the attribute values of underground freight transport applicability, then select those orders with high contribution as the service objects of M-ULS. A specific alternative signifies that the order from LPW \( s \) to SC \( m \) is transported by M-ULS. The attributes under evaluation are associated with M-ULS network performance, such as benefit and efficiency. The general evaluation process of E-TOPSIS-F is performed via four steps, namely (i) attribute quantification, (ii) fuzzy matrix normalization and entropy weighting, (iii) relative closeness calculation, and (iv) selection criteria.

3.1.1. Attribute quantification. The purpose of origin-destination (O-D) evaluation is to enhance the value and operating performance of underground freight transport by removing the unsuitable demand order flows from the planning scope of M-ULS network. In Dong et al. [9], the authors considered two attributes, named as the unity of freight flows (UFF) and the regional accessibility (RA), to decide whether the specific order could be served by M-ULS. In this study, we rewrite the original formulas of these two attributes by adding more adjustment factors from real-world perspectives. Moreover, we put forward two new attributes, named as the environmental and resource cost-saving (CV) and the order priority (OP), to conduct more comprehensive evaluation upon M-ULS network flows.

(i) Unity of freight flows: the-bigger-the-better

UFF attribute is defined as the demand weighted travel distance metric between LWP and SC. The delivery order with higher UFF value indicates that the relevant flow is more concentrated while exerting greater influence on urban road traffic. It is more necessary to shift the transport activity of this order from above to underground.

\[
a_{m_1}^{s} = E_u(s, m) \cdot (g_{s}^{m})^{\rho_{s}} \cdot \forall s, m \in M
\]

where the \( E_u(s, m) \) represents the Euclidean distance from LPW \( s \) to SC \( m \), and the \( \rho_{s} \) is the size correction factor of the delivery order \( g_{s}^{m} \).

(ii) Regional accessibility: the-smaller-the-better

RA attribute is expressed as the actual road transport distance of delivery orders multiplied by the reciprocal of corresponding travel time. The ratio of travel distance to time-cost reflects the efficiency of city logistics, with a lower value of RA indicating worse accessibility of road traffic, lower average travel speed, and higher preference of using M-ULS to transport the order.

\[
a_{m_2}^{s} = \frac{E_u(s, m) \cdot C_{dist}(s, m)}{\Phi(s, m)} \cdot \forall s, m \in M
\]

Given that urban road network is tortuous in shape, the couriers usually detour journey rather than follow the shortest road path. In order to mimic such influence, during the October 2021 to the November 2021, we conducted a preliminary survey to the local LGV drivers in Nanjing to acquire the travel paths from LPWs to in-city destinations they actually adopted. In Equation 2, the ratios of the actual trip length to the Euclidean length constitute a coefficient matrix \( C_{dist}(s, m) \). The empirical matrix \( \Phi(s, m) \) denotes the time-consuming of LGV travels during congestion period. The value of \( \Phi(s, m) \) was also obtained from survey.
(iii) Emission and resource cost-saving: the-bigger-the-better

CV attribute is to calculate the pollutant reduction benefit and non-renewable energy conservation benefit of M-ULS. Higher CV value indicates that more benefit can be generated by shifting the transport mode of order.

\[ a_{mn}^s = 2 \times g_m \cdot \vartheta^{-1} \cdot Eu (s, m) \cdot C_{dist} (s, m) \cdot \left( \frac{\zeta \cdot pri + \varepsilon_{CO2} \cdot eff_{CO2} + \varepsilon_{CO} \cdot eff_{CO} + \varepsilon_{NOx} \cdot eff_{NOx} + \varepsilon_{PM} \cdot eff_{PM}}{\mu_{min}} \right) \]  

Based on Hu et al. [17], the external cost-saving of underground freight transport is estimated via aggregating the use cost of the non-renewable energy consumed by LGV trips and the environmental loss due to LGV emissions. In Equation 3, the environmental loss of per kilometre LGV trip is calculated based on the emission factors \( eff \) of main LGV exhausts (i.e., \( CO_2, CO, NO_x \) and \( PM \)) and the corresponding treatment expenditures \( \varepsilon \). The \( \vartheta \) is the loading capacity of LGV, the \( pri \) is gasoline price, and the \( \zeta \) is the gasoline consumption factor of LGV.

(iv) Order priority: the-bigger-the-better

OP attribute is represented by the profitability of utilizing M-ULS network to serve the deliver order. Network flows with higher OP value indicates that they have higher priority to be transported underground, which could enlarge the economic performance of M-ULS operations.

\[ a_{mn}^s = g_m^s \cdot prof_{sm} \cdot \left( \frac{E_{max} - \gamma_{sm}}{E_{max} - E_{min}} \right) q_{sm}, \forall s \in S, m \in M \]  

where the \( prof_{sm} \) denotes the unit operating income for transporting \( g_m^s \) by M-ULS, the \( \gamma_{sm} \) is the width of delivery time window that satisfies the range of max-min order response period \( E_{min} \leq \gamma_{sm} \leq E_{max} \), the \( q_{sm} \) is a time sensitive factor, randomly valued between \( 0 \) and \( 1 \).

3.1.2. Fuzzy matrix normalization and entropy weighting. According to Equation 5, the triangular fuzzy number of the nth attribute of certain alternative (i.e., whether \( g_m^s \) is transported by M-ULS) under uncertain scenario \( x \) is written as a piecewise coefficient function \( \omega_{mn}^s (x) \), where \( \mu_1, \mu_2, \mu_3 \) are the randomly generated real numbers satisfying \( \mu_1 < \mu_2 < \mu_3 \). The value of \( x \) in \( \mu_2 \) presents a minimal fuzzy degree of attribute \( a_{mn}^s \). The constants \( \mu_1 \) and \( \mu_3 \) represent the upper and lower limits of function. The smaller the interval between \( \mu_1 \) and \( \mu_3 \), the greater the accuracy of the evaluation data. Define \( \tilde{a}_{mn}^s (x) \rightarrow \omega_{mn}^s (x) \cdot a_{mn}^s \).

\[ \omega_{mn}^s (x) = \begin{cases} \frac{x-\mu_1}{\mu_2-\mu_1}, & \mu_1 < x \leq \mu_2 \\ \frac{x-\mu_2}{\mu_3-\mu_2}, & \mu_2 < x \leq \mu_3 \end{cases} \]  

The min-max normalization method is adopted to eliminate the difference of evaluation criteria. Particularly, all attributes are classified into two categories: (i) the-bigger-the-better and (ii) the-smaller-the-better, the normalized equations of which are written as \( \tilde{a}_{mn}^s = \max_m \tilde{a}_{mn}^s (x) - \min_m \tilde{a}_{mn}^s (x) \) \( \max_m \tilde{a}_{mn}^s (x) - \min_m \tilde{a}_{mn}^s (x) \) and \( \tilde{a}_{mn}^s = \max_m \tilde{a}_{mn}^s (x) - \min_m \tilde{a}_{mn}^s (x) \) \( \max_m \tilde{a}_{mn}^s (x) - \min_m \tilde{a}_{mn}^s (x) \) respectively. To formulate \( \tilde{a}_{mn}^s (x) \) in a crisp form, for each attribute, the value of the independent variable \( x \) is randomly determined between \( \mu_1 \) and \( \mu_3 \) based on the normal distribution \( N = (\mu_2, 0.33 \times (\mu_3 - \mu_2)^2) \). The information entropy of the nth attribute
can be calculated by Equation 6, where \( \bar{D}_{mn} = \frac{\bar{a}_{mn}}{\sum_{m \in M} \bar{a}_{mn}} \) and \( ||M|| \) is the size of customer set. Let \( \ln \bar{D}_{mn} = 0 \) when \( \bar{D}_{mn} \) equals zero. The entropy weight of the \( n \)th attribute with regard to metro line \( s \) is calculated by Equation 7. Finally, the crisp normalized decision matrix of the whole alternatives is constructed as \( P_{mn} = \bar{a}_{mn} \times b_n^s \).

