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Spatial management for urban underground space based on complex network system

Cheng Yue[1]

Abstract. This paper sets the example of urban underground space of six administrative districts in Beijing City. The complex network model for the node distribution is established with the service radius of 400m and 800m, respectively, through adopting the theory of complex network and abiding by the nearest principle. This paper analyzes and explicates the characteristics of this network through incorporating the visualization technology of GIS. As the results indicate, the structure of urban underground spatial arrangement is primarily flattening and is has scattering connections, taking on the characteristic of small world network. Arising from the characteristic path length of the network is shortened, the clustering coefficient is strengthened. While the node efficiency is elevated, the market competition becomes increasingly severe.

Key words. Complex network, City, Underground space, Arrangement.

1. Introduction

With the advancement of urbanization, urban economic activity takes on increasingly complex irregular network structure, which on the one hand is embodied in the interaction between different activities, and on the other hand is embodied in the different location between interconnected similar activities. As an important component of urban economic activity, the distribution of underground space in the urban underground space is characterized by the interconnection between different locations in the homogeneous activity system. The study of the network characteristics taken on by the distribution of underground space arrangement in commercial cities shall be conducive to uncovering the centrality and hierarchical relationship of urban structure.

The research of urban underground space arrangement has been primarily car-

[1]School of civil engineering, Central South University of Forestry and Technology, Changsha Hunan Province, China

ried out since the end of the 20^{th} century. Foreign scholars focused on analysis of spatial diversity and factor of arrangement. Additionally, what should be reckoned with when selecting sites for the underground space of Japan in the process of its internationalization has been analyzed, from the Angle of view of the function of urban geography, through conducting mathematical model research of the underground space arrangement characteristics, and using multiple discrete model. The research contents of domestic scholars mainly include the principle of the arrangement of urban underground space, the method of site selection, the optimization of dot arrangement, and the influence factors of node arrangement. In the meantime, relevant analysis is carried out and some countermeasures are put forward to find the general solution according to the present situation and existing problems of the arrangement of underground space in different types of cities.

Besides, the satisfaction analysis is conducted on urban functions and underground space arrangement elements, and the spatial pattern of the commercial network in the Beijing office space is analyzed. With the introduction of western urban function of geography research and function of China's urban centers such as the deepening of the research, the high requirements on reasonable and scientific arrangement of urban underground space have been proposed, and various types of quantitative models arises at the historic moment. The quantitative study on the underground space arrangement had gained fruitful results. Here are the following examples. Through quantitative analysis of the spatial system changes in the underground space of Henan province, Li Xiaojian et al. analyzed the factors affecting the spatial variation of underground space arrangement from the perspective of macro and micro.

Under the major background of reform of underground spatial arrangement, He Canfei analyzes the difference between the arrangement of underground space in China and the arrangement space of China's underground space, as well as the phenomenon of "urban function exclusion". Other methods, including factor analysis, entropy weight and grey relation method, have been used by other scholars to verify that the underground space arrangement of large commercial cities is related to potential customers and market size. The underground space arrangement of large commercial cities is analyzed and the factors influencing the arrangement of underground space are determined.

The foregoing studies primarily analyze the factors influencing the arrangement of underground space, and pay more attention to the interaction between the network and the surrounding environment from the perspective of causality. Yet the network features of urban underground space arrangement and the correlation of nodes have been rarely analyzed. Generally, the existing researches primarily focus on the arrangement of different underground spaces and its influencing factors, and the research results of the application of complex network to urban underground space arrangement have been rarely gained. This paper, through adopting the complex network theory, stresses the analysis of the real network structure composed by various nodes under the spatial arrangement system of a certain city (referred to all nodes of China's underground spatial arrangement in Beijing city), as to explicate the node characteristics and the significance of geographic space.

