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A multi-objective location and channel model for ULS network

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Abstract

In this paper, we construct a multi-objective location and channel model for ULS network to alleviate the urban traffic congestion problem. First, we construct a multi-objective node selection model and obtain the position of the first-level nodes in the ULS network by using agglomerative hierarchical clustering method. Then, we obtain the position of the second-level nodes in the ULS network by using the greedy algorithm. We also calculate the service scope, actual traffic volume and transport rate of first-level node for each node based on the determined node group. After that, we select the optimal channel scheme to make nodes at different levels of the ULS and its load more balanced by using the plant growth simulation algorithm. We extract the key variables of the problem, quantify some indicators with reasonable quantification, construct a multi-objective location and channel model based on the actual logistics situation for the specific region and achieve reasonable results to meet multiple objectives. Therefore, the model could be used as a reference for the construction of urban ULS network.

Keywords Logistics engineering · Underground logistics system (ULS) · Location and channel model · Multi-objective · Plant growth simulation algorithm (PGSA)

1 Introduction

Traffic congestion is one of the most important problems that have plagued the large or medium-sized cities all over the world in recent years. The main cause of urban traffic congestion is the sharp increase in amount of vehicles led by traffic demand surge, among which, demand growth of cargo logistics. Since freight vehicles are generally large and slow while carrying heavy load, if heavy vehicles are mixed in the traffic flow, road capacity would be dramatically reduced. A great deal of practice has shown that, it is neither scientific nor realistic to meet the ever-increasing traffic demand by increasing the number of ground transportation facilities for it is impossible to increase ground roads unboundedly. As such, it is imperative to "plan as a whole the ground and underground space development". Meanwhile, more and more developed countries are attaching importance to "underground logistics system".

Underground logistics system (ULS) refers to the transportation and supply system of goods by underground pipes or tunnels similar to subways inside a city or among different cities [1]. It occupies no ground road, which effectively alleviates traffic jam; and it uses clean power, which can help reduce urban pollution. ULS network form directly influences the running efficiency of logistics system and the rationality of the system, engineering investment and the economic and social benefits brought by the system when it is completed [2]. Johan Visser [3] analysed the features of dotted, linear or net-shaped network forms and put forward suggestions on policies concerning ULS network construction. At the empirical level, van der Heijden et al. [4] analysed running characteristics of different ULS including Aalsmeer flower market and Schiphol airport, and gave an analysis of its cost and efficiency based on a simulation model. Vernimmen et al. [5] proposed that the ULS could be used as a new solution to cope

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with increasing container transportation in the Port of Antwerp.

First of all, in the process of construction and optimization of ULS, selection of network nodes becomes the first concern. Zhu et al. [6] established the ULS network location model based on 0–1 linear location and allocation model and got the solution via LINGO software. Jiang et al. [7] built the ULS location model based on set covering model. Delft et al. [8] built the ULS evaluation model for Houston downtown and selected the optimal network layout. Secondly, as to the optimal layout of urban ULS, a majority of studies have conducted analogue simulation through plant growth algorithm. Li Tong et al. [9] set up a tree-like ULS layout model meeting the requirement of increasingly expanding large cities in China based on the theoretic model of Steiner Minimal tree and obtained the optimal layout of a ULS with the phototropism theory as the heuristic intelligent algorithm. Zhou Ting et al. [10] built the optimization model of underground logistics distribution routing based on capitalized cost and time cost with the objective of minimal cost of underground logistics distribution routing and obtained solution to the model with the genetic algorithm.

At the present, basic concepts concerning ULS network planning are relatively completed. However, the planning methods are still in exploration, and the mathematic model used is generally ground location models. Given that ULS network is an integral structure composed of several terminals and channels, consideration to location of single facility is apparently not suitable for ULS network location. Besides, problems concerning channel between terminals are clearly included in ULS network location, which is the remarkable difference in location for ULS network and ground logistics network. Therefore, problems concerning ULS network are primarily problems involving in multi-facility location and channel, namely to ascertain the amount, position of the terminals and the channel structure between channels in a certain geographical area according to relationship between the geographical distribution of customer sites and allocation of goods. It is different from location and path for two reasons: first, location and channel is about connection path between terminals not path between customers and terminals; second, once channel structure between terminals is set, connection path between terminals must follow the channel structure and location path is not subject to such restriction. For this purpose, this paper establishes the ULS network through setting up the multi-objective ULS network location and channel model for the region based on its OD (origin–destination) traffic matrix and practical data of regional node information.

2 Problem description

Problem 1: selection of multi-objective ULS network node

Setting up a node selection model of the region according to its practical condition.

(2) Establishing the ULS network node group of the region.

This study mainly aims at establishing ULS network in Xianlin, Nanjing based on the situation of its logistics and ascertaining the positions of first-level and second-level nodes and freight volume and other information. At first, this paper builds a multi-objective node selection model and put forward six objective functions, including transport rate.

Firstly, in this paper, we set up the multi-objective node selection model and put forward six objective functions of: minimization of transport rate of the node, maximization of service rate of node at all levels within 3 km, maximization of rate of change in the traffic congestion level, minimization of the distance between the logistics park and the first-level node, maximization of the degree of aggregation of second-level affiliated to first-level node as well as maximization of the dispersion of first-level nodes so as to set standards for selection of nodes at various levels. And then, by the agglomerative hierarchical clustering method, we divide the centres of all regions into several types and calculate the position of first-level nodes in the ULS network according to node selection model, and thereby calculate the coordinates of the second-level nodes within the coverage area of all first-level nodes through the greedy algorithm. Finally, we calculate the service region, actual freight volume of nodes at different levels and transport rate of first-level node based on the node group we established.