\[
e(s, n) = -\ln ||M|| \cdot \sum_{m \in M} \bar{D}_{mn} \cdot \ln \bar{D}_{mn}
\]

\[
b_n^s = \frac{1 - E(s, n)}{\sum_{n \in \Omega} [1 - E(s, n)]}
\]

3.1.3. Relative closeness calculation. TOPSIS procedures are performed to calculate the relative closeness score which could reflect the relative superiority of alternatives. To formulate the ideal solution and the negative ideal solution using Equations 8 and 9, where \( n \in \Omega' \) associates with the-bigger-the-better attributes, and \( n \in \Omega'' \) associates with the-smaller-the-better attributes, satisfying \( \Omega' + \Omega'' = \Omega \).

\[
T_s^+ = \left\{ \left( \max_m \bar{a}_{mn} | n \in \Omega' \right), \left( \min_m \bar{a}_{mn} | n \in \Omega'' \right) \right\} = \left\{ A_{s1}^+, A_{s2}^+, \ldots, A_{sM}^+ \right\}
\]

\[
T_s^- = \left\{ \left( \min_m \bar{a}_{mn} | n \in \Omega' \right), \left( \max_m \bar{a}_{mn} | n \in \Omega'' \right) \right\} = \left\{ A_{s1}^-, A_{s2}^-, \ldots, A_{sM}^- \right\}
\]

Third, to measure the Euclidean distance between each alternative and two ideal points via \( Q_{sm}^+ = \sqrt{\sum_{n \in \Omega} (A_{sn}^+ - \bar{a}_{mn})^2} \), \( Q_{sm}^- = \sqrt{\sum_{n \in \Omega} (\bar{a}_{mn} - A_{sn}^-)^2} \). The relative closeness of alternative is calculated as Equation 10.

\[
RC_{sm} = \frac{Q_{sm}^-}{Q_{sm}^+ + Q_{sm}^-}
\]

The value of relative closeness reflects the relative superiority of the alternatives. Larger \( RC_{sm} \) indicates that the logistics order \( d_{sm}^s \) has higher priority to be served by M-ULS.

3.1.4. Selection criteria. The alternative can be determined by Equation 11, where \( g_{sm}^s \) and \( d_{sm}^s \) are the initial delivery order and the order after evaluation, \( v_{sm} \) is the binary variable that equals to 1 if the relative closeness value of \( g_{sm}^s \) exceeds the threshold value \( RC_{sm} \). \( RC_{sm} \) is a subjectively determined value of which meaning is to control the total order size inputted to metro line \( s \), and ensure its freight transport capacity \( cap_s \) is not exceeded.

\[
d_{sm}^s = g_{sm}^s \cdot v_{sm}, v_{sm} = \begin{cases} 1, & 1 \geq RC_{sm} \geq RC_{sm} \\ 0, & \text{otherwise} \end{cases}, \forall s \in S, m \in M
\]

3.2. Stage (II): The location-allocation-routing model. The MIP model proposed for making LAR decision-making of M-ULS network is represented by the notations, decision variables, basic constraints and objective functions.

3.2.1. Symbols and notations. Relevant indices and symbols used for modelling are listed in Table 1. Note that the values of some key exogenous parameters (e.g., construction cost and transport cost) are determined based on empirical knowledge, government documents and related literature, which guarantee the proposed model and simulation outputs with better ability to interpret real-world planning issues.
MINIMIZE THE PENALTY COST DUE TO LOW LOAD OPERATIONS OF NFSs AND CPs.

M-ULS network and the underground transfer cost at IFSs. The objective

minimize the total operating cost, which consists of the freight transport cost in

rail equipment has been integrated into the cost of NFSs. The objective

equally based on 100-year project lifecycle. The retrofit cost of metro tunnels and
daily deprecation values of facilities are calculated via sharing the total investment

fixed cost of M-ULS network facilities (i.e., NFSs, UDs and CPs). Typically, the
written as Equations 12, 13 and 14. Therein, the objective

Derivation of objective functions and constraints.

3.2.2. Derivation of objective functions and constraints. The model objectives are
written as Equations 12, 13 and 14. Therein, the objective \( f_1 \) is to minimize the total fixed cost of M-ULS network facilities (i.e., NFSs, UDs and CPs). Typically, the
daily deprecation values of facilities are calculated via sharing the total investment
equally based on 100-year project lifecycle. The retrofit cost of metro tunnels and
rail equipment has been integrated into the cost of NFSs. The objective \( f_2 \) is to
minimize the total operating cost, which consists of the freight transport cost in
M-ULS network and the underground transfer cost at IFSs. The objective \( f_3 \) is to
minimize the penalty cost due to low load operations of NFSs and CPs.

\[
\min f_1 = \sum_{i \in N} \lambda_2 \cdot \theta \cdot X_i + \sum_{m \in M} \lambda_3 \cdot \theta \cdot Y_m + \sum_{h \in H} \lambda_1 \cdot \theta \cdot W_h \cdot Eu_h \quad (12)
\]

\[
\min f_2 = \sum_{s \in S} \sum_{m \in M} d^s_m \left[ \sum_{k \in K} \alpha \cdot c \cdot Eu_k \cdot O_{skm} + \sum_{j \in L} \delta_{smj} \cdot w \right] + c \cdot \sum_{s \in S} \sum_{m \in M} d^s_m \sum_{r \in R} Eu_r \cdot \xi_{smr} + \beta \cdot \sum_{s \in S} \sum_{m \in M} d^s_m \sum_{h \in H} Eu_h \cdot T_{shm} \quad (13)
\]

Table 1. Model parameters and values

| Notation of indices | Definition | Attribute |
|---------------------|------------|-----------|
| S                   | set of LPWs, i.e., set of metro lines | indexed by \( s \) |
| M                   | set of SCs, i.e., set of candidate location of UDs | indexed by \( m \) |
| \( N \)             | set of metro stations, i.e., set of candidate location of NFSs | indexed by \( i \) |
| \( L \)             | set of metro interchanges, i.e., set of activated IFSs | indexed by \( j \) |
| \( K \)             | set of metro line arcs between two adjacent metro stations | indexed by \( k \) |
| \( H \)             | set of arcs between metro stations and SCs | indexed by \( h \) |
| \( R \)             | set of arcs between two SCs | indexed by \( r \) |