2. Data and Methods

2.1. Data sources

The data adopted in this paper primarily originate from 253 samples (Fig. 1) of urban underground spatial arrangement in terms of six administrative districts of Beijing City (hereinafter referred to as six districts of Beijing) provided by Gaode's 2010 data. The major method adopted in this paper is the complex network. Its core technique is to compartmentalize the scope contained by each node through setting the urban underground spatial arrangement as the center and in terms of different radiuses. If the contained scopes are overlapped, the nodes are deemed to be correlated, otherwise they are deemed uncorrelated. Through constructing a complex network on the basis of relational matrix, the network topology diagram of urban underground space arrangement is obtained. Accordingly, the network structure and its characteristics are further analyzed. In the meantime, this paper shall use the spatial visualization method of GIS to map the results of complex network analysis to the distribution of real nodes in space to reveal its geographical significance.

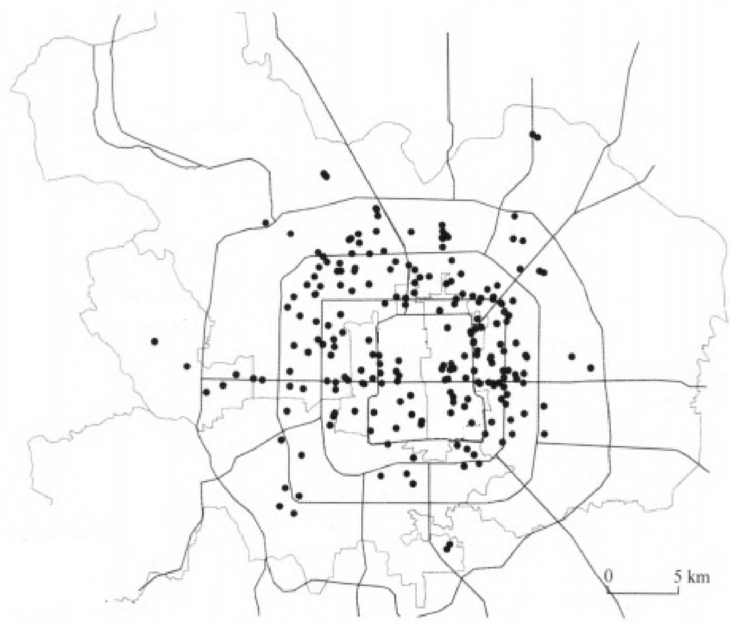

Fig. 1. Underground spatial arrangement of six districts in Beijing

2.2. Model establishing

Given the following factors, this paper sets the underground space arrangement of China as the research object: 1. In terms of the nature of the business, China's underground space arrangement not only reckons with the domestic underground space arrangement, but also handles the overseas underground space arrangement, with complete functions and wide range of service object; 2. The workload of processing data is moderate, which is conducive to display and collate the complex network.

A. Assumptions. The arrangement of urban underground space is a complicated project, and its service radius is related to the arrangement level of underground space, the number of service threshold and the level of social and economic development in the region. Therefore, in order to avoid the influence of some interfering factors on network characteristics, the following assumptions are made: (1) the underground space arrangement of any city in the study area has equal status, with the identical service radius; (2) The number of customers in each underground space arrangement service is difficult to calculate, so the capacity of the service capacity of the underground space arrangement is not considered; (3) If there is overlap between the service area of two cities' underground space arrangement, the underground space arrangement of the two cities is considered to be connected, and the overlap in the adjacent matrix shall be recorded as 1. Otherwise it shall be recorded as 0; (4) There is a dimensionless correlation between the distribution networks of underground space.

B. Selection of radius. Generally, the arrangement of urban underground space is mainly based on the nearest principle. It is mainly based on walking or l-2 bus stop ride. In the establishing of model, the service radius of China's underground spatial arrangement is set as 400 133 and 800 1TI. This is because: The 400 m is usually the most comfortable walking distance, over 400 m, and the willingness to choose walking will be reduced; The 800 m radius is more than the distance between the bus stops. In this area, people are usually willing to take either walking and or bus. After determining the experience value of the service radius, the linear distance between the underground space arrangements of any two cities needs to be calculated. The method is that, in the ARCGIS, according to the coordinates of longitude and latitude, open the window of calculation following the order of "Arc toolbox–Analysis Tools–Proximit3r–Point Distance". Take 800m as an example, input 1600m, and the distance between any two underground space arrangements in China can be obtained.