Problem 2: Multi-objective ULS network channel design

Selecting the most suitable underground route according to the node group of the ULS network so as to establish the ULS network for the region.

(2) Attempting to optimize the network and adjust positions of first-level and second-level nodes when there is no obvious change in transport rate.

Through establishing 0–1 integer planning model, this paper realizes several objectives such as minimization of total network cost, maximization of underground transportation, rate of change in traffic congestion level, maximization of node load balance degree and minimization of transport rate of first-level node, which all help realize maximum benefits of the underground network. In the process of determining channels, this paper simulates the derivation of network channels by plant growth simulation algorithm and looks for the optimal route through repeated iteration. Meanwhile, with the 0–1 integer planning model as the iteration termination condition, the optimal channel design scheme is obtained.

2.1 Basic model assumptions

Assumption I: there is no accident.
Assumption II: the things to be predicated develop in a progressive way without saltatory changes.
Assumption III: no vehicles stop suddenly during transportation.
Assumption IV: average transportation cost of each ton of goods per kilometre remains the same and not influenced by tunnel size.
Assumption V: no consideration is given to construction of logistics parks and underground nodes in the parks.
Assumption VI: demand for goods grows at 5% every year and length of road can be built every year is nearly the same.
Assumption VII: it is deemed as effective coverage of the node if the centre of the area is covered by the node (Table 1).

2.2 Data acquisition and analysis

In view of practical statistical data availability, we mainly obtain relevant data including population density, traffic flow and personnel makeup from China City Statistical Yearbook and look up cargo zoning maps in Gaode Map.

Table 1 Description of some symbols

Symbol	Symbol description
ϕ	First-level node transport rate
RPC	Service scope of the node within 3 km
RJ	Rate of change of degree of congestion at the node
BT	Cargoes loaded and unloaded on the ground of the node before completion of the ULS network
AT	Cargoes loaded and unloaded on the ground of the node after completion of the ULS network
KTI	Distance between the logistics park and the first-level node
ITJ	Distance between first-level node and second-level node
ITI	Dispersion of first-level node
MT_i	Cargoes loaded and unloaded on the ground of node in unit hour
TR_{ij}	Goods transportation efficiency from node i to node j
C	Total cost of the ULS network
C_R	Total cost of road construction
C_T	Total cost of goods transportation
C_P	Total cost of node construction and depreciation

Other symbols in the model will be illustrated specifically in the process of modelling

3 Modelling

3.1 Node selection model for multi-objective ULS network

In order to search for the optimal logistics network node group, it is necessary to set rational node selection targets so as to realize maximum transportation efficiency of the network under the premise of given conditions. According to relevant data of Xianlin area of Nanjing, while meeting the requirements of cargoes loaded and unloaded on the ground, transportation efficiency and traffic congestion level, this paper realizes to the utmost extent the following goals: minimal transport rate of the node in the system, maximum transportation coverage, optimal of traffic flow, the most dispersed first-level node and the shortest distance between the logistics park and the first-level node as well as the distance between the first-level node and second-level node in its service scope. The objective functions and constraint condition for node selection model are given in the following:

Objective functions:

NO. 1 transport rate (ϕ) minimization of first-level node

Transport rate refers to the percentage of the goods transshipped to all other first-level nodes from the nearest first-level node in the logistics park of the total shipments of the logistics park. Because transportation vehicles are changed, lower transport rate can reduce workload under given transportation requirement. The objective function is thereby set as:

$$\min \phi_i = \frac{T_{ki}}{T_{ii'}} \tag{1}$$

wherein ϕ_i represents the transport rate of the ith first-level node; T_{ki} represents the total freight volume from kth logistics park to the ith first-level node: $T_{ii'}$ represents the total freight volume from ith first-level node to other first-level nodes.

NO. 2 Maximization of service rate of node at all levels within 3 km

According to the general principle that "service radius of all nodes can be either value in the area within 3 km" and in view of small freight volume in some areas, two adjacent regional centres are included into the service region of the same second-level node under the same transportation requirements. By thus doing, expenditure on construction of nodes and roads can be reduced dramatically. Therefore, cargo transportation coverage of the nodes at different levels shall be as large as possible.

In this paper, 3 km coverage rate is the proportion of all regional centres covered within 3 km in the entire regional centres. Let set PC_i be the set of nodes covered by node i in 3 km, namely $PC_i = \{PC_{i1}, PC_{i2}, PC_{i3}, \ldots PC_{in}\}$, n is the number of elements in PC_i.

Let N be the total number of nodes, the node coordinates are $(X_i, Y_i), \quad i = 1, 2 \ldots, N$.

The objective function is:

$$\max RPC_i = \frac{\#\{\cup_{i=1}^{N} PC_i\}}{N} \tag{2}$$

wherein stands for service rate within 3 km of the ith node and $\#\{\}$ stands for the number of sets.

NO. 3 Maximization of rate of change in traffic congestion level

Construction of ULS network is aimed at alleviate the increasing traffic congestion on the ground. Especially, construction of underground logistics nodes in heavily congested areas can effectively improve traffic congestion. By comparison of the traffic congestion level before and after construction of ULS, a quantitative assessment of the effectiveness exhibited by the system; therefore, under ideal conditions, maximization of rate of change in traffic congestion level is realized:

$$\max RJ = \frac{\sum_{i=1}^{N} RJ_i}{N} \tag{3}$$

wherein RJ stands for the average of rate of change in traffic congestion level of the node, and the rate of change in traffic congestion level of the ith node is:

$$RJ_i = \frac{f(BT_i) - f(AT_i)}{f(BT_i)} \times 100\% \tag{4}$$

wherein BT stands for the actual gross cargoes loaded and unloaded of node i before completion of the ULS network and AT stands for the actual gross cargoes loaded and unloaded of node i after completion of the ULS network.

