Research on the optimization of underground logistic paths based on the positive and negative bidirectional demand model

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Abstract: With the rapid development of e-commerce, urban ground distribution pressure is increasing daily with an increasing number of vehicles transporting goods and worsening urban traffic congestion. As an important public resource for urban transportation, the metro can effectively relieve the pressure on passenger transportation as well as become an active component of urban logistics and distribution operations. In this study, we establish a metro distribution model of urban underground logistics based on the positive and negative bidirectional demand model by exploring a new mode of urban underground logistics combining metro resources and urban logistics to achieve the lowest total cost. In the proposed model, we consider the positive and negative bidirectional logistic demands of each station and solve it using a genetic algorithm. Finally, by analyzing a case study, this paper demonstrates the feasibility and validity of the proposed model and algorithm.

Keywords: Underground logistics; Subway distribution; positive and negative demand; genetic algorithm

1. INTRODUCTION

While generating huge consumer demand, the rise of the e-commerce economy has induced great challenges to urban transportation. Underground logistic systems can facilitate the transportation of
goods, allowing goods to reach all corners of the city through underground transportation. This system can significantly alleviate the traffic situation on the ground and quickly and safely meet logistic needs. Some scholars in China, such as Qian Qihu, have long proposed the use of underground logistic systems to solve traffic congestion in mega-cities [1]. Ma et al. introduced the research status of urban underground pipeline logistic systems at home and abroad and demonstrated the necessity and technical feasibility of developing such systems [2]. Huang et al. discussed the network planning of urban underground logistic system and then applied the system layout plan to arrange the distribution center of an underground logistic system [3]. The development of underground logistic systems abroad occurred as early as in the 19th century, especially in Britain and Germany, which built underground logistic pneumatic pipeline transportation systems for mail transportation. At the beginning of the 21st century, the development of container logistics promoted the construction of an underground logistic system [4].

With the development of the Chinese subway, some scholars proposed the use of the subway as the backbone network of urban distribution, which can help build the underground logistic system. Shi proposed a transformation plan that makes the subway function as both a passenger carrier and a logistic provider, thus utilizing the subway to achieve high-speed transportation and standardization of urban logistics [5]. Japan integrated subways and traditional trucks to develop a new urban logistic distribution system [6]. Zhou et al. proposed the integration of the subway network and the ground transportation network to form an urban subway distribution network, with subway trains and ground distribution vehicles as carriers [7]. Considering the synergy of the transit time between underground and surface, Yang et al. proposed to build an underground logistic distribution model based on the subway, which introduces a function of time penalty [8]. Liu et al. proposed the establishment of an optimization model of urban logistic route based on subway distribution while considering the capacity limitation of subway and terminal ground distribution vehicles [9]. This type of scenario minimizes the construction cost of underground logistic systems and integrates public resources to alleviate urban traffic problems. Furthermore, this can significantly promote research in underground logistics. However, the above articles on metro-based underground logistics mostly study the logistic path selection from outside to inside of city. In comparison, the current paper focuses on the logistic path selection inside of a city and considers the bidirectional nature of the metro and the bidirectional need for logistics.

2. Model building

2.1. Description of the problem

The pick-up vehicle obtains the goods at the nodes, transports them to the metro station, unloads them into the cargo storage area, and loads the goods that need to be distributed to the other nodes. Then, the metro passes by each metro station, picks up the goods from the cargo storage area and unloads them at the metro station nearest to the distribution destination. The process is shown in Figure 1.
2.2. Model assumptions

To facilitate the analysis, the following assumptions are made:

- The total quantity picked up every time is equal to the total quantity delivered and does not exceed the carrier capacity.
- The volume of goods unloaded at each metro station is equal to the total demand for the nodes that belong to this metro station.
- Each node and metro station is visited once and only once in a mission.
- The locations of the metro stations and nodes are known, as is the volume of goods at each node.
- Transportation between the nodes must pass through a metro station, and the nodes are not permanently assigned to a metro station.
- The transportation of goods by the metro does not affect the passenger experience, and dedicated cargo storage areas are allotted in all the metro stations.
- Time loss in transit is not included in the calculation, and the model only considers the distribution process.
- To facilitate the calculation, the distance between nodes and metro stations is represented by a straight line distance, as is the distance between adjacent nodes.
2.3. Model parameters

Assume that $i, j \in A$ are nodes; $k, p \in G$ are metro stations; $g \in M$ is a metro line; $z_{kp}$ represents the number of transshipment times when transporting cargo between $k$ and $p$; $c_z$ represents the cost per transfer; $c_c$ represents the cost by ground vehicles transporting the unit of goods per unit of distance; $c_d$ represents the cost by metro transporting unit of goods per unit of distance; $d_{ik}, d_{kp},$ and $d_{pj}$ are the distances of $(i, k), (k, p),$ and $(p, j)$ respectively; and $q_{ij}$ represents the volume of goods transported from node $i$ to node $j$.

