Network Construction of Underground Logistics System Based on System Clustering and Centre of Gravity Method

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Abstract. To alleviate the conflict between urban logistics and traffic, society, space, and the environment in the development process, it is a beneficial approach to establish an underground logistics system network within the urban area. This paper examines the selection of underground logistics nodes, explores the design of the underground channel network, applies a mathematical modelling method to enhance the channel network, and executes the construction time sequence and dynamic optimization, providing feasible solutions of significant practical importance. To address the issue of locating multiple distribution centres within a region, this study suggests employing a combination of system clustering and the centre of gravity method in order to determine the optimal locations for multi-node distribution centres. The proposed approach offers a more effective means of identifying potential sites, thereby improving distribution efficiencies in the region.

Keywords: Logistics system network; System clustering; Centre of gravity method

1 Introduction

Congestion and land restraints in major Chinese cities significantly limit the accessibility and quality of urban logistics, particularly in densely populated areas like Beijing, Shanghai and others. The authorities of these cities have implemented regulations disallowing trucks to pass through the city centre during daytime hours. In metropolitan areas, vehicle-based distribution logistics plays a crucial role in maintaining the smooth operation of the city and factory activities. Nevertheless, excessive regulations will inevitably impede the normal progress of the economy and daily life. Furthermore, it may also hinder the burgeoning popularity of online shopping and the growth of e-commerce.

The inadequate transportation of goods in the large cities of China has a direct link to urban congestion and land limitations [1]. Additionally, the difficult rational arrangement of city logistics nodes has an indirect impact. As China's metropolises continue to grow and freight transportation ranges expand, existing logistics centres are unable to offer essential functional services, and logistics nodes in urban areas face the challenge of selecting secondary sites. The limited supply of construction land and the restricted available space make it challenging to maintain a systematic and rational design of urban logistics nodes. However, if we look beyond the high-rise urban ground space, the extensive underground space presents itself as a blank canvas, offering opportunities for a well-thought-out deployment of urban logistics

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nodes, and facilitating the combined development of underground spaces with ground construction facilities. Given the limited land situation in cities, developing an underground urban logistics system is an excellent option for enhancing urban logistics innovation.

To achieve sustainable urban logistics development, it's essential to promote logistics industry construction and enhance industry supervision. Traditional trade circulation and e-commerce are expanding quickly due to efficient logistics support, leading to amplified demand for diversified, multi-level, and high-level logistics services and raising the degree of dependence. The logistics industry as a whole is expected to experience an upsurge in the number of logistics companies, truck ownership, and the circulation of goods alongside other positive macro-phenomena. However, overloaded lorries, truck accidents, truck exhaust emission, vehicle noise, and low-speed lorries lead to an increase in high-speed road bottlenecks and other social problems. These issues could result in the degradation of the urban environment, the depletion of road and social resources, and more considerable investment gaps. Based on the current urban logistics model, city managers face challenges in balancing the competing needs of "promotion" and "regulation". Therefore, several city managers in the United States, the Netherlands, Germany, Japan and other countries are considering the establishment of an underground logistics system to enhance the security of urban freight transportation and mitigate the negative environmental effects. The construction of an urban underground logistics system [2] is recognised as the future development direction of urban logistics, which can serve as a "life-saving straw" and a "killer app". The development of an urban underground logistics system is recognised as the future construction direction for urban logistics.