If the line distance between the two nodes is less than the sum of the service radius, i.e. 1600 m, the overlapped parts of the service area of the two nodes are indicated. The overlap shall be recorded as 1. Otherwise, it shall be recorded as 0. Accordingly, a 253×253 matrix can be obtained. Introduce the matrix to the UCINET for processing and analysis to attain the network topology. The dots in the topology indicate the urban underground space arrangement, and sides indicate the ligature of two dots.

2.3. Complex network analysis

In recent years, complex network theory has been applied to many scientific fields, such as Internet, neural network, social network, power network, network traffic, etc. American scholars, Barabasi and Albert proposed the scale-free network model (hereinafter referred to as BA network). The underground space arrangement is a kind of small world network [9], which is a scale-free network. But in reality, the formation of its network needs to undergo a more complicated process, which requires a variety of mechanisms for network simulation. Therefore, to ensure a better effect of the simulation network, more practical factors should be considered, as well as detailed steps and methods. The underground space arrangement network is composed of a large number of underground space arrangement nodes, and has been widely existed in the fields of optical electricity, wind power, geothermal energy, oil and gas, etc. The underground space arrangement and information are stored and transferred in the network between the network [10], and realize the network transmission and balance of underground space arrangement. Moreover, the Internet network structure of underground space has the characteristics of Internet model structure [11], and the system simulation of complex hybrid network has certain similarities with traditional forms, and also has certain differences. The Internet model is worthy referencing for the design and analysis of underground space arrangement model [12]. The comparison between Internet topology and topological topology of underground space is shown in Fig. 2.

(a) Topology of local internet model (b) Topology of local complex hybrid network

Fig. 2. Visualized two network topologies

Through the comparison of the model structure, the complex hybrid network model is found to have a certain similarity structure with the Internet, which has the properties of node distribution and connection distance. The formation of simulation model can provide more reliable basis for the distribution of node location and the setting of node energy [13]. At present, there is less research on the distance between nodes and nodes in complex networks. Node energy consumption increases with the distance between nodes, and the topology model of the node affects the distance between nodes to some extent.

Table 1. Comparison between topology of network model and parameters of internet model

Model parameter	**topology of network model**	**internet model**
Node amount	2000	4967
Link amount	5680	7326
Maximum extent	162	472
Average shortest path	3.716	3.957
Network diameter	9	12

The network research of large-scale underground space arrangement needs to be divided into regions, so its network structure has the characteristics of certainty and limitation. In the research of model, m_0 nodes and e_0 sides are set in the complex network. The topological parameters of network model are listed as follows:

(1) Connection mode of nodes

The model takes on m_0 nodes, and every step of this model's change shall add a new node with m sides. The newly added node shall be connected to the m node, $m \leq m_0$.

(2) Possibility of preferential connection

The$\prod i$, indicating the possibility of a new node to be connected to an existing node, shall be related to the connectivity of this node. Accordingly, the following equation shall be given as:

$$\prod k_i = \frac{E_i * k_i \left(d_{ij}\right)^{-1}}{\sum_j^k E_i * k_i \left(d_{ij}\right)^{-1}} . \tag{1}$$

Where E_i- indicates the residual energy of node i; k_i refers to the connectivity of the current node; d_{ij} refers to the distance between node i and new node j. As the research indicates, in the internet of underground space, the energy of each node is limited, and the node energy refers to the ability to connect the nodes. The nodes with more energy shall be more able to be connected with the new node. The connectivity of node refers to the amount of node side and the ability of node to be connected to other nodes. The connection of node can be unidirectional, bidirectional and multi-sided. The underground space arrangement in the process of consumption are widespread in the transmission between nodes, which means that the energy dissipations of the node connection, the connection distance increases, more energy shall be consumed by the connection of node. Hence, the actual distance parameters shall be added to make more practical the entire network model.

