Node Location Study of an Urban Underground Container Logistics Network

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Abstract: Underground logistics systems are becoming a new way to solve the problems of urban logistics delivery and surface traffic congestion. Among them, intelligent containers, as a means of transport in the underground logistics trunk network, will allow for significantly less volumes for the logistics OD (starting point to the destination of the flow of goods), where container logistics network node site selection has been a key issue of the city's underground logistics network planning. Based on an analysis of the characteristics of urban logistics OD, this paper builds a model that targets and optimizes parameters, such as infrastructure cost and operating cost, from the perspective of the system builder. The cplex algorithm was used to solve the model. Finally, the validity and logic of the model and algorithm are verified via case study analysis.

Keywords: Urban underground logistics; container logistics networks; node siting; cplex algorithms

Introduction

In recent years, China's rapid economic development, an acceleration of the urbanization process, and the number of vehicles in the city has dramatically increased, which has led to peak period traffic congestion causing environmental pollution, frequent accidents, and waste of resources, which has had serious impacts on the quality of life of residents and increased the number of safety hazards and accidents [1]. This has led to increasing pressure on above-ground transportation, which has forced society to shift from above-ground to underground spaces for new ways of transport. As technologies such as automated transport and underground construction continue to mature, research and development of the fifth type of transport and supply system, the “underground logistics system,” provides new ideas to resolve the contradiction between urban development and the demand for goods transport, [2]. Yiqun and Qihu [3] proposed the container as a primary means of transportation for the underground environmental logistics system. Feifei et al. [4] took the layout of underground container logistics and transport system as the object and established an integrated transport network optimization model to analyze the rationality of underground logistics systems in container port area implementation. Yi et al. [5] established an underground logistics multi-objective planning model and the design of ant colony algorithm to analyze the impact of logistics systems on container transport network. Linghui et al. [6] analyzed the benefits of constructing an underground logistics system for an open harbor passage based on current traffic characteristics and future traffic volume. Xiaomeng [7] evaluated the risks of underground logistics system construction by establishing an evaluation index system and applying an entropy weighting method to determine the weights. Min et al. [8] optimized the underground container logistics system of the Shanghai port from the perspective of site design and established a two-layer planning model based on a genetic algorithm. The abovementioned research results have conducted preliminary studies on the means of transport of underground logistics systems, their rationality in specific situations, their impact on the transport network, and its benefits and risks, but few studies have been conducted on the location of logistics nodes for container transport, where most of them have used highly
complex algorithms. Therefore, this paper relates logistics node location to infrastructure and operating costs, establishes the objective function of total cost minimization, and uses the cplex algorithm to solve such problems.

1 Construction of a logistics node location model

1.1 Description of the problem

This paper studies the city underground container logistics system as a use of containers in the underground space for logistics distribution and reduces the number and use frequency of urban ground distribution vehicles, while relieving road traffic pressure and environmental pressure. In this paper, the underground logistics system consists of primary nodes, underground logistics channels, and secondary nodes. The cargo is loaded into containers and transported to other primary nodes via large pipelines between the primary nodes; the cargo is then loaded onto pallets and transported to secondary nodes, depending on the requirements of the secondary nodes. A certain number of nodes in the city are selected, such as bus stations, train stations, airports, ports, and other high traffic convergence points to become underground logistics level 1 alternative nodes. A calculation is completed to select the optimal position of the first level node. The hierarchy of the underground logistics pipeline is currently under discussion, but judging from the construction of the underground pipeline under construction in the Shanghai Port and the Xiongan New Area, the hierarchy is reasonable. Therefore, the transport network topology of the underground logistics system studied in this paper is shown in Figure 1.