**Exogenous parameters**

| \( g^s_m \) | size of delivery orders from LPW \( s \) to SC \( m \) (original value) | [0,15] parcel per-day |
| \( d^s_m \) | size of delivery orders from LPW \( s \) to SC \( m \) (after evaluated) | – |
| \( c \) | freight travel cost by LGV | ¥ 0.2 per-parcel per-km |
| \( \alpha \) | ratio of the freight travel cost by metro to the freight travel cost by LGV | 10% |
| \( \beta \) | ratio of the freight travel cost by CPs to the freight travel cost by LGV | 25% |
| \( w \) | underground transfer cost at IFS | ¥0.1 per-parcel |
| \( \lambda_1 \) | fixed cost for CP construction | ¥4 × 10^7 per-km |
| \( \lambda_2 \) | fixed cost for NFS retrofit | ¥1 × 10^7 |
| \( \lambda_3 \) | fixed cost for UD construction | ¥2 × 10^7 |
| \( \eta_{NFS} \) | allowable level for low load operations at UD | 60% |
| \( \eta_{CP} \) | allowable level for low load operations at CP | 50% |
| \( \sigma_{NFS} \) | penalty cost due to low load operations of UD | ¥2 per-parcel |
| \( \sigma_{CP} \) | penalty cost due to low load operations of CP | ¥1.5 per-parcel |
| \( R_{max} \) | maximal road travel distance from UD to SC | 2km |
| \( Q_{max} \) | order handling capacity of NFS | 1 × 10^6 parcel per-day |
| \( Z_{max} \) | transport capacity of CP | 4 × 10^6 parcel per-day |
| \( G_{max} \) | order handling capacity of UD | 3.5 × 10^6 parcel per-day |
| \( T_{max} \) | order transfer capacity of IFS | 1.5 × 10^6 parcel per-day |
| Eu | Euclidean distance of arc \( k, r \) and arc \( h \), respectively | – |
| \( \theta \) | depreciation coefficient of M-ULS network facilities | 1/25550 |

**Binary variables**

| \( X_i \) | 1, if metro station \( i \) is selected as NFS | – |
| \( \delta_{smj} \) | 1, if \( d^s_m \) is transferred at IFS \( j \) | – |
| \( Y_m \) | 1, if SC \( m \) is selected as UD | – |
| \( W_h \) | 1, if arc \( h \) is selected as CP | – |
| \( U_{sm} \) | 1, if the trip of \( d^s_m \) on the second-tier M-ULS network is assigned by NFS \( i \) | – |
| \( \xi_{sr} \) | 1, if \( d^s_m \) traverses on arc \( r \) via road segment | – |
| \( O_{skm} \) | 1, if \( d^s_m \) traverses on arc \( k \) via metro segment | – |
| \( T_{sh} \) | 1, if \( d^s_m \) traverses on arc \( h \) via CP segment | – |
\[
\min f_3 = \sum_{i \in N} \max \left\{ \sum_{s \in S} \sum_{m \in M} \eta_{NFS} \cdot [Q_{\text{max}}] - d_m^{\sigma} \cdot U_{smi}, 0 \right\} \cdot \sigma_{NFS} \\
+ \sum_{h \in H} \max \left\{ \sum_{s \in S} \sum_{m \in M} \eta_{CP} \cdot [Z_{\text{max}}] - d_m^{\sigma} \cdot T_{smh}, 0 \right\} \cdot \sigma_{CP}
\] (14)

Constraint 15 ensures that the size of orders handled at each NFS and the size of orders transferred at each IFS do not exceed their respective capacity.

\[
\sum_{s \in S} \sum_{m \in M} d_m^{\sigma} \cdot U_{smi} \leq [Q_{\text{max}}], \sum_{s \in S} \sum_{m \in M} d_m^{\sigma} \cdot \delta_{smj} \leq [T_{\text{max}}], \forall i \in N, j \in L
\] (15)

Constraint 16 ensures the handling capacity of UD and the maximal road travel distance on the third-tier M-ULS network are not violated.

\[
\sum_{s \in S} \sum_{m \in M} d_m^{\sigma} \cdot V_{smmr} \leq [G_{\text{max}}], Eu \cdot \xi_{smr} \leq [R_{\text{max}}], \forall s \in S, m \neq m' \in M, r \in R
\] (16)

Constraint 17 states that the transport capacity of CP is not violated.

\[
\sum_{s \in S} \sum_{m \in M} d_m^{\sigma} \cdot T_{smh} \leq [Z_{\text{max}}], \forall h \in H
\] (17)

Constraint 18 indicates that the arc \(k\), arc \(r\) or arc \(h\) can only be visited by certain flow for once. Each order served by M-ULS is allocated to unique NFS and unique UD.

\[
\sum_{i \in N} U_{smi} = \sum_{h \in H} T_{smh} = \sum_{m' \in M} V_{smmr} = \sum_{r \in R} \xi_{smr} = 1, \forall s \in S, m \in M
\] (18)

Constraint 19 indicates that the assignments of flows on the second-tier M-ULS network and the third-tier M-ULS network will not occur if relevant NFS or UD is not established.

\[
U_{smi} \leq X_{si}, V_{smmr} \leq Y_{m'r}, \forall s \in S, i \in N, m \neq m' \in M, r \in R
\] (19)

Constraint 20 implies that no flow travels on arc \(h\) if relevant CP segment is not established.

\[
\sum_{i \in N} U_{smi} \cdot T_{smh} \leq W_{sh}, \forall s \in S, m \in M, h \in H
\] (20)

Constraint 21 guarantees that the arc \(r\) cannot be selected as a road path on the third-tier network if it has been selected as CP.

\[
\xi_{smr} \leq (1 - Y_{m}), V_{smmr} \leq (1 - Y_{m}), \forall s \in S, m \neq m' \in M, r \in R
\] (21)

Constraint 22 indicates that each UD is directed connect to unique NFS via CP, and each SC is allocated to unique UD. Constraint 23 ensures that each order flow must pass through at least one metro line segment (i.e., arc \(k\)). No order shall be transferred over twice on the metro network.

\[
\sum_{s \in S} \sum_{i \in N} U_{smi} = 1, \sum_{s \in S} \sum_{m' \in M} V_{smmr} = 1, \forall m \in M
\] (22)

\[
\sum_{k \in K} O_{smk} \geq 1, \sum_{j \in L} \delta_{smj} \leq 2, \forall s \in S, m \in M
\] (23)
Constraint 24 is flow conservation constraint that assures the equilibrium of O-D flow size among different network tiers.

\[
\begin{align*}
\sum_{s \in S} \sum_{m \in M} \sum_{k \in K} O_{smk} &= \sum_{s \in S} \sum_{m \in M} \sum_{i \in N} U_{smi} = \sum_{s \in S} \sum_{m \in M} \sum_{h \in H} T_{smh} \\
\sum_{s \in S} \sum_{m \in M} \sum_{m' \in M} V_{smm'} &= \sum_{s \in S} \sum_{m \in M} \sum_{r \in R} \xi_{smr} > \sum_{s \in S} \sum_{m \in M} \sum_{j \in L} \delta_{smj}
\end{align*}
\] (24)

3.2.3. Pareto front optimality. The proposed LAR model aims to solve a multi-objective optimization problem (MOP) where the three sub-objectives are conflicting with each other, considering that more underground facilities (i.e., NFSs and CPs) could help diminish the M-ULS network operating cost (i.e., \( f_1 \)) but also increase the fixed network cost and the penalty cost (i.e., \( f_2 \) and \( f_3 \)). In many cases, it might be hard for decision makers to clearly weight the importance of model objectives, especially when their measurement standard is inconsistent. The Pareto optimal set is a concept to achieve an ideal assignment of optimality among different objectives of MOP. Instead of optimizing each objective to its fullest, the Pareto-based algorithm tries to seek to a group of trade-off solutions simultaneously for which each objective has been optimized to the extent. The solutions with advantageous performance consist a Pareto front in the searching space of MOP. As depicted in Figure 3, in order to compare the advantage of solutions, the non-domination sorting is applied to assign each solution with a priority rank. There are two main parameters in this procedure [1], namely the number of solutions dominating a specific solution (\( N_p \)) and a set of solutions prevailed by the specific solution (\( S_p \)). The decision makers can determine Pareto front shape by configuring the archive of non-dominated solution list and adjusting the estimation approach of crowding distance metric among objective functions, then select the most favourable solution from Pareto front according to personal preference. In terms of obtaining high-quality non-dominated solutions, two well-known evolutionary-based algorithms, i.e., the non-dominated sorting genetic algorithm II (NSGA-II) and the multi-objective particle swarm optimization algorithm (MOPSO) have been proposed. They have been largely applied in solving different MOPs, such as hub location-allocation problem [21] and urban delivery network planning problem [31].