3. Model of urban underground space arrangement based on complex network

3.1. Density of modules

Literature [7] proposes a modularized density theory for network (D value), and on that basis, the simplified mixed integer nonlinear programming model (MINLP) is proposed. Yet the amount of requirements in such model is known. Otherwise the algorithm fails to be adopted for calculation. First and foremost, the D value-based network model shall be introduced.

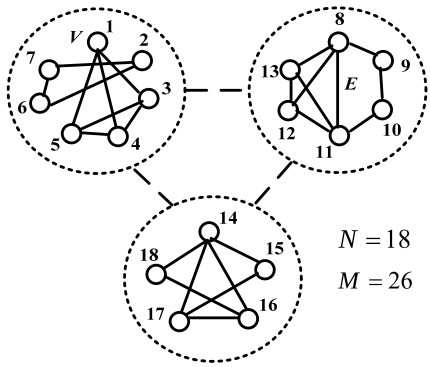

Fig. 3. Simplified model of network

For the given network $G = (V, E)$, N nodes and M sides are taken on, V refers to the set of N nodes, E refers to the set of M sides (ligature of node). As indicated in Fig. 3, C model of D can be defined as:

$$D = \sum_{i=1}^{C} d(G_i) = \sum_{i=1}^{C} (1-\lambda) L(V_i, V_i) - \lambda L(V_i, -V_i) / |V_i| . \tag{2}$$

Where λ refers to adjustment parameter, V_i is the node set of i, $-V_i$ indicates the set of node not pertaining to the i in network, $|V_i|$ denotes the cardinal number of i, and the function L can be defined as:

$$L(V_a, V_b) = \sum_{i \in V_a} \sum_{i \in V_b} a_{i,j} . \tag{3}$$

Where $a_{i,j}$ denotes the i-th row and j-th column of adjacent matrix A. To establish the mathematic model for complex network, literature [7] defines a binary variable x_{il}, and the following relation exists as:

$$x_{il} = \begin{cases} 1, \; i \in l \\ 0, \; i \notin l \end{cases} \tag{4}$$

Hence MINLP model can be defined as:

$$\begin{cases} f = \max \sum_{l=1}^{C} \left[(z_1 - z_2) \Big/ \sum_{j=1}^{N} x_{il} \right] \\ z_1 = (1-\lambda) \sum_{i=1}^{N} \sum_{j=1}^{N} a_{ij} x_{il} x_{jl} \\ z_2 = \lambda \sum_{i=1}^{N} \sum_{j=1}^{N} a_{ij} x_{il} (1 - x_{jl}) \end{cases} \tag{5}$$

The limiting conditions of model are defined as:

$$\begin{cases} 0 < \sum_{i=1}^{N} x_{il} < N,\ l = 1, 2, \cdots, C \\ \sum_{l=1}^{C} x_{il} = 1,\ i = 1, 2, \cdots, N \\ x_{il} = \{0, 1\},\ i = 1, 2, \cdots, N,\ l = 1, 2, \cdots, C \\ 0 < \lambda < 1 \end{cases} \tag{6}$$

3.2. Framework of algorithm

The crux of estimation of distribution algorithm (EDA) is how to establish the probability model more efficiently and establish the corresponding studying and sampling mechanisms. However, there are two disadvantages of the traditional EDA algorithm: firstly, the problem of dimensionality limitation and coupling phenomenon in high dimensions; the second is unsupervised learning problem, and the algorithm is not ideally precise. In this regard, this chapter shall design the improvement for EDA algorithm on the basis of sampling possibility model.