As urbanisation advances, cities are experiencing an agglomeration effect. China's major cities are expanding their peripheries into the old centres, causing a shortage of space due to the influx of people and vehicles, resulting in a chaotic and cramped environment. This condition of "people and land scarcity" has resulted in various issues in the development of big cities. To meet the design concept of a "people-oriented" approach and sustainable urban development, there is a need to modernise the conventional logistics operation and industry. This entails constructing an all-encompassing social logistics infrastructure platform and operation management system, comprising the underground logistics system. Urban underground logistics systems have become a topic of significant interest in related fields around the world. The International Symposium on Underground Freight Transportation by Capsule Pipelines and Other Tube/Tunnel Systems has been held eight times since 1999, covering a diverse range of issues. The research has progressed beyond pipeline transport to investigate underground logistics systems. Such systems are intricate, integrating modern logistics principles and operational modes. As a result, planning and design of these systems are becoming a new focus for urban planners, managers, and researchers in various countries. Zevgolis et al. [3] have proposed the new "underground warehouse" to cooperate with ground transportation to solve the traffic congestion problem caused by the nearly saturated ground space in the city. Subsequently, Shahooeiet al. [4], after analyzing the security risks brought by the excessive cargo volume to the airport perimeter, also proposed the idea of establishing an underground cargo system at Dallas Fort Worth International Airport to improve road capacity and safety.This paper will critically examine the vital technologies that underpin the planning of an underground logistics system in the Xianlin region of Nanjing, offering constructive methods. Specifically, a network simulation experiment of the "underground logistics system" will be performed to optimise the network layout scheme [5].

2 Model Assumptions and Symbolic Description

There are five assumptions before our study. (1) It is assumed that the average cost of transporting one tonne of cargo per kilometre is constant and not affected by the size of the tunnel it passes through. (2) A region is considered covered by a node if the node covers its centre. (3) The service radius of each node is three kilometres, and there is no restriction on the distance between nodes. (4) Goods are transferred from secondary hubs to the ground using human labour or small vehicles within the hub's service area, without any considerable impact on traffic. (5) The level of regional congestion is directly proportional to the overall regional freight volume as depicted in the Origin-Destination (OD) data.

There are some symbolic description. I∈{1,2,……,NI}, the set of logistics level 1 point alternatives; J∈{1,2,……,NJ}, the set of logistics secondary point alternatives; K∈{1,2,……,NK}, the set of demand point regions; T∈{1,2,……,NT}, the set of hierarchical decision cycles. Dit, 0-1variable, 1 indicates that the supply point is open in period t and 0 the opposite; yjt, 0-1variable, 1 indicates that logistics point j is open in period t and 0 the opposite; zjt, 0-1variable, 1 indicating that logistics point j expands in period t and 0 the opposite; Vjt, a multiple of the modulus of expansion of logistics and distribution centre j in period t; xijt, positive material flow from logistics point i to logistics point j in period t; xjkt, positive material flow from logistics point j to logistics point k in period t; xkjt, the reverse material flow from logistics point k to logistics point j in period t; xjit, the reverse material flow from logistics point j to logistics i in period t.

3 Problem Analysis and Related Principles

3.1 Problem analysis

To address the issue of selecting "underground logistics nodes," this research advocates the integration of system clustering [6] and the centre of gravity method to establish the location of multi-node distribution centres [1]. First, the system clustering method using the shortest distance is employed to classify nodes. This divides the entire distribution area into distinct sub-areas. Next, the centre of gravity method is used to locate the distribution centre in each sub-area. The concept of multiple centre of gravity method is introduced to aid site selection. Lastly, the distribution centre site selection process, based on the shortest distance method and centre of gravity method, is developed. A strategically located distribution centre can reduce costs, expedite the flow of goods, and enhance the profits of logistic organisations [7]. Thus, the distribution centre placement decision holds strategic significance within the logistics system. Multi-node siting refers to the challenge of determining the optimal location for multiple new nodes in the presence of m existing nodes. The new nodes, which may number n, must service the existing nodes. When m=n, adding a new node next to each existing node suffices. However, when m>n, it becomes necessary to take into account the cost of transportation and the opening of a continuous solution space.

This paper employs the system clustering and centre of gravity method to determine the location of a multi-node distribution centre. Initially, the shortest distance method of system clustering is utilised to classify nodes and divide the distribution area into distinct sub-areas. Subsequently, the centre of gravity method determines the precise location of the distribution centre within each sub-area. The centre of gravity method is solved by implementing the site selection procedure designed for the method. However, the location of the initial point is uncertain, making it impossible to determine the transportation rate linked to the distance. As a consequence, a fixed rate replaces the initial solution process, which can later be replaced by the actual rate after it is solved for N (N>1) times. This method is known as the multi-centre of gravity method for site selection.

