Node classification of urban underground logistics system

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Abstract: With the development of artificial intelligence and internet of things technology, an underground logistics system will gradually become one of the novel ideas to alleviate urban traffic problems. Such a system consists of underground logistics nodes, but their classification is a key problem in the planning of an underground logistics network. On the basis of the analysis of the demand and supply characteristics of underground logistics, the underground logistics node determination model for multi-objective planning was established for logistics in which the nodes were graded and solved by CPLEX. Finally, this paper verified the rationality and validity of the model, method, and algorithm through the calculation analysis of samples. Thus, this work provides some theoretical support for the classification of urban underground logistics nodes.

Keywords: Urban underground logistics, Node classification, Multi-objective planning, CPLEX

1 Introduction

As the product of the combination of information technologies such as the internet of things and big data with urban management and underground engineering technologies, the fifth type of transportation and supply system[1], namely, underground logistic system, came into being with the development of the times. Its main process is to divert most of the aboveground storage and transportation of goods to the underground to alleviate the pressure of urban surface traffic and reduce environmental pollution.

There has been some domestic and international research on the issue of underground logistics. Delft and Texas[2] addressed this issue by constructing an underground logistics system network evaluation model to select the optimal network layout structure. Dietrich Stein[3] analyzed the processes of regional network planning and terminal model design within the scope of their work. Li Peng and Zhu Hehua[4] discussed the role of underground logistics systems in the sustainable development of a city. Zeng Linghui[5] established a mathematical model to analyze the layout of an underground logistics network. Yi Mei[6] studied and analyzed the network planning of urban underground logistics by establishing a mathematical model. Zhou Anbang[7] constructed a double-layer model to analyze the location of underground logistics nodes. Wang Man[8] solved the location of logistics nodes at all levels on the basis of the simulated annealing-greed algorithm and the maximum amount of freight that can be transported between each node. Liu Guiru[9] investigated the
site selection of logistics transit distribution nodes. Liu Chuankun[10] studied the optimal design of network channels in an underground logistics system.

The above literature conducted preliminary studies on the location and route optimization of urban underground logistics networks, but the research resulted mainly focused on the cost. The influence of the regional traffic congestion coefficient on the planning of an underground logistics channel network is seldom considered in the control of the target. In this work, this study analyzed urban logistics operation characteristics in terms of the total cost of the system, the ability to ease traffic congestion, and logistics efficiency of the three aspects. The scientific grading of the underground pipeline network was considered, the feasibility of the grading model was explored, and a decision-making basis for the construction of the city’s underground logistics system was provided.

2. Model building

2.1 Problem description

The urban underground logistics network consists of logistics nodes and network channels. Logistics nodes are generally divided into first-level nodes, second-level nodes, and third-level nodes. The first-level node receives and sends goods from the logistics park to the second-level node, and the goods are transported to the third-level node after arriving at the second-level node. This study adopted a scientific method to classify the first- and second-level nodes. Suppose a city has established a complete underground logistics system. On the basis of the existing nodes for grading, primary and secondary nodes should be distinguished. Each first-level node and its connected secondary node are defined, followed by each second-level node and its connected node to reach the overall optimal.

Figure 1. Node network structure diagram

2.2 Model assumptions

- The cost of construction and depreciation of each logistics node is known.
- The cost of transporting goods between nodes at each stage is known and the same.
- The maximum amount of goods handled by the primary and secondary nodes is known.
- Assumed that all secondary nodes are connected only to the primary node in the region and not to other primary or secondary nodes.
- The transit costs of the nodes are not considered.