NO. 4 Minimization of the distance between the logistics park and the first-level node

In ULS, the logistics park is only connected with first-level node, and the transportation efficiency from the logistics park to first-level node affects that of the first-level node to its affiliated second-level node also that of the first-level node to other first-level nodes. Therefore, it is of vital importance to minimize the distance between the logistics park and first-level node:

$$\min KTI = \frac{\sum_{k=1}^{4} \sum_{i \in K_i} \sqrt{(X_{K_k} - X_{I_i})^2 + (Y_{K_k} - Y_{I_i})^2}}{\sum_{k=1}^{4} K_{im}} \tag{5}$$

wherein KTI represents the distance between the logistics park and first-level node; (X_{K_k}, Y_{K_k}) represents the coordinates of the kth logistics park; (X_{I_i}, Y_{I_i}) represents the coordinates of the ith node; K_i represents the number of the first-level node corresponding to the kth logistics park; and the total amount is K_{im}.

NO. 5 Maximization of the degree of aggregation of second-level affiliated to first-level node

In order to improve comprehensive transportation efficiency, the distance between first-level node and its affiliated second-level shall be as short as possible, that is to say, the positioning of first-level node shall enhance degree of aggregation of second-level node to first-level node; therefore, the objective function is:

$$\min ITJ_{ij} = \sum_{i=1}^{NI} \sqrt{(X_{J_j} - \overline{X_I})^2 + (Y_{J_j} - \overline{Y_I})^2} \tag{6}$$

wherein ITJ stands for the distance between first-level node and second-level node; $(\overline{X_I}, \overline{Y_I})$ stands for the coordinates of central points of all first-level nodes; (X_{J_j}, Y_{J_j}) stands for coordinates of the ith first-level node;

NO. 6 Maximization of the dispersion of first-level nodes

First-level nodes are the intermediate node of the entire ULS, for they are not only connected with the logistics park, but also with other first-level nodes and their affiliated second-level node. Hence, the more dispersed the first-levels is, the bigger the network transportation coverage is and the higher the total transportation efficiency is.

Let the amount of first-level nodes is NI, then the set of second-level nodes affiliated to first-level node i is:

$$IJ_i = \{I_{j1}, I_{j2}, I_{j3} \ldots I_{jm}\} \tag{7}$$

wherein m stands for the number of second-level nodes included in the first-level nodes; let ITI be the dispersion of first-level nodes, then the objective function is:

$$ITI = \sum_{i=1}^{NI} \sum_{I_i \in IJ_i} \sqrt{(X_{I_i} - X_{J_j})^2 + (Y_{I_i} - Y_{J_j})^2} \tag{8}$$

Restriction conditions:

NO. 1 Restriction on cargoes loaded and unloaded on the ground of all nodes:

According to the freight OD flow matrix of Xianlin area of Nanjing, the designed cargoes loaded and unloaded of the node shall be larger than the actual value. At the same time, let "upper limit of the cargoes loaded and unloaded first-level node on the ground is 4000 ton, and 3000 ton of the second-level node", this paper defines α coefficient is the ratio of underground freight volume and the actual freight demand of all nodes. As such, the restriction condition is:

$$\sum_{i=1}^{N} IO_i \geq \left(\sum_{i=1}^{NI} \sum_{j=1}^{NJ} A_{ij} \right) \times \alpha_i \tag{9}$$

wherein A_{ij} stands for the gross freight volume from node i to node j

$$IO_i \leq IO_{\max} \begin{cases} \text{When } i \text{ is a first-level node, } IO_{\max} = 4000t \\ \text{When } i \text{ is a second-level node, } IO_{\max} = 3000t \end{cases} \tag{10}$$

NO. 2 Restriction on traffic congestion level

Traffic congestion level affects amenity of the urban residents, in order to manifest the role of ULS and alleviate the traffic pressure on the ground to the best extent, ground traffic shall be as smooth as possible, namely congestion level shall not exceed 4:

$$RJ_i \leq 4 \tag{11}$$

As per the question and assumption, congestion level of ground traffic is only related to freight volume. Let $RJ_i = k \times YH_i$, k be the correlation coefficient of the two variables, wherein YH_i stands for the cargo quantity on the ground after completion of the ULS:

$$YH_i = \begin{cases} AH_i - MT_i, & \text{When } AH_i \geq MT_i \\ 0, & \text{When } AH_i < MT_i \end{cases} \tag{12}$$

MT_i stands for the cargoes loaded and unloaded on the ground of node i within unit hour:

$$\begin{aligned} MT_i = & \sum_{i=1}^{NI} \sum_{j=1}^{NJ} TR_{ji} + \sum_{i=1}^{NI} TR_{i'i} + \sum_{k=1}^{4} TR_{ki} \\ & + \sum_{i=1}^{NI} \sum_{j=1}^{NJ} TR_{ij} + \sum_{i=1}^{NI} TR_{ii'} + \sum_{k=1}^{4} TR_{ik} \end{aligned} \tag{13}$$

TR_{ij} stands for cargo transportation efficiency from node i to node j:

$$TR_{ij} = \frac{NJ \times M}{NNI_{ij} \times {}^{12}\!/_{60} + \frac{D_{ij}}{V}} \tag{14}$$

wherein NNI_{ij} represents the number of first-level nodes in transportation of goods from node i to node j; D_{ij} represents the total distance between node i to node j; NJ represents the maximum amount of one troupe of vehicles, with the value range of 4–8; V represents the transportation speed per hour of one troupe of vehicles; M represents the number of goods transported by one troupe of vehicles, assuming the roads between the logistics park and first-level node is provided with 10-ton deadweight trucks, and other roads are provided with 5-ton deadweight trucks.