3.2.4. Model complexity analyses. The proposed LAR model incorporates the portfolio decisions from the capacitated location-allocation problem (CLAP) and the multi-depot vehicle routing problem (MVRP). Therein, the latter could be regarded as a sub-problem and the former is the master problem. Wide-ranging evidences have showed that either CLAP or MVRP belongs to NP-hard problem [24]. As a result, their combination also has NP-hard complexity. Taking the Nanjing Metro case for instance, the total number of binary variables and constrains in the presented model is estimated to be 300 million (see Table 2). Moreover, rising in facility quantity and O-D pairs will lead to a sharply exponential increase of model constraints. Obviously, the conventional exact algorithms or commercial MIP solvers is intractable to deal with the large-scale simulation of LAR model within an affordable period of time. By contrast, the meta-heuristic techniques show advantage in enhancing computational efficiency. In this study, we propose a hybrid procedure combining MOPSO algorithm and A* algorithm to solve the 3EM-ULSND problem.

4. Solution approach. The holistic flowchart of the proposed hybrid heuristic algorithm is depicted in Figure 4. Therein, the location-allocation decisions from the master problem are derived and iterated by MOPSO, which act as the main
loop of optimization. For each loop, the A* algorithm is invoked to quickly find the shortest path of flows under current M-ULS network layout scheme, so that a set of complete LAR solutions can be structured for the following fitness evaluation and non-dominated sorting. The A* algorithm, proposed by Hart et al. [18], is a famous pathfinding algorithm that enables rapid estimation for the shortest route in a weighted multi-start graph using the Breadth-First-Search heuristics. Previous studies have proven that such divide and conquer strategy can significantly downgrade the searching dimension of optimization problems and accelerate the overall convergence efficiency [14].

PSO is an efficient evolutionary algorithm based on swarm intelligence, firstly proposed by Kennedy and Eberhart [20]. The idea of PSO originated from studying the predatory behavior of bird populations, that is, the fast way to find food is to search the area around the bird which is currently closest to food. PSO treats each individual as a particle, and uses fitness function to assess whether the particle is in the right place. Particle’s velocity determines the direction and distance of its movement, and can be dynamically adjusted to the best position according to the moving experience of other particles in the swarm. PSO has advantages in terms of memorability, premium information sharing and strong global searching ability.
The variants of PSO have been largely applied, such as the MOPSO. However, it is easy to be trapped in local optima due to early-maturing. Moreover, the traditional PSO treats particle position and velocity updates as continuous function, which may confine its performance in solving large-size discrete location problems.

In this study, the MOPSO algorithm is improved from two aspects. Firstly, the particle update process incorporates a binary discrete procedure to deal with vast 0-1 encoded decision strings. Secondly, the single-dimensional full-component chaotic local search operators and the immune operators are jointly used to enhance the local searching quality of MOPSO.

4.1. Encoding and initialization. The performance of evolutionary algorithm heavily depends on the problem’s encoding method. In this regard, we a hybrid binary and real number encoding scheme to represent specific LAR decisions in M-ULS network. Each particle is encoded by four numerical arrays with different length. Therein, the first 0-1 array (N dimensions) denotes if the metro station corresponds to the array bit number is selected as NFS or not. The second 0-1 array (M dimensions) denotes if the SC is selected as UD. The real number in the third array (M dimensions) represents to which number of metro station the SC is directly connected through CP, while it in the fourth array (M dimensions) represents to which number of SC (i.e., UD) the current bit SC is allocated.

In line with particle structure, the initial population is generated. The fitness of individual $i$ is formulated as a vector. As seen Equation 25, the vector elements denote the reciprocal values of three sub-objectives multiplied by an amplification coefficient. Controlled by the binary variable $\varphi (i)$, a punishment factor $G$ will acts on the objective values if individual do not obey relevant model constraints.

$$F (i) = \left\{ \frac{f_1(i)^{-1}, f_2(i)^{-1}, f_3(i)^{-1}}{1 + G \cdot \varphi (i)} \right\}$$ (25)

4.2. Particle state updates. Let $pbest$ be the historical best position of individual $i$, and $gbest$ be the global best position of the particle swarm achieved until current generation $t$. The update of particle velocity from generation $t$ to $t + 1$ is written as Equation 26, where $c_1$ and $c_2$ are learning factors; $r_3$ and $r_4$ are random numbers between $[0,1]$; $\theta$ is the inertia weight that keeps individual motion, calculated as $\theta = \theta_{\text{max}} - (\theta_{\text{max}} - \theta_{\text{min}}) (t - GEN_{\text{max}})$; $GEN_{\text{max}}$ is the maximum generation numbers.

$$v_{t+1}(i) = \theta \cdot v_t(i) + c_1 \cdot r_3 \cdot [pbest_t(i) - p_t(i)] + c_2 \cdot r_4 \cdot [gbest_t - p_t(i)]$$ (26)

For the binarization of location-allocation decisions, we use the Sigmoid function to convert the continuous particle velocity into an exponential form of which value is between $[0,1]$. The update of particle position at generation $t + 1$ is written as Equation 27.

$$F_{t+1}(i) = \begin{cases} 1, \text{if rand} < \frac{1}{1 + e^{-v_{t+1}(i)}} \\ 0, \text{otherwise} \end{cases}$$ (27)

The single-objective optimization problems commonly use a roulette method to select extremums. However, this method does not work for MOPs, because there is no absolute dominance exist among Pareto solutions corresponding to different objectives. Therefore, we propose a new selection strategy for choosing multidirectional global extremum and individual historical extremum from Pareto-optimal set. Supposing the Pareto-optimal set is $R = \{ R_1, R_2, \cdots, R_n \}$, the selection strategy of $pbest$ is depicted as Equation 28. Therein, $F_t(i)$ is the fitness vector of particle $i$
at generation $t$, and $s(R_i, R_j)$ represents the included angle between $F_t(i)$ and the fitness vector of the solution $R_j$ in Pareto-optimal set. Then update the historical best position of particle $i$ according to $S(R_i)$.

$$ S(R_i) = \min_{j \in \{1, 2, \ldots, n\}} s(i, R_j) = \min_{j \in \{1, 2, \ldots, n\}} \arccos \frac{F_t(i) \cdot F_t(j)}{|F_t(i)| \cdot |F_t(j)|} $$  \hspace{1cm} (28)

4.3. **Local exploration.** In order to improve population diversity and local searching ability of algorithm at early stage, the immune selection procedure with crossover
operator is first conducted upon those 50% worse particles with low fitness. We determine the intersectable position of particles based on the feasible LAR decisions. The antibody concentration of the particle is used as the crossover probability. Equation calculates the probability of particle being selected for crossover, where $\varsigma$ is a constant regulator ranged between $[0,1]$.

$$PB(i) = \frac{1}{N} \cdot e^{-\varsigma \sum_{k=1}^{N} |\vec{F}_i(i)| - |\vec{F}_i(k)|}^{-1}$$ (29)

Meanwhile, to produce better offspring, the proximity of the parent particles needs to be evaluated. The crossover is performed only when the Euclidean distance between particle $i$ and particle $j$ is greater than the threshold value $D_a$. Otherwise, the particles will be deleted and reselected. The above logic is expressed as Equation 30, where $x_i^{f_1}(i)$ is the projection of particle position $p_i(i)$ on the axis of objective $f_1$.