2.3 Description of symbols

- \( P \) - set of logistics node candidates, \{1,2,...,n\}.
- \( K \) - set of networks \{1,2,...,m\}.
- \( q_{ij} \) - the transport volume from primary node \( i \) to secondary node \( j \).
- \( q_{jk} \) - transport volume from secondary \( j \) to network \( k \).
- \( d_{ij} \) - the distance from primary node \( i \) to secondary node \( j \).
- \( d_{jk} \) - the distance from the secondary node \( j \) to the network \( k \).
- \( C \) - the cost of transporting the goods per unit weight over a distance.
- $C_f$ - construction costs for a primary node.
- $C_s$ - construction costs for a secondary node.
- $B_{ij}$ - average traffic index for aboveground traffic at node i to node j.
- $B_{jk}$ - average traffic index for aboveground traffic at node j to point k.
- $r_1$ - the maximum service radius of the primary node.
- $r_2$ - the maximum service radius of the secondary node.
- $N_1$ - the maximum cargo handling capacity at the first node.
- $N_2$ - the maximum cargo handling capacity of the secondary node.
- $x_i = \begin{cases} 1, & \text{first - level underground logistics node is established at candidate node } i \\ 0, & \text{first - level underground logistics node is not established at candidate node } i \end{cases}$
- $y_j = \begin{cases} 1, & \text{second - level underground logistics node is established at candidate node } j \\ 0, & \text{second - level underground logistics node is not established at candidate node } j \end{cases}$
- $z_{ij} = \begin{cases} 1, & \text{the primary node } i \text{ serves the secondary node } j \\ 0, & \text{the primary node } i \text{ does not serve the secondary node } j \end{cases}$
- $w_{jk} = \begin{cases} 1, & \text{the secondary node } j \text{ serves the network } k \\ 0, & \text{the secondary node } j \text{ does not serve network } k \end{cases}$

### 2.4 Model development

The role of the underground logistics system is to relieve traffic pressure, reduce logistics costs, and improve the efficiency of logistics operations. Therefore, node selection is considered from three aspects: total cost of a logistics system, traffic congestion capacity, and logistics efficiency. The objective function was determined as follows:

- **Objective function 1:** total cost of logistics system

The total cost of the logistics system includes the construction of primary and secondary underground logistics nodes, as well as the total cost of transportation between the nodes.

$$\min S_1 = \sum_{i=0}^{n} \sum_{j=0}^{n} q_{ij} \cdot z_{ij} \cdot d_{ij} \cdot c + \sum_{j=0}^{n} \sum_{k=0}^{m} q_{jk} \cdot w_{jk} \cdot d_{jk} \cdot c + \sum_{i=0}^{n} C_f + \sum_{j=0}^{n} C_s$$  \hspace{1cm} (1)

- **Objective function 2:** Maximum traffic congestion capacity.

The superiority of the underground logistics system is the ability to ease traffic pressure on the ground, not affected by the ground traffic congestion. In other words, the more congested the surface traffic is, the greater the significance of transferring the aboveground logistics to underground.

$$\max S_2 = \sum_{i=0}^{n} \sum_{j=0}^{n} B_{ij} \cdot Z_{ij} + \sum_{j=0}^{n} \sum_{k=0}^{m} B_{jk} \cdot w_{jk}$$  \hspace{1cm} (2)

- **Objective function 3:** Maximum logistics efficiency.

On the premise of meeting the requirements of transportation, it can ensure the relative balance of goods transported between each second-level node and its connected networks, shorten the time, and improve logistical efficiency.

$$\min S_3 = \max \left\{ \sum_{j=1}^{m} w_{jk} \cdot q_{jk}, P \in (1,2,...,n), K \in (1,2,...,m) \right\}$$  \hspace{1cm} (3)

The fuzzy membership function is used to unify the objects with different meanings into a dimensionless single-objective function. Thus, the multi-objective problem is transformed into a single-objective problem with weights and uniform dimensions.

First, the fuzzy affiliations of goals one, two, and three were calculated as follows.

$$f_1 = \frac{S_1 - S_{min}}{S_{max} - S_{min}}$$ \hspace{1cm} (4)

$$f_2 = \frac{S_{max} - S_2}{S_{max} - S_{min}}$$ \hspace{1cm} (5)
The multi-objective function was converted to a single-objective function

\[ \text{Min } S = \lambda_1 f_1 + \lambda_2 f_2 + \lambda_3 f_3 \]

\( \lambda_1, \lambda_2, \text{ and } \lambda_3 \) are the weights of the three objective fuzzy affiliation functions.

Thus, the mathematical model of this paper is

\[ \text{Min } S = \lambda_1 f_1 + \lambda_2 f_2 + \lambda_3 f_3 \]

\[ d_{ij} \cdot z_{ij} \leq r_1 \]

\[ d_{jk} \cdot w_{jk} \leq r_2 \]

\[ x_i \leq \sum_{j=0}^{n} z_{ij}, \quad i \in (1,2, \ldots, n) \]

\[ \sum_{i=0}^{n} x_i \cdot \sum_{j=0}^{n} z_{ij} = \sum_{j=0}^{n} y_j, \quad i, j \in (1,2, \ldots, n) \]

\[ w_{jk} = 1, \quad k \in (1,2, \ldots, m) \]