From the above, node group selection model for ULS network is as follows:

$$\begin{cases} \min \phi_i = \dfrac{T_{\mathrm{ki}}}{T_{ii'}} \\ \max RPC_i = \dfrac{\#\{\cup_{i=1}^{N} PC_i\}}{N} \\ \max RJ = \dfrac{\sum_{i=1}^{N} RJ_i}{N} \\ \min KTI = \dfrac{\sum_{k=1}^{4} \sum_{i \in K_i} \sqrt{(X_{K_k} - X_{I_i})^2 + (Y_{K_k} - Y_{I_i})^2}}{\sum_{k=1}^{4} K_{im}} \\ \min ITJ_{ij} = \sum_{i=1}^{NI} \sqrt{(X_{J_j} - \overline{X_I})^2 + (Y_{J_j} - \overline{Y_I})^2} \\ ITI = \sum_{i=1}^{NI} \sum_{I_i \in IJ_i} \sqrt{(X_{I_i} - X_{J_j})^2 + (Y_{I_i} - Y_{J_j})^2} \end{cases} \tag{15}$$

$$s.t \begin{cases} RJ_i = \dfrac{f(BT_i) - f(AT_i)}{f(BT_i)} \times 100\% \\ \sum_{i=1}^{N} IO_i \geq \left(\sum_{i=1}^{NI} \sum_{j=1}^{NJ} A_{ij} \right) \times \alpha_i \\ IO_i \leq IO_{\max} \begin{cases} \text{When } i \text{ is a first-level node, } IO_{\max} = 4000t \\ \text{When } i \text{ is a second-level node, } IO_{\max} = 3000t \end{cases} \\ RJ_i \leq 4 \\ RJ_i = k \times YH_i \\ YH_i = \begin{cases} AH_i - MT_i, \text{ When } AH_i \geq MT_i \\ 0, \text{ When } AH_i < MT_i \end{cases} \\ MT_i = \sum_{i=1}^{NI} \sum_{j=1}^{NJ} TR_{ji} + \sum_{i=1}^{NI} TR_{i'i} + \sum_{k=1}^{4} TR_{ki} \\ \qquad + \sum_{i=1}^{NI} \sum_{j=1}^{NJ} TR_{ij} + \sum_{i=1}^{NI} TR_{ii'} + \sum_{k=1}^{4} TR_{ik} \\ TR_{ij} = \dfrac{NJ \times M}{NNI_{ij} \times {}^{12}\!/_{60} + \dfrac{D_{ij}}{V}} \end{cases} . \tag{16}$$

3.2 Multi-objective ULS network channel design model

On the basis of node determined in question I, the plant growth simulation algorithm is used for global intelligent search so as to choose the optimal network channel design path by repeated selection and iteration; meanwhile, with the objectives of minimal total cost, maximum underground transportation, maximum rate of change in traffic congestion level, maximum balance degree of node load and minimal transport level of first-level node, the 0–1 planning model is built as the iteration termination condition of plant growth simulation in view of restrictions on 0–1 decision-making variable, channel transportation capability, cargoes loaded and unloaded on the ground of all nodes at different levels and traffic congestion level.

Objective function:

NO. 1 Minimization of total cost

For large-scale engineering projects, cost is an essential factor influencing decision-making, in order to increase project benefits, minimization of cost shall be realized under the premise of qualified engineering. Generally speaking, total cost of the system includes road construction cost, cargo transportation cost and construction and depreciation cost of node.

Objective function is:

$$\min C = C_R + C_T + C_P \tag{17}$$

wherein C_R is road construction cost:

$$C_R = \sum_{i=1}^{N}\sum_{j=1}^{N} P_{ij}\times L_{ij} \times X_{ij} \tag{18}$$

C_T is the cargo transportation cost:

$$C_T = \sum_{i=1}^{N}\sum_{j=1}^{N} TR_{ij} \times DC \tag{19}$$

C_P is the construction and depreciation cost of the node:

$$C_P = MF \times NI + CF \times NI + MV \times NJ + CV \times NJ \tag{20}$$

wherein P_{ij} stands for the length of underground passage from node i to node j; L_{ij} stands for unit cost for cargo transportation from node i to its adjacent node; DC stands for the transportation cost of the cargo with unit length and unit weight; MF stands for construction cost of first-level node; CF stands for repair cost of first-level node; MV stands for construction cost of second-level node; CV stands for repair cost of second-level node.

NO. 2 Maximization of underground transportation

For meeting the actual logistics demand, in the process of road design, efficiency of underground transportation shall be improved as much as possible. It is defined that YX is the total underground freight volume in a unit hour, then the objective function is:

$$\max YX = \sum_{i=1}^{N}\sum_{j=1}^{N} TR_{ij} \tag{21}$$

NO. 3 Maximization of rate of change in traffic congestion level

Likely, design of channel shall meet the requirement of alleviating ground traffic. Therefore, in construction of the network, maximization of rate of change in traffic congestion shall be included into the objective function of question II:

$$\max RJ = \frac{\sum_{i=1}^{N} RJ_i}{N} \tag{22}$$

wherein: $RJ_i = \frac{f(BT_i) - f(AT_i)}{f(BT_i)} \times 100\%$.