$$D_a < d_{i,j} = \sqrt{[x_i^{f_1}(i) - x_j^{f_1}(j)]^2 + [x_i^{f_2}(i) - x_j^{f_2}(j)]^2 + [x_i^{f_3}(i) - x_j^{f_3}(j)]^2}$$ (30)

Chaotization procedure ensures the particles traverse through searching space without repeating in a certain range, so as to enhance the ergodicity and randomness of individuals when performing local search. The single-dimensional full-component chaotic operator is exerted upon those 50% best particles with high fitness to reduce the possibility of being trapped in local optima. Equation 31 describes the chaotic operation, where $b^n_m$ and $b^m$ are the chaotic solution of the $n$th objective and the $m$th component of the current optimal solution; $B^n_m$ is the $m$th component of $B_n$; $Y^n_m$ is a random number between $[0,1]$; $\kappa$ is the chaos control factor; $\Delta^m_{up}$ and $\nabla^m_{low}$ are upper and lower searching bounds of the $m$th components from $R$. For the Pareto-optimal set of current population, if the $n$th fitness value has been repeated with the historical data for the third time, then the chaotic operator is activated. Firstly, assign the chaotic perturbation $B_n$ to the $[1^{st}, m^{th}]$ components of the solution set $R$, respectively. Then generates $b$ number of chaotic solution vectors. Secondly, calculate the fitness of chaotic solutions and compare them with the original value in $R$. Thirdly, substitute the chaotic solution with best fitness for its counterpart, and regard it as the global best solution of current generation.

$$b^n_m = b^m + \kappa \cdot (\Delta^m_{up} - \nabla^m_{low}) \cdot B^n_m; B^n_m = \left\{ \begin{array}{ll} 4\sin \frac{2\pi}{\gamma_m}; & \forall m = n \\ 0; & \forall m \neq n \neq 0 \end{array} \right.$$ (31)

5. Case study.

5.1. Simulation setup. This section demonstrates the effectiveness of the proposed methodology in optimizing a large-scale real-world 3EM-ULSND problem based on Nanjing city metro case. The studied area and the parameter values of LAR model for simulation have been presented in Figure 2 and Table 1. The parameter values referring to the E-TOPSIS-F model are determined based on available literatures [17], inputted as follows: $\theta=200$ parcel per-LGV; $\varsigma=0.125$ liter per-km; $pri=7.14$ per-litter; $capa=7.5 \times 10^2$ parcel per-day; $\varepsilon_{CO_2}=712$ per-ton; $eff_{CO_2}=284.7$ gram per-km; $\varepsilon_{CO}=3.390$ per-ton; $eff_{CO}=1.67$ gram per-km; $\varepsilon_{NO_2}=103.201$ per-ton; $eff_{NO_2}=1.01$ gram per-km; $\varepsilon_{PM}=263.354$ per-ton; $eff_{PM}=0.12$ gram per-km; $\overline{RC}_{sm}=0.575$. Moreover, to ensure high-quality solution, the parameters for running MOPSO are calibrated as follows: $c_1=1.5; c_2=1.5;$
Table 3. Evaluation outputs of Nanjing M-ULS network flows

| LPW 1 | LPW 2 | LPW 3 | LPW 4 |
|-------|-------|-------|-------|
| Accessed metro line | Line 1 | Line 2 | Line 3 | Line 4 |
| Total demand orders ($ \times 10^3$ parcel per-day) | 1,237 | 1,028 | 1,141 | 654 |
| Average value of $RC_{sm}$ | 0.3025 | 0.269 | 0.3207 | 0.3436 |
| Average value of $RC_{sm}$ | 0.3025 | 0.269 | 0.3207 | 0.3436 |
| Maximum value of $RC_{sm}$ | 0.9471 | 0.9226 | 0.8901 | 0.9284 |
| Average value of $a_{s1}$ ($ \times 10^3$ parcel·km) | 58.47 | 60.2 | 58.01 | 21.83 |
| Average value of $a_{s2}$ (km/h) | 36.59 | 37.98 | 41.31 | 22.84 |
| Average value of $a_{s3}$ (¥ per-day) | 13,921 | 10,380 | 8,990 | 3,897 |
| Average value of $a_{s4}$ (¥ per-day) | 704 | 647 | 621 | 446 |
| Size of orders inputted into metro | 255 | 265 | 264 | 271 |
| Served SC number | 93.9% | 86.3% | 82.8% | 59.5% |
| Fulfillment rate of underground logistics | 57.9% | 60.2% | 60% | 61.6% |

$\theta_{max} = 0.9; \ \theta_{min} = 0.4; \ \varsigma = 0.35; \ \kappa = 0.01; \ N = 150; \ G = 200\%; \ GEN_{max} = 500$. Models and algorithms have been coded using MATLAB R2018b software package on a Windows 10 desktop with Intel Core i7-10885H CPU at 2.4 GHz and 48 GB of RAM. The best results are recorded out of ten runs.

5.2. Results discussion. The outputs of E-TOPSIS-F model are presented in Table 3. A total of 421 SCs receive M-ULS service. A total of 1,055 orders in the whole $4 \times 440$ demand O-D matrix are transported underground. The M-ULS service coverage rate of the total customer orders is calculated to be 59.94%. The business volume of M-ULS network is 2.45 million pieces of parcels per day, accounting for 60.29% of the total delivery demand in the covered area. Therein, the Nanjing Metro Line 1 captures 0.74 million parcels to be sent from LPW 1 to 255 SCs, which consumes 93.9% of freight transport capacity of the metro line. The utilization rates of the Metro Line 2 and Line 3 are calculated to be 86.3% and 82.8%, respectively. In comparison, the Metro Line 4 is much less occupied, but the served orders have the most SC destinations among all metro lines.

Table 3 depicts the evaluation results of relative closeness indicator and four aforementioned attributes. Firstly, flows from LPW 2 perform the best in terms of UFF attribute. The average point-to-point traffic volume of LPW 2 orders is $6.02 \times 10^4$ parcel·km, indicating that the orders sent from LPW 2 have longer road travel distance. Therefore, it is preferential to assign underground logistics service to the LPW 2 orders, so that more LGV trips can be eliminated. Secondly, flows from LPW 4 are featured by the best RA attribute. The average speed of LGVs for transporting LPW 4 orders is 22.84km/h, indicating that shifting a higher proportion of LPW 4 orders from road to underground can bring greater improvement on urban traffic accessibility. Thirdly, the LPW 3 orders have higher priority for underground transport according to the CV attribute. Evaluation shows that using M-ULS to transport the orders from LPW 3 to each SC can generate ¥2,189 pollution reduction and energy conservation benefits on average. Fourthly, flows from LPW 1 have better OP attribute, where the underground transportation from LPW 1 to each SC can generate an average operating income of ¥13,921.

An average CPU time of 78.262 seconds per run was spent to get the Pareto-optimal solutions of LAR model. The MOPSO-based algorithm proposed in this
Figure 5. Pareto-optimal front obtained with MOPSO

study could achieve approximately 39% of improvement in computational efficiency, when comparing with the single-objective meta-heuristic algorithm that has been developed by Dong et al. [9] to optimize a simpler M-ULS network case. After 500-generation particle updates, it is witnessed that the average $f_1$ value of particle swarm has decreased from 1,106 to 834, while for $f_2$ and $f_3$, the average values have decreased from 2,413 to 2,160, and from 1,159 to 1,086, respectively. This indicates that the high-quality Pareto-optimal solutions of 3EM-ULSND problem can be found by the proposed algorithm within a considerably short period of time.