When goods at node $i$ enter the metro station from station $k$, $w_{ik} = 1$; otherwise, $w_{ik} = 0$; when the transportation of $(k, p)$ is served by the metro line $g$, $g_{kp} = 1$; otherwise, $g_{kp} = 0$; when the goods at node $i$ are transported out of the metro station from station $p$, $y_{ip} = 1$; otherwise, $y_{ip} = 0$.

2.4. Model building

The following equations are used during the calculations:

Transshipment costs: $C_1 = \sum_{i \in A} \sum_{k, p \in G} w_{ik}^k \cdot g_{kp}^p \cdot z_{kp} \cdot c_z \cdot y_{ip}^p$

Transportation costs: $C_2 = \sum_{i, j \in A} \sum_{k, p \in G} w_{ik}^k \cdot d_{ik} \cdot q_{ij} \cdot c_c + g_{kp}^p \cdot d_{kp} \cdot q_{ij} \cdot c_d + y_{ip}^p \cdot d_{pj} \cdot q_{ij} \cdot c_c$

Therefore, the objective function is expressed as $\min f = \min (C_1 + C_2)$. (1)

s.t.

\[ \sum_{k \in G} w_{ik}^k = 1, \forall i \in A; \sum_{p \in G} y_{ip}^p = 1, \forall i \in A \]  (2)

\[ \sum_{i \in A} w_{ik}^k \geq 1, \forall k \in G; \sum_{i \in A} y_{ip}^p \geq 1, \forall p \in G \]  (3)

Equation (1) is the objective function representing the minimization of cost. The first item here is the transshipment cost, which represents the cost of transferring the goods during metro transportation. The second item is the transportation cost, which includes the cost of transporting goods from each node to the metro entrance and underground, and from the metro exit to the destination. Equation (2) represents those goods that enter the metro line from only one metro entrance and are transported out of the metro station from only one exit. Equation (3) represents the assumption that each metro station serves at least one node.

3. Algorithmic design

3.1. Establishment of data sources

The following process is performed to establish the data sources:

(1) We investigate the distribution of metro lines and nodes in the area and pre-select the appropriate metro stations as entrances and exits according to the locations of the nodes; then, we draw out the
coordinates of the nodes and metro stations as well as those of the optional metro lines to generate the initial data.

(2) Based on the coordinates, we obtain the distances between adjacent metro stations, between nodes and entrances, and between exits and destinations. The distance of non-adjacent metro stations to consider a maximum N indicates that the two metro stations cannot be directly connected, thus determining the distribution along the metro line.

(3) Next, to encode each metro station, we generate a sequence containing multiple lines as the initial solution, after which we use a genetic algorithm to calculate the objective function and determine the solution that minimizes the value of the objective function.

3.2. Algorithmic steps

(1) In encoding, this paper adopts natural numbers to encode chromosomes, which is easier for route construction and modeling. Label M points from 1 to M and forms a set of sequences as an individual of the population by this M non-repeating numbers. For example, individual 12345 represents the following path: node - metro station 1 - metro station 2 - metro station 3 - metro station 4 - metro station 5 - destination.

(2) Next, we randomly generate multiple individuals and form the initial population.

(3) For the fitness assessment, individual fitness is judged by whether it satisfies the objective function and constraints. The reciprocal of the objective function is used as the fitness function:

\[ f_{\text{fitness}} = 1 / f \]

The values of the function reflect the fitness of the chromosome wherein larger values are considered better than smaller ones.

(4) As for choice, the tournament operator is efficient and easy to implement. It is a commonly used choice operator, because it does not easily fall into the local optimum and does not need to rank the fitness values. Here, we choose the tournament operator, select L individuals from the entire population, let them play a tournament, and select the individual with the highest fitness value.