Assume X is the high-dimensional random vector, with the joint probability density of $f_X(x)$. Given the irregularity of X, the model fails to be directly established. The solution is to model its probability distribution $f_{X_i|X^{(i)}}\left(x_i \,|x^{(i)}\right)$. The framework of algorithm is indicated in Fig. 4.

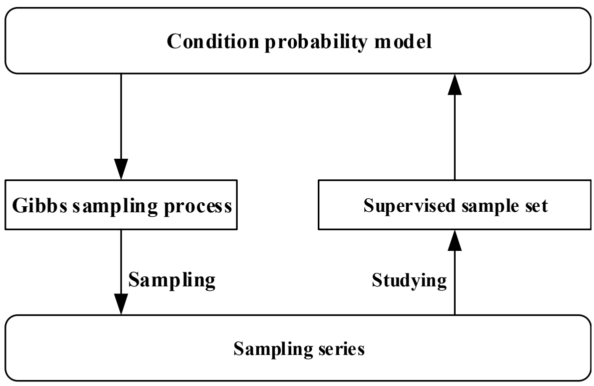

Fig. 4. Model of sampling probability

Through adopting the foregoing Gibbs sampling, a conditional probability distribution based on Markov chain can be established, to realize the progressively approaching of united probability distribution $f_X(x)$.

3.3. Gibbs sampling

The sampling process of Gibbs is to randomly generate a new individual in each variable position, according to its conditional probability and population variable distribution. Accordingly, the sample sequence of Markov chain can be obtained.

Hence, the distribution in steady state of this condition can be approached to through adopting the joint probability distribution of such sample sequence, i.e. to be evenly divided by approximate statistics $\phi(X)$. *It is defined in mathematics as:*

$$\lim \sum_{t=1}^{T} \phi(X(t)) \Big/ T = E\{\phi(X)\} . \tag{7}$$

3.4. Algorithm flow

Set $(x_{opt}, fit_{opt}) = IEDA(eval)$ as the form of EDA, where eval is the function of evaluation indicator, thus the flow of algorithm shall be denoted as pseudocode 1.

pseudocode 1: statistics of sampling probability distribution

1. Initialized algorithm:

   $P = \{x(i) \,|i = 1, \cdots, N\}, x(i) \sim Uniform(S), P_{opt} = \emptyset;$

2. Perform iterative process:

   optimizing:

   for $ep = 1 : epoch$ do

   $x^* = \arg\max_{x \in P} \{eval(x)\}; \quad P_{opt} = P_{opt} \cup \{x^*\}; \quad P = P \backslash \{x^*\};$

   endfor

   studying

   for $i = 1 : D$do

   $P_i = \{(x^{(i)}, x_i) \,|x \in P_{opt}\}; \quad g_i = \arg\min_{g \in \mathcal{G}} \left\{ \sum_{\mathcal{Q}_i} L(y, g(x)) \right\};$

   $P(X_i \,|X^{(i)}) \sim \exp(-L(X_i, g(X^{(i)})));$

   endfor

   sampling

   $P_{new} = sample\left(N - N_0, \left\{\hat{P}(X_i \,|X^{(i)})\right\}\right);$

   updating

   $P = P_{new} \cup P_{opt}; \qquad P_{opt} = \emptyset;$

   output of algorithm

   $x_{opt} = \arg\max_{x \in P} \{eval(x)\}; \quad fit_{opt} = eval(x_{opt}).$

Update P whereby truncation, and weed out the individuals with poor adaptive value. Then adopt the sampling probability for generate the new sample, replace the old sample. $(N - N_0)/N$ denotes the ratio of weeding out.

4. By means of spatial visualization, the main parameters of the complex network are made corresponding to the distribution of dot space, and the geographical characteristics of urban underground space arrangement are analyzed.