3.2 Related Principles

3.2.1 Fundamentals of cluster analysis

Cluster analysis is a fundamental technique for investigating the classification of individuals based on transaction characteristics. The basic principle is that individuals in the same class share greater similarity, while those in different classes share lower similarity. Clustering methods encompass systematic clustering, ordered sample clustering, dynamic clustering, fuzzy clustering, graph theory clustering, and clustering prediction. Systematic clustering is utilised in this paper using the shortest distance method, and the basic principles and steps are outlined below. (1) Samples are separated by absolute value distance while classes are separated by the shortest distance; (2) Calculation is conducted to obtain the distance matrix of N samples; (3) A class is constructed, which only comprises of a single sample; (4) Merge the two classes that meet the requirements of the definition of inter-class distance into a new class; (5) Calculate the distance between the new class and the current class. If the number of classes is 1, go to step 6, otherwise go back to step 4; (6) Draw a clustering diagram; (7) Decide the number of classes and the class. The absolute value distance is shown in Equation 1, and the shortest distance between classes is shown in Equation 2. And x_i is the x-axis direction coordinate, y_j is the y-axis, $D(G_1, G_2)$ is the aggregation index and G is the category.

$$\mathrm{d}\ (\mathrm{x}, \mathrm{y}) = \sum_{j=1}^{p} \left| x_j - y_j \right| \tag{1}$$

$$D\ (G_1, G_2) = \min_{\substack{\mathrm{Xi} \in G1 \\ Y\mathrm{j} \in G2}} \left\{ \mathrm{d}\ (x_i, y_j) \right\} \tag{2}$$

3.2.2 Basic principles of the centre of gravity method

The centre of gravity technique, alternatively termed the grid or exact method, is applicable in resolving facility siting quandaries by computing the exact centre of gravity of a set of distinct mass points, as rooted in physics principles. The centre of mass technique is suitable in circumstances when transportation expenses make up a significant proportion of production costs, when goods are shipped from one factory to several distribution centres or storage facilities, or when they are shipped from one storage facility or warehouse to several sales points. The objective function is depicted in equation 3.

$$MinTC = \sum_{i=1}^{n} f_i v_i d_i \tag{3}$$

Where d_i is solved in equation 4,

$$d_i = \sqrt{(X_c - d_{ix})^2 + (Y_c - d_{iy})^2} \tag{4}$$

When partial derivatives are zero, solve for the partial derivatives of d_{ix} and d_{iy}, see equation 5,

$$\frac{\partial TC}{\partial dix} = 0, \frac{\partial TC}{\partial diy} = 0 \tag{5}$$

The resulting solutions for X_c and Y_c are shown in equation 6 and equation 7, the objective functions corresponding to X^*_c and Y^*_c can take the minimum value.

$$X_C^* = \frac{(\sum_{i=1}^{n} f_i v_i d_{ix} / d_i)}{(\sum_{i=1}^{n} f_i v_i / d_i)} \tag{6}$$

$$Y_C^* = \frac{(\sum_{i=1}^{n} f_i v_i d_{iy} / d_i)}{(\sum_{i=1}^{n} f_i v_i / d_i)} \tag{7}$$

At this point, Where C (X_c, Y_c) represents the co-ordinates of the proposed logistics facility, there exist n locations for the distribution, warehousing or provision of raw materials, referred to as D_i, each with its own set of co-ordinates (d_{ix}, d_{iy}). The cost per unit length of product transported from the logistics facility to each location i (distribution centres, warehouses or raw material supply places) is denoted by f_i, V_i is the volume of material that is required to be transported to each location i, while d_i represents the distance of transportation from the factory to each location i upon the introduction of d_x. The total cost of transportation is TC.

4 Conclusions

Through investigation into the planning of urban underground logistics systems in the Xianlin area of Nanjing City, this paper conducts network simulation experiments of "underground logistics systems". The resultant optimization of the underground logistics system network layout scheme serves to select the locations of multiple distribution centres within one area. Table 1 displays the collection and delivery volume of each region according to the existing OD matrix.