NO. 4 Maximization of balance degree of node load

In this paper, variance of freight volume of the nodes at the same level is used to evaluate network load balance. In order to avoid seriously imbalanced freight volume of all nodes and enhance overall stability of the network, it is necessary to balance load of all nodes, that is to say, minimize the variance. The objective function is thereby as:

$$\min BL = BLI + BLJ \tag{23}$$

wherein BLI is the balance degree of the load of first-level node and BLJ is the balance degree of the load of first-level node

$$BLI = \sqrt{\sum_{i=1}^{NF} \left(MT_{F_i} - \overline{MT}\right)^2} \tag{24}$$

$$BLJ = \sqrt{\sum_{i=1}^{NF} \left(\sum_{k \in SF_i} \left(S_{ik} - \overline{S_i}\right)^2\right)} \tag{25}$$

NO. 5 Minimization of transport rate of first-level node (ϕ)

Transport rate directly affects the working efficiency of the network, and it is found by the OD flow matrix of all regions, the transport rate can be greatly reduced and the transportation duration can be shortened by building a direct road in two points with high transportation demand. The objective function is hereby set as:

$$\min \phi_i = \frac{T_{ki}}{T_{ii'}} \tag{26}$$

Restriction conditions:

NO. 1 0–1 Decision-making variable

Suppose X_{ij} is the channel between node i to node j, and if there is a channel between the two nodes, the value is 1, or the value is 0, namely:

$$\begin{cases} X_{ij} = 1, & j \in SF_i \text{ or } i \in SF_j \\ X_{ij} = 0, & j \notin SF_i \; and \; i \notin SF_j \end{cases} \tag{27}$$

NO. 2 Restriction on channel transportation capacity

According to the question, the first-level node is connected with the logistics park and provided with 10-ton load-carrying trucks for underground transportation and other roads are provided with 5-ton load-carrying trucks; in addition, all nodes are provided with dispatch of trucks every 12 min, 5 shifts at most in an hour and 18 h of operation a day. Thus, we can calculate the transportation capacity of each channel. The restriction condition is:

$$EF \leq UEF \tag{28}$$

wherein EF is the actual freight volume, UEF is the maximum transportation capacity of the channel, and

$$UEF = \begin{cases} 18\times 5\times 10 = 900\ t/\text{day}, & \text{the logistics to the first-level node} \\ 18\times 5\times 5 = 450\ t/\text{day}, & \text{other channel} \end{cases} \tag{29}$$

NO. 3 Restriction on total cargoes loaded and unloaded of all nodes on the ground

Similar to question I, restriction on cargoes loaded and unloaded of all nodes on the ground shall be taken into consideration in the process of channel design. The restriction condition is:

$$\sum_{i=1}^{N} IO_i \geq \left(\sum_{i=1}^{NI}\sum_{j=1}^{NJ} A_{ij}\right)\times \alpha_i \tag{30}$$

wherein A_{ij} stands for the gross freight volume from node i to node j

$$IO_i \leq IO_{\max}\begin{cases} \text{When } i \text{ is a first-level node, } IO_{\max} = 4000t \\ \text{When } i \text{ is a second-level node, } IO_{\max} = 3000t \end{cases} \tag{31}$$

NO. 4 Restriction on traffic congestion level

Similarly, the requirement that traffic congestion level is not greater than 4 shall be met in this paper:

$$RJ_i \leq 4 \tag{32}$$

Suppose $RJ_i = k \times YH_i$ and k be the correlation coefficient of two variables.

Wherein YH_i is the cargo quantity on the ground after completion of ULS network:

$$YH_i = \begin{cases} AH_i - MT_i, & \text{When } AH_i \geq MT_i \\ 0, & \text{When } AH_i < MT_i \end{cases} \tag{33}$$

MT_i represents the cargoes loaded and unloaded on the ground of node i in a unit hour:

$$\begin{aligned} MT_i = &\sum_{i=1}^{NI}\sum_{j=1}^{NJ} TR_{ji} + \sum_{i=1}^{NI} TR_{i'i} + \sum_{k=1}^{4} TR_{ki} \\ &+ \sum_{i=1}^{NI}\sum_{j=1}^{NJ} TR_{ij} + \sum_{i=1}^{NI} TR_{ii'} + \sum_{k=1}^{4} TR_{ik} \end{aligned} \tag{34}$$

TR_{ij} represents the transportation efficiency of cargoes transported from node i to node j:

$$TR_{ij} = \frac{NJ \times M}{NNI_{ij} \times {}^{12}/_{60} + \frac{D_{ij}}{V}} \tag{35}$$

From the above, multi-objective ULS network channel design model is as follows:

$$\begin{cases} \min C = C_R + C_T + C_P \\ \max YX = \sum_{i=1}^{N}\sum_{j=1}^{N} TR_{ij} \\ \max RJ = \frac{\sum_{i=1}^{N} RJ_i}{N} \\ \min BL = BLI + BLJ \\ \min \phi_i = \frac{T_{ki}}{T_{ii'}} \end{cases} \tag{36}$$

$$s.t.\begin{cases} C_R = \sum_{i=1}^{N}\sum_{j=1}^{N} P_{ij}\times L_{ij}\times X_{ij} \\ C_T = \sum_{i=1}^{N}\sum_{j=1}^{N} TR_{ij}\times DC \\ C_P = MF\times NI + CF\times NI + MV\times NJ + CV\times NJ \\ RJ_i = \frac{f(BT_i) - f(AT_i)}{f(BT_i)}\times 100\% \\ BLI = \sqrt{\sum_{i=1}^{NF}\left(MT_{F_i} - \overline{MT}\right)^2} \\ BLJ = \sqrt{\sum_{i=1}^{NF}\left(\sum_{k\in SF_i}\left(S_{ik} - \overline{S_i}\right)^2\right)} \\ X_{ij} = 0 \text{ or } 1 \\ EF \leq UEF \\ \sum_{i=1}^{N} IO_i \geq \left(\sum_{i=1}^{NI}\sum_{j=1}^{NJ} A_{ij}\right)\times \alpha_i \\ RJ_i \leq 4 \end{cases} \tag{(37)}$$