\[ x_i > 0, \quad i \in (1,2, \ldots, m) \]

\[ y_j > 0, \quad j \in (1,2, \ldots, m) \]

\[ \sum_{j=0}^{n} q_{ij} \cdot z_{ij} \leq N_1, \quad j \in (1,2, \ldots, n) \]

\[ \sum_{k=0}^{m} q_{jk} \cdot w_{jk} \leq N_2, \quad k \in (1,2, \ldots, m) \]

\[ z_{ij} \leq x_i \]

\[ w_{jk} \leq y_j \]

\[ x_i + y_i = 1 \]

\[ x_i, y_j, z_{ij}, w_{jk} \in \{0,1\}, \quad i, j \in P, \quad k \in K \]

\[ \lambda_1 + \lambda_2 + \lambda_3 = 1 \]

Eqs. (9) and (10) indicate that the service scope of the first- and second-level nodes does not exceed its maximum service radius. Eq. (11) represents that each first-level node serves at least one second-level node. Eq. (12) represents that each second-level node has one and only one first-level node serving it. Eq. (13) represents that each network can only be served by one secondary node. Eqs. (14) and (15) represent that the primary and secondary nodes cannot be zero. Eqs. (16) and (17) represent that the total freight volume of the first- and second-level nodes shall not exceed its maximum service limit. Eqs. (18) and (19) represent that a node may serve other nodes only under the conditions of primary and secondary node construction. Eq. (20) represents that both primary and secondary underground logistics centers cannot be established at a single node.

3 Algorithm design

In this paper, we used the CPLEX algorithm, which is a software known for solving large-scale linear planning constraints. It can represent complex mathematical programming problems as mathematical models. Its built-in branch cutting algorithm can solve linear programming with millions of variables and constraints in a short time. CPLEX can be used to solve linear delineation, quadratic constraint planning, and mixed-integer type planning problems. CPLEX is now widely used in various industries.
such as logistics, manufacturing, and communication. By using CPLEX software, the above model was programmed and solved by substituting the objective function, data, and constraints.

(1) Create decision variables
Use binvar to create 0-1 decision variables, which are only selected and unselected for a node’s hierarchy. The decision variables created in this paper are a first-level node picking decision variable, a second-level node linking decision variable, a second-level node selecting decision variable.

(2) Add constraints
with F = set(constraint [], tag): Create a tag that starts with “The constraint is specified by constraint.” The optional parameter tag can assign a string tag to the constraint. Add the constraint to the model.

(3) Parameter configuration
Write as ops = sdpsettings(option1, value1, option2, value2,...), e.g., ops = sdpsettings ('solver', 'lpsolve', 'verbose', 2).

(4) Solve
with result = solvesdp(F, f, ops), where the objective function is solved by f specified, the constraint is specified by F, the ops specifies the solution parameter, and the final result is stored in the result structure.

4. Case analysis
A city has the conditions for the establishment of an urban underground logistics system. Suppose that underground logistics has been constructed and classified according to existing nodes, the fixed construction cost of a first-level node is 5 million, with a maximum treatment capacity of 6,000 tones and a maximum service area of 8 km. By contrast, the fixed construction cost of the secondary node is 3 million, with a maximum treatment capacity of 4,000 tons, a maximum service area of 4 km, and a transportation fee of ¥1/ton-kilometers between nodes. The expert scores were used to calculate the weight of this paper: $\lambda_1 = 0.487$, $\lambda_2 = 0.285$, and $\lambda_3 = 0.228$.

| Table 1. Node coordinates |
|----------------------------|
| Node | X(*10^5m) | Y(*10^5m) |
| A    | 1.468     | 1.151     |
| B    | 1.432     | 1.523     |
| C    | 1.514     | 1.537     |
| D    | 1.398     | 1.562     |
| E    | 1.447     | 1.576     |
| F    | 1.416     | 1.601     |
| G    | 1.504     | 1.593     |