![Figure 1 Transport network topology diagram of underground logistics system](image)

1.2 Model assumptions

To model the actual problem and facilitate its mathematical expression and solution, the following basic assumptions were made:

1) The construction cost of the primary node is known.
2) At the initial construction stage, regardless of geological conditions, the shortest straight line distance is allowed for all underground passages.
3) The location of the coordinates of the secondary nodes and its requirements are known.
4) Each secondary node is connected to only one primary node.
5) A primary node has at least one secondary node.
6) The maximum investment in the underground logistics system and the maximum capacity
of the primary nodes are known.
7) No underground logistics nodes already exist, so the impacts of other original nodes are not considered.

1.3 Model building

\[ 
\min F = \left( \sum_{e=1}^{q} F_e Z_e + 2 \sum_{e=1}^{q} \sum_{g=1}^{q} PL_{eg} W_{eg} + 2 \sum_{e=1}^{q} \sum_{j=1}^{a} P_{1ej} V_{ej} \right) 
+ \left( \sum_{e=1}^{q} \sum_{g=1}^{q} C X_{eg} L_{eg} W_{eg} + \sum_{e=1}^{q} \sum_{j=1}^{a} C_1 X_{ej} L_{ej} V_{ej} \right) 
\]  

(1)

\[ \sum_{e=1}^{q} F_e Z_e \leq G \]  

(2)

\[ \sum_{g=1}^{q} X_{eg} + \sum_{j=1}^{a} X_{ej} \leq H, e = 1, 2, 3, \ldots, q \]  

(3)

\[ \sum_{e=1}^{q} V_{ej} = 1, j = 1, 2, 3, \ldots, a \]  

(4)

\[ \sum_{j=1}^{a} V_{ej} \geq Z_e, e = 1, 2, 3, \ldots, q \]  

(5)

\[ W_{eg} \geq Z_e Z_g \]  

(6)

\[ W_{eg} \leq \frac{1}{2} (Z_e + Z_g), e \neq g \]  

(7)

\[ V_{ej} \leq Z_e \]  

(8)

\[ Z_e \in (0,1) \]  

(9)

\[ W_{eg} \in (0,1) \]  

(10)

\[ V_{ej} \in (0,1) \]  

(11)

Variable definitions:
Q - number of alternative first level nodes, e, g = 1, 2, ..., q and e \( \neq \) g
A - the sum of all secondary nodes, j = 1, 2, ..., a
F_e - construction cost of primary node

\[ Z_e = \begin{cases} 
1, \text{ First level node is selected} \\
0, \text{ Primary node is not selected} 
\end{cases} \]  

P - Unit piping costs between primary nodes
P_1 - Unit pipe laying costs from primary to secondary nodes
C - Unit transport costs between level 1 nodes
C1 - Unit transport costs from primary to secondary nodes
X_{eg} - constant, fixed transport between first level nodes
X_{ej} - transport from primary node e to secondary node j
L_{eg} - the distance from node e to node g
L_{ej} - the distance from primary node e to secondary node j

\[ W_{eg} = \begin{cases} 
1, & \text{The lines between the first level nodes are selected} \\
0, & \text{The line between the first level nodes is not selected}
\end{cases} \]

\[ V_{ej} = \begin{cases} 
1, & \text{The lines between the primary and secondary nodes are selected} \\
0, & \text{The line between the primary and secondary nodes is not selected}
\end{cases} \]

H - maximum capacity of the primary node
G - maximum investment

From the above model, Equation (1): the formula in the first bracket: the first formula is the total cost of laying the two-way pipeline between the primary nodes, and the third formula is the total cost of laying the two-way pipeline from the primary node to the secondary node; the formula in the second bracket: the first formula is the total cost of transportation from primary node e to primary node g, and the second formula is the total cost of transportation from primary node e to secondary node j. Equation (2): The sum of the construction costs of the primary node is not greater than the total investment amount. Eq. (3): The amount of transportation to that primary node is not greater than the maximum capacity of that node. Eq. (4): Each secondary node is served by only one primary node. Eq. (5): A primary node serves at least one secondary node. Eq. (6): A primary node must have routes to each other when selected. Eq. (7): A primary node will have lines between primary nodes only if the primary node is selected. Eq. (8): The line from the primary node to the secondary node is only available if the primary node is selected.