The ultimate Pareto solution space and the Pareto fronts are demonstrated in Figure 5. The projection of the best particle positions on the $f_1$, $f_2$ and $f_3$ axis ranges between [718,1005], [2092,2287] and [816,1392], respectively. We have identified ten non-dominated solutions (NDSs) exist between $f_1$ and $f_2$, ten NDSs between $f_2$ and $f_3$, and five NDSs between $f_1$ and $f_3$. Spacial distribution of dominant solutions and NDSs on the bi-objective coordinate planes is relatively uniform, and the regular Pareto front curves are formed. Additionally, one can observe that the particles with different optimization orientations are well-partitioned, which represents the locally optimal solutions if the decision-makers only cares about minimizing fixed cost, operating cost or penalty cost of M-ULS network, respectively.

The Pareto-optimal solution that corresponds to the minimum of sum of the three objective values is picked as the best M-ULS network schemes and visualized in Figure 6. The detailed configurations of each metro freight station are depicted in Table 4. We focus first on the underground facilities. The best M-ULS network layout contains a total of 39 NFSs, 7 IFSs, 191 UDs and 254km CP segments. The
number of NFSs established on each metro line is optimized to be 13 (Line 1), 10 (Line 2), 7 (Line 3), and 4 (Line 1), excluding those NFSs that are retrofitted from the passenger interchanges. Therein, the size of orders received by the Line 1 NFSs is the largest, which amounts to 0.787 million parcels, followed by the Line 2 (0.6 million), Line 3 (0.445 million), and Line 4 (0.246 million). The average size of orders handled at each NFS that locates on Metro Line 1 is $6.05 \times 10^4$ parcels. For the NFSs locate on other lines, this figure is almost unchanged. In the Nanjing metro network, there are five NFSs of which the freight volume occupies over 95% of the in-station freight handling capacity, namely the Xin–Mo–Fan–Ma–Lu station (load rate equals 98.5%), the Zhu–Shan–Lu station (95.4%), the Tian–Yuan–Xi–Lu station (98.4%), the Cheng–Xin–Da–Dao station (97.8%), and the Yun–Nan–Lu station (96%). Furthermore, simulation results show that three NFSs, i.e., the Gang–Zi–Cun station, the Wang–Jia–Wan station, and the Nan–Jing–Jiao–Yuan station, are assigned with the least delivery orders, where only 31%-34% of the in-station logistics handling capacity are utilized.

It is noteworthy that more NFSs are configured in the downtown district of Nanjing (see the central parts of the given map). This enables the huge underground logistics orders demanded by this district is transported dispersedly, so that the
workload of single NFS can be considerably reduced. Results show that the NFS with the most affiliated SCs and the least affiliated SCs is the Zhu–Shan–Lu station (32) and the NFS-26 virtual station (2), respectively. The NFS with the most affiliated UD is the Zhu–Shan–Lu station (12). Meanwhile, a total of 15,892 parcels are handled at each UD on average, reaching an operating load rate of 45.4%. The accumulative penalty cost of NFSs due to low load operations amounts to ¥0.754 million.

The station Zhu–Shan–Lu owns the largest local CP network with a length of 20.2km, followed by the Ming–Gu–Gong station (13.8km) and the Yan–Zi–Ji station (13.1km). In M-ULS network, each NFS configures with 6.5km pipelines on average. The average transport load rate of CP segments is 39.7%, resulting a total penalty cost of ¥0.351 million. The average terminal travel distance from UD to SCs is 514 meters. The total freight transport cost of the first-tier M-ULS network equals to ¥1.19 million, therein, the freight transport cost related to Metro Line 1 occupies the biggest share, followed by the Metro Line 3. The average metro travel distance of orders from LPWs to the scheduled NFSs is calculated to be 39.74km. The total transport cost of the second-tier and the third-tier M-ULS networks are ¥0.168 million and ¥0.227 million, respectively. Among IFSs, the station Xin–Jie–Kou is featured by the largest underground freight turnover, where $7.46 \times 10^5$ parcels are transferred from Line 1 to Line 2 and $5.13 \times 10^5$ parcels are transferred reversely. The overall underground freight transfer cost of Nanjing metro network amounts to ¥0.597 million.

Results show that the total fixed cost and transport cost of Nanjing M-ULS network under the best layout scheme is ¥2.907 million per day. Therein, ¥2.19 million expenditure is related to the underground logistics activities, which is 2.05 times higher than the daily depreciated system construction investment. By multiplying (i) the unit road freight transport cost, (ii) the actual trip distance of LGVs, and (iii) the size of order O-D matrix, together, one can measure the overall in-city parcel delivery cost of Nanjing under the conventional road-based mode as ¥18.72 million per-day. In this regard, the transport modal shift from LGV to M-ULS network can reduce the current urban logistics operating expenditures by 48.4%. Finally, we calculate the external benefit of M-ULS based on Equation 3. It is found that the annual operations of M-ULS saves ¥96 million losses due to truck emission pollution, and generates ¥249 million benefits for reducing gasoline consumption. Moreover, the sum of indirect economic return and external benefit of M-ULS network amounts ¥3.62 billion per-year. Regardless of the direct incomes and fiscal revenues brought by the market and business of underground logistics, the rate of return on investment for the Nanjing M-ULS project is calculated to be 1:13.9, which ensures an excellent economic performance during system development and long-term implementation.

6. Conclusions. Shifting logistics activities from road to urban underground space has been recognized as an intelligent measure to promote sustainable development of future megacities. This paper addresses the metro-based underground logistics system network planning problem. The entire M-ULS network is designed as three interconnected tiers, where the conventional metro lines and stations are retrofitted to incorporate logistics functions, and the capsule pipelines are newly built to support further underground freight transportation from metro stations to in-city customer points. The modeling and optimization of M-ULS network decisions are
Table 4. Best configurations of Nanjing M-ULS network