4 Algorithm design

4.1 Determination of ULS network first-level node based on agglomerative hierarchical clustering algorithm

4.1.1 Agglomerative hierarchical clustering algorithm

By now, clustering algorithms commonly used in data mining include hierarchical clustering method, partitioning clustering method, density-based clustering method and grid-based clustering method [11]. Hierarchical clustering creates a hierarchical nested cluster tree by calculating the similarity between different categories of data points. According to different directions of the trees created, the bottom-up hierarchical clustering is called agglomerative hierarchical clustering and a top-down hierarchical clustering is called divisive hierarchical clustering.

Agglomerative hierarchical clustering algorithm contains four methods for measurement of cluster distance, namely:

1. Minimum distance method: refers to the method by which the distance between two clusters is represented by the shortest distance of data points of the two clusters.

$$d_{\min}(c_i, c_j) = \min_{p \in c_i, p' \in c_j} |p - p'| \quad p \in c_i,\ p' \in c_j \tag{38}$$

2. Maximum distance method: refers to the method by which the distance between two clusters is represented by the longest distance of all data points of the two clusters.

$$d_{\max}(c_i, c_j) = \max_{p \in c_i, p' \in c_j} |p - p'| \quad p \in c_i,\ p' \in c_j \tag{39}$$

3. Mean distance method: refers to the method by which the distance between two clusters is represented by the distance between the central points of the two cluster.

$$d_{\text{mean}}(c_i, c_j) = |m_i - m_j| \tag{40}$$

wherein m_i is the mean of cluster c_i and m_j is the mean of cluster c_j.

4. Average distance method: refers to the method by which the distance between two clusters is represented by the average distance between all the data points of the two clusters.

$$d_{avg}(c_i, c_j) = \frac{1}{n_i n_j} \sum_{p \in c_i} \sum_{p' \in c_j} |p - p'| \quad p \in c_i,\ p' \in c_j \tag{41}$$

wherein n_i is the amount of objects in cluster c_i and n_j is the amount of objects in cluster c_j.

4.1.2 Calculation process of agglomerative hierarchical clustering algorithm

In this paper, location of first-level node in ULS network is determined by agglomerative hierarchical clustering algorithm with the minimum distance as the measurement criterion of distance between clusters. Meanwhile, in combination with the node selection mode established in the above, the position coordinates of first-level code are calculated. The basic selection process of first-level node based on agglomerative hierarchical clustering algorithm is as follows:

Step 1 Determine the initial cluster: position coordinates of every single central point in the region are regarded as a cluster, and each cluster only contains one object. According to Euclid distance matrix formula, the distance between all data points is calculated and the initial distance matrix D is obtained;
Step 2 Obtain new cluster: pursuant to the minimum distance clustering criterion, the data points with the shortest distance are combined into a new cluster, which is the second layer of the clustering tree.
Step 3 Aggregate: recalculate the distance $d(i, j)$ between the new and all other clusters that is to say, to regard the minimum distance between the new combined cluster and the original cluster as the similarity of the two clusters;
Step 4 Terminate clustering: repeat step 2 and step 3 until the coverage areas of the cluster to which the data belong are over 3 km, and then clustering is terminated;
Step 5 Select first-level node: in the classified clusters, select a model according to the node type and search for the best position to establish a node in the cluster so as to realize maximal service region and transportation efficiency of the node.

Figure 1 shows the flow chart of agglomerative hierarchical clustering algorithm based on the minimum distance.

4.2 Selection of second-level node in ULS network based on greedy algorithm

Owing to its simplicity and high efficiency, greedy heuristic (GR) has been applied into optimization of various combinations, such as travelling salesman problem [12], matching problem [13] and scheduling problem [14]. In this paper, the greedy algorithm is used to determine the position coordinates of the second-level node affiliated to first-level node.

In the process of calculation by greedy algorithm, the problems to be solved are firstly divided into several small problems. And then, according to the given optimization measurement, the locally optimal solution is obtained each time. Finally, optimal solutions to all sub-problems are combined into the solution to the problem to be solved. Based on the above, optimization of transportation efficiency of the second-level node affiliated to each first-level node is taken into consideration in the process of calculation of position of second-level nodes in this paper. Meanwhile, in combination with node selection model, the final position of second-level nodes is determined through calculation.

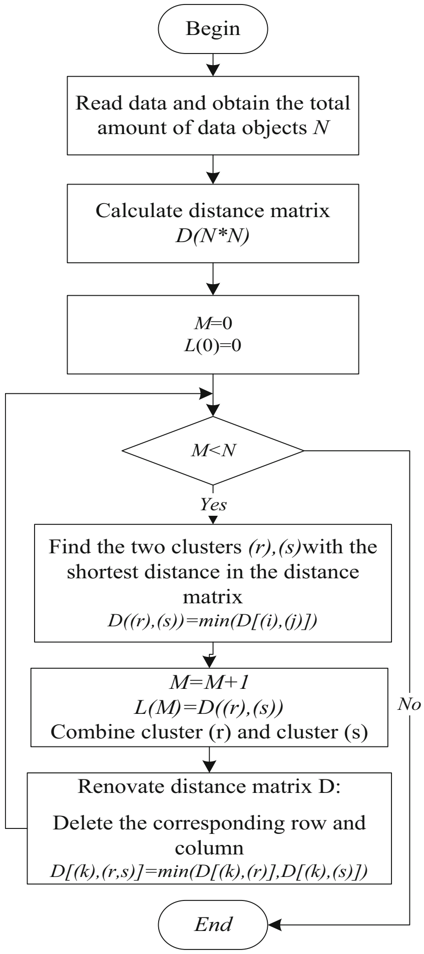

Fig. 1 Flowchart of agglomerative hierarchical clustering algorithm based on minimum distance