2. Model solving

In this paper, the cplex algorithm was used for the computational screening of the selection of underground logistics primary node locations. CPLEX is a high-performance mathematical planning problem solver from IBM that can quickly and reliably solve linear planning, mixed-integer planning, quadratic planning, and other planning problems. CPLEX is fast and can solve many large-scale problems in the real world, and it is capable of handling problems with millions of constraints and variables. Compared with the genetic algorithm, the result of CPLEX is the optimal solution, while the genetic algorithm is prone to partial optimization and sometimes cannot find the optimal solution, and can only take the average of several results. Therefore, the CPLEX algorithm is chosen for solution in this paper. In this paper, the choice of primary nodes, paths between primary nodes, and paths between primary and secondary nodes is made to achieve the lowest total cost, so all of them choose the CPLEX algorithm for 0-1 decision variables, and the steps to calculate the CPLEX algorithm for 0-1 decision variables are as follows:

(1) Creating decision variables. This paper uses binvar- to create 0-1 type decision variables for nodes and channel construction between nodes only to be selected and unselected, therefore the selection of a node in this paper with \( Z = \text{binvar}(1,n,'full') \) and the establishment of 1 row and n columns of an asymmetric matrix. Likewise \( W = \text{binvar}(n,n) \), which represents the creation of a symmetric matrix of n rows and n columns, and \( V = \text{binvar}(n,d,'full') \), which represents the creation of an asymmetric matrix of n rows and d columns.

(2) Add constraints. \( F = \text{set}(\text{constraint[, tag]}) \): create a constraint specified by constraint, and an optional tag can assign a string tag to the constraint. If you want to keep adding constraints, it is simple, supporting a direct link with \( +: F = F + \text{set(constraint1[, tag1])} \).

(3) Parameter configuration. It can be written as \( \text{ops = sdpsettings(option1, value1, option2,} \ldots) \).
value2,...), e.g. ops = sdpsettings ('solver', 'lpsolve', 'verbose', 2). The 'solver' parameter specifies that the program uses the lpsolve solver (which will report an error if it is not installed), and that the program will use the lpsolve solver (which will report an error if it is not installed), but if it is not specifying the 'solver' parameter, it will automatically choose the installed and most appropriate solver based on the decision variable type; 'verbose' specifies the degree of redundancy to be displayed (the greater the redundancy, the more detailed information about the solving process can be obtained).

(4) Solve the problem. In one sentence: result = solvesdp(F, f, ops), solves a mathematical planning (minimization) problem with objective function specified by f, constraints specified by F, and solution parameters specified by ops. The final result is stored in the result structure.

3. Algorithm analysis

Suppose there is a limit of 10 primary node alternatives (e = 10) in a city's underground logistics system (Q1, Q2,...,Q10). Due to the absence of old logistics nodes, 20 secondary nodes (j = 20) (A1, A2, A3,...,A20), are not considered to impact the system (The values in this case are all hypothetical values, the reality is subject to the actual statistics, and the following currencies are in RMB). The total investment cost is G = 100 (million). Unit transportation cost C =15 yuan/ton between primary nodes and C1 = 13 yuan/ton from primary nodes to secondary nodes. The unit cost of pipe laying between primary nodes is P = 300 (thousand), and the unit cost of pipe laying from primary to secondary nodes is P1 = 250 (thousand). X_{eq} = 100 tons of fixed transport between the primary nodes, and the maximum capacity of the primary nodes is H = 10,000 tons. The relevant data are shown in the table below. (The latitude and longitude information is based on the location of the node on the map, while the construction cost, the cost of construction, and the demand are assumed to be)