Table 1. Regional transport volumes of receipts and deliveries

Area number	Quantity received	Shipment	Total volume of transport
1	19299.366	18441.365	37740.731
2	18981.112	18168.524	37149.636
3	18684.818	17912.878	36597.696
4	8923.678	8453.797	17377.475

791	1596.093	1687.7	3283.793
792	747.995	758.654	1506.649
793	941.196	944.887	1886.083
……			
898	1880.603	2378.161	4258.764
899	2012.481	1789.829	3802.31
900	1213.692	1203.344	2417.036

According to the data, the traffic congestion index ranges from 0 to 10 with each 2-number increment corresponding to a different level: "0-2 smooth", "2-4 basic smooth", and "4-6 mild congestion". Traffic congestion becomes more severe as the value increases. Given the low population density of the region, the regional congestion index is expected to be proportional to the combined regional freight traffic (both inbound and outbound) as indicated in the OD data. It follows that the maximum value of the index, derived from the proportional relationship, may exceed 10.

Each region's congestion coefficient will be separated into five categories based on objective criteria. To maintain smooth traffic flow, the congestion factor upon the opening of the underground network should not exceed 4, and the proportionality coefficient between the congestion factor and the volume of goods received and shipped provides the basis for determining each region's minimum shunting requirements through the underground logistics system, as presented in Table 2 (to reduce the coefficient of ground freight, for example to 1, representing surface freight with no need for underground logistics, and 0.33 indicating that no more than 33% of current surface transport volume should be maintained).

Table 2. The range of values for the traffic congestion index and traffic distribution within the underground logistics system.

Congestion coefficient	<4	4~6	6~8	8~10	10~12
Area	866	791	792	814	846
	895	795	793	815	851
	896	810	794	819	888
		865	796	820	
		871	797	845	
		874	798	848	
		.....	.....	....	
Reduce ground freight coefficient	1	0.65	0.5	0.4	0.33

It is feasible to ascertain the maximum quantity of surface transportation to be maintained in each region alongside the requisite amount of subterranean transportation in Table 3.

Table 3. Maximum values retained for surface transport and requirements for underground transport.

Area number	The amount of ground traffic retained	The amount of underground transportation required
791	2134.5	1149.293
792	753.3	753.349
793	943	943.083
794	675.7	675.714
795	852.4	458.956
796	806.7	806.616
797	915	915.028
...	...	...
898	1880.603	2378.161
899	2012.481	1789.829
900	1213.692	1203.344

The clustering method is used to analyse the 110 regional nodes between 791 and 900 based on their coordinates. And then taking the class spacing of d = 0.6 divides the 110 regions from 791 to 900 into 15 initial class nodes, as illustrated in Table 4.

Table 4. Distribution of Regional Points and Freight Volumes Included in the 15 Tier 1 Nodes.

Primary node number	Contains area points	Freight volume in the Tier 1 node area
1	791，792，797，794，793，804，797，801，802	6560.2
2	803，805，807，808，809，811，818，814，817，	7783.4
3	820，812，813，815，819，820，821，823，826	8872.5
4	835，837，834，839，836，837，840，843，845	6783.7
5	845，846，848，849，850，852，853，855	6793.4
6	857，858，859，860，861，862，864，866，868	6268.4
7	841，842，847，855	3473.4
8	851，854，853，862，861	4153.8
9	856，858，859，860，	2576.4
10	852,870,885，871，874，883	3567.2
11	878，873，872,897，900，890	3671.2
12	864，858，859，860，861，878，887	4347.7
13	869，877，876，879	1214.7
14	884，897，882，896，880，888	4753.6
15	892，891，893，881，871，895	3537.8

Using the centre of gravity method, the primary node coordinates for each of the 15 regions were selected. Additionally, the secondary node was increased based on the region's freight volume to achieve the target of surpassing the actual demand for sending and receiving freight volume in the region. Furthermore, the node's service radius of 3 kilometres is limited to user-selected areas, factoring in the exclusion of remote points unable to meet the criteria for inclusion in the service area. Additionally, secondary node coverage is necessary to supplement primary node coverage. To summarise, primary and secondary node coordinates can be calculated based on Table 5 and Figure 1.