4.3 ULS network channel design base on plant growth simulation algorithm

4.3.1 Plant growth simulation algorithm

Plant growth simulation algorithm (PGSA) is one of the bionic random optimization algorithms presented on the basis of integer planning and aims at shortening rimming time of algorithm, enhancing accuracy of the optimal solution through researches and improvement, respectively, made on reinitialization, step size in search, criterion of algorithm termination. This algorithm is characterized with good scalability, high calculation accuracy, high rate of convergence and reliable stability. The earliest study on the algorithm was made by Li et al. [15] from Tianjin University in 2005, whom also applied such algorithm into solving integer planning problems and achieved satisfactory results.

Huang et al. [16] solved the express vehicles scheduling model with the objective of maximal customer's satisfaction and perception on average waiting time and minimal transport mileage with the plant growth simulation algorithm and verified the validity of the algorithm. In this paper, PGSA algorithm is used for channel design of the ULS network.

4.3.2 Calculation process of plant growth simulation algorithm

In this paper, growing environment of plants is regarded as feasible region of the ULS network, P is the finite point set composed by node ground in the ULS network, and then the specific steps of PGSA are as described in the following:

Step 1 Calculate the minimal spinning tree network composed by finite point set P with Prim algorithm;
Step 2 Generate a new Steiner minimal tree (SMT) topological structure based on the minimal spinning tree and establish n initial Steiner points $(S_1, S_2, \cdots, S_n)$;
Step 3 Calculate the morpheme concentration of $(S_1, S_2, \cdots, S_n)$:

$$p_i = \frac{f(S_i)}{\sum_{i=1}^{n} f(S_i)} \tag{42}$$

wherein $f(S_i)$ is the sum of length of the sides adjacent to S_i

Step 4 Calculate the morpheme concentration of p_{i+1}:

$$\begin{aligned} p_{i+1} &= p_{i+1} + p_i \\ p_i &= p_i / p_n \end{aligned} \tag{43}$$

Step 5 Generate a random number at the range [0, 1], if the random number is greater than p_i and less than p_i, $F \leftarrow S_i$;
Step 6 Branch growth process is as follows:

In the initial state ω: F; rotation angle: $\delta = 90°$, growing rule: $F \rightarrow F[-F][+F]F$.

After the branch splits, the new growing points are $S_i(1),\ S_i(2), S_i(3)$.

Let (x, y, α) be the current condition of the Steiner point (simulated plant growing point) randomly chosen, among which, x and y are the coordinates of the plant growing point, α is the direction of the growing point, d is the length of the knot, δ is the angle increment of the top, "[" means to save the information of the node, namely location where the branch splits and draws the first smaller branch; while, "]" means to release the information recorded at "[". After the first smaller branch is drawn, "]" is used to take out the information in the previous node and then the second

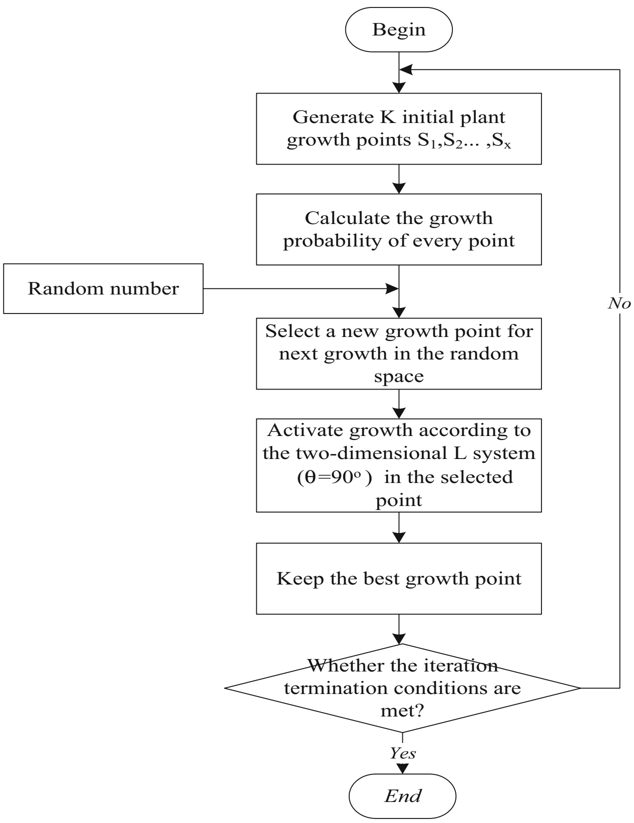

Fig. 2 PGSA algorithm flow chart

smaller branch is drawn from the point where the branch splits. Other relevant symbols mean:

Step 7 $S_i \leftarrow \min\{f(S_i), f(S_i(1)), f(S_i(2)), f(S_i(3))\}$;
Step 8 If there is no new smaller branch after n times of iteration (or set a certain number of iterations, for example 200), the plant growth stops, otherwise, step 3 is repeated.

Figure 2 gives the flow chart of PGSA algorithm.