Table 1: Geographic location information and node construction costs for primary nodes (10 thousand)

|   | Q1   | Q2   | Q3   | Q4   | Q5   |
|---|------|------|------|------|------|
| longitude | 110.3077 | 110.2732 | 110.0545 | 110.2895 | 110.3772 |
| latitude  | 25.3358  | 25.3617  | 25.2237  | 25.2012  | 25.2217  |
| construction costs | 100 | 100 | 100 | 100 | 200 |

|   | Q6   | Q7   | Q8   | Q9   | Q10  |
|---|------|------|------|------|------|
| longitude | 110.2888 | 110.1497 | 110.3489 | 110.3018 | 110.2029 |
| latitude  | 25.2677  | 25.2081  | 25.2877  | 25.1417  | 25.2305  |
| construction costs | 100 | 200 | 200 | 200 | 200 |

Table 2: Geographical location information and demand for secondary nodes (t)

|   | A1   | A2   | A3   | A4   | A5   |
|---|------|------|------|------|------|
| longitude | 110.3256 | 110.3139 | 110.3340 | 110.0974 | 110.0293 |
| latitude  | 25.3206  | 25.3014  | 25.4144  | 25.3801  | 25.2110  |
| demand    | 152    | 136    | 168    | 149    | 188    |
| A6        | A7    | A8    | A9    | A10   |      |
| longitude | 110.2898 | 110.3201 | 110.4161 | 110.3385 | 110.2337 |
| latitude  | 25.2266  | 25.2106  | 25.1906  | 25.2544  | 25.2633  |
| demand    | 157    | 100    | 164    | 175    | 100    |
| A11       | A12   | A13   | A14   | A15   |      |
| longitude | 110.2693 | 110.1878 | 110.1788 | 110.3215 | 110.3359 |
| latitude  | 25.2831  | 25.2554  | 25.2287  | 25.2818  | 25.3053  |
| demand    | 120    | 110    | 135    | 110    | 111    |
longitude 110.3056 110.2166 110.2895 110.2870 110.2863

latitude 25.0948 25.2512 25.2923 25.3064 25.2533

demand 115 118 122 199 151

Based on the geographic location information in Tables 1 and 2, apply the distance formula \( d = ((x_1-x_2)^2 + (y_1-y_2)^2)^{0.5} \times 110 \) to find the distance between the primary nodes, \( L_{eg} \), and the distance from the primary node to the secondary node, \( L_{e2} \).

Based on the above data, calculations using CPLEX 12.90 take only a few seconds to arrive at the best solution for node selection. By calculation, there are: \( Z_1, Z_3, Z_4, Z_7, Z_{10} = 1 \), and the others are 0 (the layout is shown in Figure 2). Therefore, the selected nodes are Q1, Q3, Q4, Q7, and Q10. The total cost of node construction: 6 (million), the total cost of pipeline laying: 66.91 (million), the total cost of transportation occurring between nodes: 695.766 (thousand), and the total cost of the entire network: 73.607 (million).

4. Summary
(1) In this study, we aim to minimize the total cost of the underground logistics network based on infrastructure cost and operation cost, and the CPLEX algorithm with 0-1 decision variables was selected for calculations. Through examples, this study verifies the feasibility of the proposed model and calculation method and reflects the superiority of the CPLEX algorithm in solving such problems. It does not require complicated programming and only requires to correctly express the constraints and objective function. An optimal solution was obtained in a short time. The genetic algorithm is not easy to solve some problems or it is difficult to find an optimal solution and the running time is longer. In comparison, CPLEX has a major advantage.
(2) In the data above, the final cost of the whole network is 73.607 (million), which does not exceed our total investment of 100 (million), indicating that this approach is desirable and that the CPLEX algorithm is able to serve as a new way to find the optimal solution for such problems.
(3) The model in this study has limitations, mainly in making simple assumptions on costs, but in the actual process, these variables will have some variability. Thus, in future research, the next step is to reconsider these factors.

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