| Table 2. Coordinates and requirements of the network points |
|---------------------------------------------------------|
| Node | X (*10^5m) | Y (*10^5m) | Cargo volume (t) | Node | X (*10^5m) | Y (*10^5m) | Cargo volume (t) |
|------|------------|------------|-----------------|------|------------|------------|-----------------|
| 1    | 1.481      | 1.495      | 398.5           | 2    | 1.451      | 1.515      | 190.1           |
| 3    | 1.417      | 1.499      | 215.1           | 4    | 1.479      | 1.511      | 289.1           |
| 5    | 1.463      | 1.502      | 211.7           | 6    | 1.438      | 1.518      | 287.2           |
| 7    | 1.439      | 1.501      | 199.6           | 8    | 1.422      | 1.519      | 167.4           |
| 9    | 1.451      | 1.501      | 337.5           | 10   | 1.492      | 1.517      | 389.7           |
| 11   | 1.428      | 1.500      | 406.1           | 12   | 1.443      | 1.522      | 282.6           |
| ...  | ...        | ...        | ...             | ...  | ...        | ...        | ...             |
| 65   | 1.439      | 1.511      | 409.1           | 66   | 1.404      | 1.521      | 249.0           |
| 67   | 1.415      | 1.512      | 500.8           | 68   | 1.416      | 1.524      | 305.7           |
| 69   | 1.426      | 1.512      | 114.1           | 70   | 1.453      | 1.527      | 155.5           |

| Table 3. Traffic coefficients between nodes |
|--------------------------------------------|
| Node | A | B | C | D | E | F | G   |
|------|---|---|---|---|---|---|-----|
| A    | 0 | 6.1| 6.8| 7.4| 6.6| 6.4| 7.5 |
By solving the problem, we obtained the grading result that satisfied the optimal objective function: two primary nodes and five secondary nodes. The total logistics cost was ¥2,918,20000 when the objective function was optimal.

![Figure 2. Results of node classification](image)

The distribution of primary nodes, secondary nodes, and networks can be seen in Figure 4.

**Table 4. Traffic coefficients between nodes and networks**

| Node | 1  | 2  | 3  | 4  | 5  | ... | 67 | 68 | 69 | 70 |
|------|----|----|----|----|----|-----|----|----|----|----|
| A    | 6.5| 6.6| 6.5| 5.9| 6.4| ... | 6.4| 6.6| 6.7| 6.7|
| B    | 6.9| 7.0| 6.8| 6.2| 6.7| ... | 6.8| 7.0| 7.1| 7.0|
| C    | 6.4| 6.5| 6.3| 5.7| 6.3| ... | 6.3| 6.5| 6.6| 6.6|
| D    | 8.3| 8.3| 8.3| 7.7| 8.2| ... | 8.3| 8.4| 8.6| 8.5|
| E    | 6.4| 6.6| 6.4| 5.8| 6.3| ... | 6.4| 6.6| 6.7| 6.6|
| F    | 4.7| 4.8| 4.7| 4.1| 4.6| ... | 4.6| 4.8| 4.9| 4.9|
| G    | 6.2| 6.3| 6.2| 5.6| 6.1| ... | 6.1| 6.3| 6.4| 6.4|

**Table 5. Level 1 node results**

| Primary node | Secondary nodes served |
|--------------|------------------------|
| C            | A, G                   |
| F            | B, D, E                |

**Table 6. Secondary node results**

| Secondary node | Locations Served |
|----------------|------------------|
| A              | 1, 3, 7, 12, 15, 26, 29, 32, 34 |
|                | 2, 4, 5, 6, 8~11, 13, 14, 16, 18~ |
| B              | 25, 28, 31, 37 |
| D              | 17, 27, 30, 33, 36, 44~59 |
| E              | 38, 39, 40, 60~65, 67, 69 |
| G              | 35, 41, 42, 43, 66, 68, 70 |
5 Conclusions
(1) In this paper, underground logistics nodes were classified to minimize the total cost of a logistics system, alleviate traffic congestion, and maximize logistics efficiency. Considering the constraints such as the service scope and the maximum processing capacity of the first and second nodes, an urban underground logistics system classification model was established. The CPLEX algorithm was used to calculate the number of nodes and the range of services; verify the rationality and validity of the model, method, and algorithm through the calculation analysis of samples; and provide some theoretical support for the classification of urban underground logistics nodes.
(2) According to the calculation results, the total logistics cost was found to be 29.182 million yuan, which could be divided into two first-level nodes and five second-level nodes. The range of nodes served by each node was known. The feasibility of the algorithm and model was illustrated.
(3) Given that the model does not consider the actual situation of the external environment, such as geological conditions, future research may improve this aspect.

Acknowledgement
The research was funded by Hunan Provincial Education Department Key Scientific Research Project (19A014) and Changsha University of Science and Technology Science Foundation Project (2019Q1CZ004).

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