Spatial distribution of urban underground space is shown in Table 2. The underground space arrangement, which has a high degree of radius of 800 m, is mainly distributed in CBD and Sanyuanqiao area, which is an area of high grade office gathering area and agglomeration of multinational companies in Beijing city. The nodes in moderate level are primarily distributed in the North city area of Beijing as in the irregular shape of Chinese character “mouth”. The nodes in comparatively low levels are scattering. Generally, following the traditional axis of Beijing city, the distribution of urban underground space in the east is relatively concentrated. Despite the competitive pressure, the customer base has a relatively stable structure and has a relatively stable structure. The distribution is relatively evenly distributed in the west, but the structure is unstable.

(2) Aggregated distribution of urban underground space arrangement with enormous centrality

As shown in Fig. 5, the central nodes with K value greater than or equaling to 7, and tend to centrally and contiguously distributed. In the red region, the majority of the central nodes with K values greater than or equaling to 7 are covered. Accordingly, the cohesion of urban underground space distribution in CBD and Sanyuanqiao area is significantly higher than that of other regions. Additionally, the other three nodes with K value larger than 7 are located in Hepingli, Asian Sports Village and Zhongguancun area, respectively, taking on the relatively strong cohesion.

(3) Nodes are unevenly distributed from the street scales

Urban underground space arrangement tends to be distributed in inner cities and economically developed regions, and to be rarely distributed in peripheral areas. Figure 6 shows the total number of nodes in each street, and as the number rises, it doesn’t mean that the number of nodes in this street increases. The number of nodes in the street of Donghuashi is 11, which indicates that the node has a strong cohesive force and significant importance. Certainly, for the streets with high degree of node, the connection between the underground space and the underground space of the city is strong, and the convenience of business is preferable. It is convenient to handle the underground space arrangement of China in Sanlitun, Chaoyang, Jianwai, Jianguo, Donghua gate, West Changan Street and urban functional street. Yet in many streets of the outskirts of the city, there is no distribution of urban underground space, and residents must travel long to go through the business. Also, the “urban function exclusion” exists.

Table 2. Complex network node distribution with radius of 800m in Beijing

Network extent	0	1	2	3	4	5	6	7	8	9	10
Node amount	18	14	12	28	18	31	19	25	15	11	10
ratio	7.1	5.5	4.7	11.1	7.1	12.2	7.5	9.4	5.5	4.3	4.1
Network extent	11	12	13	14	15	16	17	18	19	20	21
Node amount	9	8	6	9	7	3	2	1	3	1	3
ratio	3.5	3.2	3.4	3.6	2.8	1.2	0.8	0.4	1.2	0.4	1.2

5. Conclusion

The complex network theory is widely used in the research on the real existence of large-scale non-rule network, and it is integrated with social network and other research methods to find the rules of network operation and elevate the operational efficiency. In the study of human geography, adopting complex network technology to analyze urban economic activities can in a certain extent, improve the distribution pattern of geographical phenomenon and its evolution. And the essential characteristics of the geographical network formed by various activities can be studied deeply.

Based on the study of the complex network of urban underground space arrangement in Beijing, this paper finds the following characteristics of such space arrangement: (1) the arrangement structure of urban underground space is mostly flat and sparse, with the characteristics of small world network; to improve the management level and business efficiency, all underground space arrangements have adjusted their nodes and institutions. (2) With the expansion of service radius, the arrangement of urban underground space is enhanced and the stability is reduced. Specifically, the optimal service radius of urban underground space arrangement is between 400 and 800 m, which is firstly convenient for the residents to handle the business nearby, and secondly conducive to the efficient operation of urban underground space arrangement.

Furthermore, while establishing the complex network model, this paper merely establishes the node network from the geographical distance, factoring out the expansibility and continuity of network, i.e. how the urban underground space arrangement network will change over time is not studied in this paper. In the meantime, this paper only takes the urban underground space arrangement as the research object, and factors out the influence of the competition of underground space arrangement in other cities on the destruction of the network. The comparative studies are lacked. On that basis, in the ongoing studies, the foregoing problems shall be delved into.

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