(5) For crossing, the commonly used crossover operators are PMX, OX, PBX, OBX, CX, among others. Here, we choose the PMX crossover operator.

(6) Regarding variation, it has been said that variation can improve the global search ability of the algorithm and maintain the diversity of the population, thus preventing iterations from appearing locally optimum. The variation method chosen here is to randomly select two genes in a chromosome, swap their order, and put them back into the chromosome.

(7) Finally, for circulation, we go back to (3) after forming a new population until the number of iterations reaches the set value.

4. Case study
The logistic transfer station of an enterprise in Beijing is located in Taidatong Logistics Park. This station needs to distribute goods to 10 customer points in the city. After leaving the Taidatong Logistics Park, the goods will be transported by distribution trucks to a metro station on the Yizhuang Line (Line) 7 or Batong Line to enter the metro. Then, the goods will be transported by metro lines to the vicinity of each customer point at the lowest cost, before they are finally delivered to their respective destinations by the delivery trucks. The coordinates of each customer point and metro station can be picked up by Baidu Map. Thus, the distance of adjacent metro stations, the distance between each customer point and the exit, and the distance between the logistic park and the entrance can all be calculated. At this point, we also assume that the cost of transporting unit goods per unit distance is 0.1 Yuan and 0.3 Yuan for the metro and distribution vehicles, respectively, and that the cost of distributing unit goods per unit distance is 0.5 Yuan for the distribution vehicle alone. Furthermore, the cost is 150 Yuan per change of route, the average transport speed of the metro is 60 km/h, and the average transport speed of distribution vehicles is 25 km/h. The optimization process is shown in Figure 2.

**Table 1. Demand at each customer point.**

| Customer point number | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|-----------------------|----|----|----|----|----|----|----|----|----|----|
| Demand/kg             | 55 | 67 | 56 | 70 | 63 | 49 | 77 | 84 | 62 | 88 |

**Figure 2.** Optimization process diagram.

In MATLAB encoding, the size of population is set at 100, the probability of crossover is 0.8, and the probability of variation is 0.05. P stands for logistic parks, and A, B, C, D, E, F, G, H, R, and S
represent the individual customer points. Hence, the metro-based distribution path optimizations are represented as follows: P→1→8→13→14→16→A→F, P→3→10→17→20→21→B→D, P→4→15→18→19→25→E→R, P→1→8→13→6→9→C, and P→4→15→11→22→23→G→R, P→3→10→17→26→27→H.

| Table 2. Comparison of the two distribution modes. |
|---------------------------------|----------|----------|
| **Delivery method**             | **Delivery cost/Yuan** | **Delivery time/minute** |
| Metro-based distribution         | 1239.7   | 94       |
| Individual truck delivery        | 3780.3   | 196      |

From the data in the table above, it can be seen that the metro-based intra-city logistic delivery saves 2,540.6 Yuan and reduces the transportation time by 102 minutes compared to the truck-based delivery alone.

5. Conclusions

Through a comprehensive analysis of domestic and international research on urban distribution and underground logistic systems, this study proposes the use of metro resources to solve the demand for inner-city logistic distribution and relieve traffic pressure. This work also proposes a metro distribution model of urban underground logistics based on the positive and negative bidirectional demand model and solves it using a genetic algorithm.

(1) The surface traffic congestion in Chinese cities is becoming increasingly severe. Thus, it is crucial to maximize the underground logistic system to share the traffic burden and flow of surface roads. The reasonable use of metro resources for intra-city logistics and distribution, which is also a form of sharing economy, can effectively improve traffic congestion.

(2) The article infers that in a metro-based urban underground logistic and distribution model, each metro station has bidirectional demand and the reasonable planning of routes to meet this demand can save costs and optimize the model to a great extent.

(3) The case analysis of the article proves that the model can optimize the choice of inner-city logistics and distribution routes. Furthermore, the proposed metro-based inner-city logistics and distribution can reasonably utilize public resources and save time and capital costs compared with only truck distribution. Thus, the proposed model has a potential significance on the integration of urban road and metro resources.

Subsequent studies must consider the capacity limit of the distribution vehicles, storage area of metro stations, remaining capacity of metro trains, and other constraints to further explore the optimization of metro-based inner-city logistic distribution paths.
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