| ID     | Station full name         | $N_{SC}^1$ | $N_{UD}^2$ | $d_{sm}^3$ | $d_{sm}^4$ | $L_{CP}^5$ | $R_{UD}^6$ |
|--------|---------------------------|------------|------------|------------|------------|------------|------------|
| Line 1 | NFS-1 Er-Qiao-Gong-Yuan   | 11         | 6          | 40.5       | 6.8        | 5.5        | 4.63       |
|        | NFS-2 Da-Dou-Shan         | 17         | 5          | 44.9       | 9          | 8.8        | 11.23      |
|        | NFS-3 Yan-Zi-Ji           | 17         | 9          | 80.5       | 8.9        | 13.14      | 6.6        |
|        | NFS-4 Xin-Mo-Fan-Ma-Lu    | 11         | 4          | 98.5       | 24.6       | 7.44       | 8.18       |
|        | NFS-5 Xuan-Wu-Men         | 9          | 3          | 77.8       | 25.9       | 3.36       | 3.87       |
|        | NFS-6 Zhang-Fu-Yuan       | 6          | 5          | 67.6       | 11.3       | 4.29       | 1.68       |
|        | NFS-7 San-Shan-Jie        | 4          | 3          | 37         | 12.3       | 3.66       | 0.84       |
|        | NFS-8 Zhong-Hua-Men       | 2          | 2          | 35         | 17.5       | 3.95       | 4.87       |
|        | NFS-9 Ruan-Jian-Da-Dao    | 9          | 4          | 44.9       | 11.2       | 6.01       | 4.51       |
|        | NFS-10 Hua-Shen-Miao      | 8          | 5          | 39.4       | 7.9        | 4.66       | 2.26       |
|        | NFS-11 Sheng-Tai-Lu       | 18         | 4          | 93.1       | 23.3       | 9.58       | 12.85      |
|        | NFS-12 Zhun-Shan-Lu       | 32         | 12         | 95.4       | 8          | 20.2       | 17.29      |
|        | NFS-13 Nan-Jing-Jiao-Yuan | 9          | 4          | 35.1       | 8.8        | 4.34       | 5.23       |
| Line 2 | NFS-14 Qing-Lian-Jie      | 8          | 1          | 32.1       | 32.1       | 0.29       | 10.04      |
|        | NFS-15 You-Fang-Qiao      | 15         | 4          | 71.8       | 18         | 3.09       | 11.65      |
|        | NFS-16 Yuan-Tong          | 6          | 3          | 44.8       | 14.9       | 3.39       | 2.07       |
|        | NFS-17 Xiong-Long-Da-Jie  | 13         | 7          | 84.6       | 12.1       | 8.6        | 6.29       |
|        | NFS-18 Yun-Jing-Lu        | 14         | 7          | 90.5       | 12.9       | 10.99      | 6.45       |
|        | NFS-19 Virtual station    | 8          | 1          | 49.6       | 12.4       | 3.48       | 3.19       |
|        | NFS-20 Ming-Gu-Gong       | 19         | 9          | 79.3       | 8.8        | 13.83      | 9.47       |
|        | NFS-21 Xia-Ma-Fang        | 1           | 34         | 34         | 2.17       | 3.27       |
|        | NFS-22 Ma-Qun             | 13          | 3         | 55.6       | 18.5       | 2.45       | 10.65      |
|        | NFS-23 Xian-Lin-Zhong-Xin | 14          | 8         | 44.8       | 5.6        | 12.54      | 4.49       |
| Line 3 | NFS-24 Virtual station    | 7          | 2          | 38.4       | 19.2       | 2.53       | 5.55       |
|        | NFS-25 Fu-Qiao            | 9          | 6          | 59.4       | 9.9        | 5.65       | 2.46       |
|        | NFS-26 Virtual station    | 2          | 1          | 34.8       | 34.8       | 0.29       | 0.36       |
|        | NFS-27 Ka-Zi-Men          | 11         | 7          | 74.1       | 10.6       | 9.41       | 2.82       |
|        | NFS-28 Hong-Yun-Da-Dao    | 5           | 2         | 41.6       | 20.8       | 1.65       | 1.72       |
|        | NFS-29 Tian-Yuan-Xi-Lu    | 26         | 9          | 98.4       | 10.9       | 13.02      | 12.26      |
|        | NFS-30 Cheng-Xin-Da-Dao   | 24         | 9          | 97.8       | 10.9       | 11.06      | 16.12      |
| Line 4 | NFS-31 Hui-Tong-Lu        | 16         | 6          | 85.1       | 14.2       | 11.63      | 9.38       |
|        | NFS-32 Wang-Jia-Wan       | 4          | 1          | 33.4       | 33.4       | 1.48       | 2.7        |
|        | NFS-33 Gang-Zi-Cun        | 7          | 3          | 31.5       | 10.5       | 3.23       | 3.9        |
|        | NFS-34 Yun-Nan-Lu         | 11         | 6          | 96.8       | 16         | 9.76       | 10.61      |
|        | IFS-1 & NFS-35 Nan-Jing-Zhan | 13   | 9          | 83.8       | 9.3        | 11        | 3.09      |
|        | IFS-2 & NFS-36 Gu-Lou     | 7          | 5          | 91         | 18.2       | 6.93       | 0.99      |
|        | IFS-3 & NFS-37 Xin-Jie-Kou | 8          | 4          | 89.3       | 22.3       | 4.91       | 2.55      |
|        | IFS-4 & NFS-38 Nan-Jing-Nan-Zhan | 8          | 3          | 67.4       | 22.5       | 3.01       | 4.54      |
|        | IFS-5 & NFS-39 Da-Xing-Gong | 8          | 4          | 46         | 11.5       | 2.38       | 1.92      |
|        | IFS-6 & Jin-Ma-Lu         | -          | -          | -          | -          | -          | -         |
|        | IFS-7 & Ji-Ming-Si        | -          | -          | -          | -          | -          | -         |

1 number of SCs allocated to NFS;  
2 number of UD wrapped by NFS;  
3 total size of orders handled by NFS ($\times 10^3$ parcel per-day);  
4 average size of orders handled by UD ($\times 10^2$ parcel per-day);  
5 length of CP segments connected to NFS (km);  
6 average service radius of UD (km).
| ID     | Station full name         | $T_{st}$ | $T_{tot}$ | $P_{NFS}$ | $P_{CP}$ | $V_{IFS}$ |
|--------|---------------------------|----------|-----------|-----------|----------|----------|
| Line 1 | NFS-1 Er-Qiao-Gong-Yuan   | 21.6     | 1.39      | 2.08      | 39       | 13.2     |
|        | NFS-2 Ba-Dou-Shan         | 20       | 3.78      | 7.64      | 30.2     | 11       |
|        | NFS-3 Yan-Zi-Ji           | 37.8     | 4.41      | 6.28      | 0        | 11.1     |
|        | NFS-4 Xin-Mo-Fan-Ma-Lu    | 56.3     | 6.49      | 19.69     | 0        | 0        |
|        | NFS-5 Xuan-Wu-Men         | 27.7     | 3.4       | 7.1       | 0        | 0        |
|        | NFS-6 Zhang-Fu-Yuan8      | 42.9     | 2.29      | 1.57      | 0        | 8.7      |
|        | NFS-7 Su-Shan-Jie         | 13.2     | 2.33      | 0.64      | 46       | 7.7      |
|        | NFS-8 Zhong-Hua-Men       | 16.4     | 3.8       | 9.11      | 50       | 2.5      |
|        | NFS-9 Ruan-Jian-Da-Dao    | 19.4     | 4.44      | 2.09      | 30.2     | 8.8      |
|        | NFS-10 Hua-Shen-Miao      | 22.5     | 2.48      | 1.1       | 41.2     | 12.1     |
|        | NFS-11 Sheng-Tai-Lu       | 53.2     | 12.18     | 27.86     | 0        | 0        |
|        | NFS-12 Zhu-Shan-Lu        | 59.4     | 9.99      | 14.86     | 0        | 12       |
|        | NFS-13 Nan-Jing-Jiao-Yuan | 12.5     | 1.89      | 3.04      | 49.8     | 11.2     |
| Line 2 | NFS-14 Qing-Lian-Jie      | 17.9     | 0.52      | 13.34     | 55.8     | 0        |
|        | NFS-15 You-Fang-Qiao      | 40.1     | 3.29      | 5.16      | 0        | 2        |
|        | NFS-16 Yuan-Tong          | 17.1     | 2.34      | 1.30      | 30.4     | 5.1      |
|        | NFS-17 Xiong-Long-Da-Jie  | 33.3     | 4.87      | 5.53      | 0        | 7.9      |
|        | NFS-18 Yan-Jing-Lu        | 56.3     | 6.45      | 8.99      | 0        | 7.1      |
|        | NFS-19 Virtual station    | 20.2     | 2.92      | 2.97      | 20.8     | 7.6      |
|        | NFS-20 Ming-Gu-Gong       | 38.3     | 7.19      | 8.4       | 0        | 11.2     |
|        | NFS-21 Xia-Ma-Fang        | 3.69     | 5.67      | 52        | 0        | –        |
|        | NFS-22 Ma-Qun             | 35.3     | 2.68      | 8.16      | 8.8      | 1.5      |
|        | NFS-23 Xiao-Lin-Zhong-Xin | 27.9     | 4.41      | 2.41      | 30.4     | 14.4     |
| Line 3 | NFS-24 Virtual station    | 13.7     | 2.41      | 5.69      | 43.2     | 0.8      |
|        | NFS-25 Fu-Qiao            | 25.6     | 3.48      | 2.24      | 1.2      | 10.1     |
|        | NFS-26 Virtual station    | 11       | 0.61      | 0.86      | 50.4     | 0        |
|        | NFS-27 Ka-Zi-Men          | 40.5     | 3.67      | 1.15      | 0        | 9.4      |
|        | NFS-28 Hong-Yun-Da-Dao    | 18       | 2.06      | 2.71      | 36.8     | 0        |
|        | NFS-29 Tian-Yuan-Xi-Lu    | 51.2     | 6.49      | 8.49      | 9.1      |
|        | NFS-30 Cheng-Xin-Da-Dao   | 53.4     | 6.58      | 7.59      | 0        | 9.1      |
| Line 4 | NFS-31 Hui-Tong-Lu        | 33.5     | 11.11     | 5.42      | 0        | 5.8      |
|        | NFS-32 Wang-Jia-Wan       | 15.3     | 2.65      | 4.76      | 53.2     | 0        |
|        | NFS-33 Gang-Zi-Cun        | 15.2     | 1.17      | 4.33      | 57       | 9.5      |
|        | NFS-34 Nan-Nan-Lu         | 53.6     | 9.16      | 4.96      | 0        | 4        |
|        | IFS-1 & NFS-35 Nan-Jing-Zhan | 36.2 | 5.02      | 1.13      | 0        | 10.7     | 871 |
|        | IFS-2 & NFS-36 Gu-Lou 40.4 | 7.34 | 1.58      | 0         | 1.8      | 759   |
|        | IFS-3 & NFS-37 Xin-Jie-Kou | 47.6 | 4.93      | 4.01      | 0        | 0      | 1,259 |
|        | IFS-4 & NFS-38 Nan-Jing-Nan-Zhan | 24 | 2.96 | 9.24 | 0   | 0 | 804 |
|        | IFS-5 & NFS-39 Da-Xing-Gong | 16.4 | 1.87 | 1.95 | 28  | 8.5 | 1,090 |
|        | IFS-6 Jin-Ma-Lu           | –       | –         | –         | –       | –       | 566  |
|        | IFS-7 Ji-Ming-Si          | –       | –         | –         | –       | –       | 622  |