5 Experiment and analysis

5.1 Position coordinates of network node group in model solution

According to the node selection model, agglomerative hierarchical clustering algorithm is adopted to calculate position coordinates of first-level node, and greedy algorithm is adopted to calculate position coordinates of second-level node. Through clustering analysis of freight OD flow matrix of Xianlin area in Nanjing via MATLAB, the clustering results as shown in Fig. 3 are obtained. After further quantitative analysis of the nodes, the relation between first-level node and second-level node is determined, as shown in Table 2: the maximum service radius and actual freight volume of first-level node are as shown in Fig. 3.

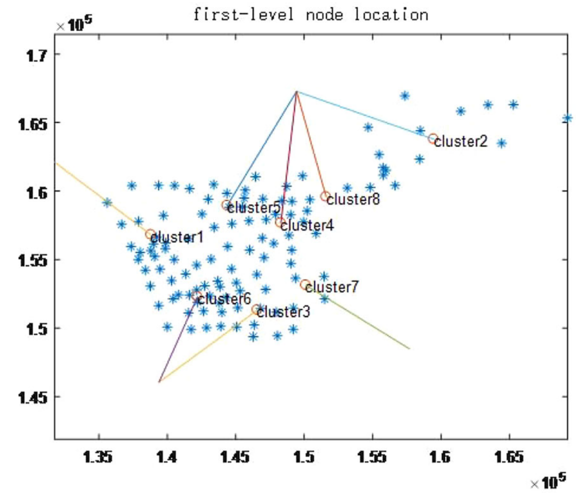

Fig. 3 Coordinate diagram of first-level node

Through analysis of Tables 2 and 3, it can be found that, there are 4 first-level nodes in the ULS network, including 19 s-level nodes and the amount of the nodes set in the network can basically meet freight demand.

5.2 Channel design results of ULS network

Through solving of 0–1 planning model, the optimal design of pipe network layout is determined and realized a pipe network with the total length of 72,179.68 m and 19 nodes. Figure 4 gives the specific structure of the ULS network.

It can be seen from the ULS network structure that, most of the nodes are in the left side of the grid and second-level nodes concentrate in this part. Therefore, this region is business accumulation area, with great freight demand and the nodes and channels are comparatively complex, which coincides with the actual situation.

6 Conclusion

In this paper, the underground logistic network is designed according to the actual data including geographical position, population density, freight traffic situation, which achieves ideal results in alleviating traffic congestion and reducing logistics cost and also realizes several objectives of: minimization of transport rate of the node, maximization of service rate of node at all levels within 3 km, maximization of rate of change in the traffic congestion level, minimization of the distance between the logistics park and the first-level node, maximization of the degree of aggregation of second-level affiliated to first-level node as well as maximization of the dispersion of first-level nodes.

Table 2 Relation table of the first-level node and contiguous second-level node

First-level node	*X* coordinate	*Y* coordinate	Second-level node	*X* coordinate	*Y* coordinate
1	140,283.3	153,392.63	813	139,366.74	151,652.59
			814	140,416.57	152,146.08
			815	141,612.02	152,424.78
			827	141,339.45	153,959.72
			857	137,889.68	157,781.66
			859	139,713.81	158,198.05
2	138,687.2	157,201.11	844	137,872.62	155,016.21
			852	137,348.14	155,938.46
			861	144,512.67	158,820.03
			864	144,348.86	159,828.82
			834	144,403.29	155,930.01
			875	145,488.59	158,833.25
3	144,364.7	159,166.48	838	148,886.18	156,757.98
			882	148,723.84	160,336.69
			876	148,375.72	159,294.26
			829	149,026.56	154,716.68
4	148,832.6	158,220.06	832	149,088.16	155,678.19
			884	149,877.22	161,091.04
			839	149,951.90	157,738.28

Table 3 Maximum service radius of the first-level node and actual freight volume of node

First-level node	Largest service region/m	Actual freight volume/*t*	Transport rate
1	3234.2	12,351.517	0.0278
2	3508.7	13,254.414	0.0189
3	3282.7	29,854.089	0.1457
4	2157.5	27,573.809	0.0987

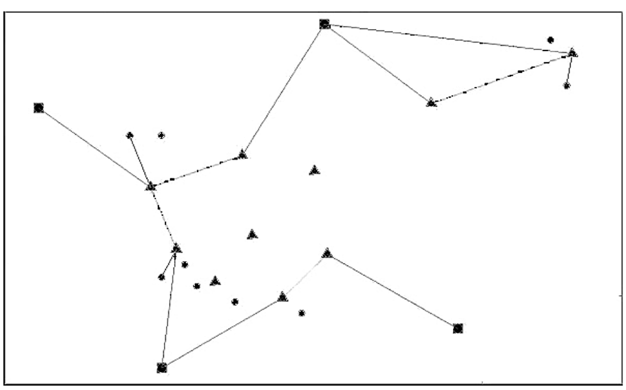

Fig. 4 ULS network structure

Therefore, the ULS network built in this paper can be applied into design of underground logistics network of other areas.

The model is with the following advantages: first, on the basis of in-depth analysis of the problem and in combination with practical data, it screens out the key variables influencing the problem and thus establishes a rational and effective mathematical model; second, reasonably quantify some unquantified indicators, such as service region of all nodes and degree of aggregation, and gives more precisely node selection and channel design results of the ULS network. Whereas, it also has the disadvantages: in this paper, the relationship between freight volume on the ground and traffic congestion level is simplified into linear relationship; however, in reality, there are much more factors influencing traffic congestion level, such as rush hour, urban population, urban economical development level and so on. The simplification would lead to overly ideal simulated situation. And in the process of practice, the role of alleviating traffic congestion of ULS network would be slightly reduced, which needs further improvement.

Compliance with ethical standards

Conflict of interest We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work; there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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