Table 5. Coordinates of primary and secondary nodes

Primary node number	Primary node coordinates (X,Y)		Secondary node number and coordinates（X，Y）		
1	149366.8900	153648.0500	A1	139465.5100	154309.7300
			A2	146987.6800	159418.2100
2	141339.4500	153959.7200	B1	145693.6500	160063.0700
			B2	148723.8400	160336.6900
3	144690.9800	154316.9900	C1	146444.3400	161044.5800
			C2	149877.2200	161091.0400
4	149026.5600	154716.6800	D1	156650.5300	160402.7300
			D2	154830.0900	160255.0500
5	142144.7900	154597.2600	E1	155780.6100	161155.0600
			E2	155973.6900	161520.8100
6	147066.4000	155149.2900	F1	155757.6200	161698.6300
			F2	153146.9700	160216.4700
7	149088.1600	155678.1900	-		
8	143191.8600	155025.2100	G1	145488.5900	158833.2500
9	144403.2900	155930.0100	-		
10	146013.2900	155683.1200	-		
11	146935.2600	156555.2700	H1	165295.9600	166307.4800
12	147771.4400	156163.0400	I1	149100.7800	159241.6700
13	148886.1800	156757.9800	-		
14	149951.9000	157738.2800	J1	157354.7000	166956.6600
15	150870.2500	156890.8400	-		

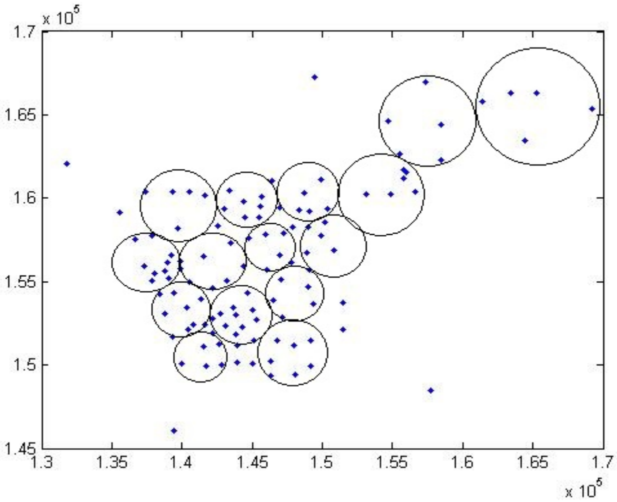

Fig. 1. Distribution of first-level coordinate areas

Next, the actual freight volume of each node and the transit rate of the first-level node can be obtained, as shown in Table 6.

Table 6. Actual freight volume of each node and transhipment rate of primary nodes

Primary node number	Actual freight volume	Transfer rate %	Secondary node number	Actual freight volume
1	3768.4	25.7	A1	1212.7
			A2	1723.7
2	3658.5	21.3	B1	1127.4
			B2	1237.5
3	3812.4	23.5	C1	1457.9
			C2	1275.9
4	3712.4	14.2	D1	1127.9
			D2	1378.5
5	3224.2	11.2	E1	1247.4
			E2	1527.6
6	3217.7	11.7	F1	1224.5
			F2	1447.6
7	3712.5	8.7		
8	3782.1	11.7	G1	1242.7
9	3211.7	17.3		
10	3114.2	13.7		
11	3567.2	14.0	H1	1273.4
12	3671.2	11.8	I1	1275.6
13	1214.7	19.7		
14	3141.7	12.1	J1	1725.3
15	3537.8	14.7		

In conclusion, the underground logistics system network, using the system clustering and gravity centre method, can effectively address the conflicts between urban logistics, traffic, society, spatial resources, and the environment in the development process. This also allows for selecting the location of multiple distribution centres in a region. These confirm the construction of underground logistics system network as a viable solution to the current traffic congestion and a means to reduce logistics costs.

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