7 transport cost of NFS orders on first-tier M-ULS network ($\times 10^3$ ¥ per-day);
8 transport cost of NFS orders on second-tier M-ULS network ($\times 10^3$ ¥ per-day);
9 transport cost of NFS orders on third-tier M-ULS network ($\times 10^3$ ¥ per-day);
10 penalty cost of NFS ($\times 10^3$ ¥ per-day);
11 penalty cost of CP segments connected to NFS ($\times 10^3$ ¥ per-day);
12 size of orders transferred at IFS ($\times 10^5$ parcel per-day).

IMPLEMENTED by two stages. Firstly, an E-TOPSIS-F method is proposed to evaluate the applicability of M-ULS for transporting urban delivery order with different O-D flows, thus determining the service scope of underground network. Four indicators, i.e., UFF, RA, CV and OP, were proposed from the evaluation, considering both M-ULS environmental benefit and accessibility. Secondly, a tri-objective MIP model which simultaneously minimizes the fixed cost, operating cost and low load penalty cost of M-ULS network is developed to interpret the optimal decisions of node location-allocation, pipeline layout and flow routing. A hybrid algorithm combining improved MOPSO and A* algorithm is applied to obtain the high-quality
Pareto-optimal solutions of the proposed LAR model. The aforementioned optimization approach has been testified in a real world M-ULS network planning issues using Nanjing city metro case. The model works effectively in generating ideal M-ULS network layout and configurations, and the Pareto front of the studied multi-objective optimization problem can be found efficiently by our algorithm. From simulation results, the following findings are summarized.

(i) The metro network has considerable potential to be utilized for urban freight transport. For the high-density urban regions with over five million residents, a wide-spread M-ULS network that consists of a few metro lines and dozens of freight stations could realize a 50%-60% modal shift rate of the inbound urban parcel deliveries from road to underground. Take the Nanjing case for example, the overall logistics utilization of metro system maintains at a reasonable level, where the majority of underground network facilities have an operating load rate around 65%-85% of their maximal freight handling capacity. Moreover, the co-building of metro freight stations and secondary capsule pipelines is conductive to improve the accessibility of underground logistics network and alleviate the freight traffic congestion around metro stations.

(ii) Note that over half of the original stations in Nanjing metro network are decided to be retrofitted. Such crowded location of freight stations might obstruct the normal scheduling and organization of collaborative metro passenger-and-freight transport. It is found that the logistics flows have a relatively low one-time arrival rate along the current metro line, that is, over 61% orders have to be transferred once at least before reaching the designated NFS. As the scale and topological complexity of metro network increase, the situations of “multiple transfer” and “underground detours” would be more frequent, which heavily increase the operating cost of M-ULS network. Therefore, in real-life M-ULS planning, decision-makers should prudently choose the parameter values of the NFS handling capacity and the IFS transfer capacity, so as to adjust the number and location distribution of the metro freight stations to be established.

(iii) The metro-based underground logistics system is featured with evident economic feasibility and substantial social-environmental benefit. The fixed investment for metro retrofit and pipeline construction can be completely offset by the modal shift benefit and external benefit of underground freight transport. Furthermore, as capacity growth, the M-ULS operator (usually refers to the metro operator) can sell the underground logistics services to the market, so as to attract third-party logistics companies and supply chain companies to use M-ULS network for their own business. In this context, the urban underground logistics project is expected to yield considerable operating incomes, while generating broad social welfares. The profitability of urban public rail transit system can be enhanced accordingly.

From practical perspective, the development of a large-scale M-ULS network should undergo multiple stages. In the early project stage, priority could be given to renovate the single metro line in high-density urban areas as a logistics pilot, whereas for newly developing district, the technical requirements of collaborative passenger-freight transport should be satisfied. It is appropriate to configure three to five metro freight stations in the pilot line, of which the location decision orients to meeting the customers’ delivery demand in the congested area. The interchange freight stations are further established to connect the pilot line with broader metro network. As the M-ULS network is gradual expanded to the whole city, the social-environmental benefits and economies of scale of underground freight transport can
be greatly improved. On this basis, it is advisable to establish the underground depots and spoke-level pipeline network to improve the terminal distribution efficiency. The integrated development of road-based logistics system and M-ULS can enhance the emergency capability of cities in the period of disaster and pandemic, and enhance the resilience of urban traffic.

Despite the findings, this work has some limitations in terms of modeling boundaries and the diversity of network topologies, for example, we simply specified a point-to-point structure for the capsule pipeline network layout, rather than other mainstream topologies such as tree-type or ring-type. In order to further enrich the knowledge of M-ULS network planning, the following aspects could be considered in further research. On one hand, it is essential to explore a more complicated modeling framework which integrates the compound metro network with loop line, the diversified pipeline networks, as well as the simultaneous delivery-and-pickup process of in-bound orders, out-bound orders and intra-city orders. On the other hand, more modeling and optimization techniques such as stochastic programing, dynamic programming, and robust optimization deserve being developed to investigate M-ULS network performance under demand uncertainty and supply failures.

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