Topology Analysis of Constructing Large-Cargo Transportation Network

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Abstract **— A lot of research on large-cargo transportation mainly focus on the selection, optimization of transportation route and design of transportation network rather than considering the essence of the entire network from a macro point of view. Owing to that, a large-cargo transportation network model based on complex network theory is proposed. According to the characteristics of large-cargo transportation, it can be divided into two categories: physical network and service network. This paper studies the evolution model of service network and introduces the evolution algorithm of the network, analyse the model of the degree of distribution by using mean-field theory and propose an analytic formula for the degree of distribution. The numerical simulation results show that the relationship between the node degree of service network and cumulative node degree follows the power-law distribution and has scale-free properties. The network produced by the model incarnates the dynamic evolutionary process of increase and decrease of nodes and edges, which agrees well with the real situation. This kind of network can simulate the features of logistics service network objectively.**

Keywords - construction logistics; topological structure; complex network; large-cargo transportation network; degree distribution

I. INTRODUCTION

Along with the economic globalization, more and more international engineering projects are emerging, among which are construction programs of electric power, petrochemical, etc. These programs are characterized by complicated logistic links, wide scope of services, high technical requirements together with considerable uncertainties in the practical operation process. Therefore, project logistics plays an essential role in the successful completion of the project. Document research makes clear that the management in construction logistics not only can guarantee the successful completion of the project, but also can save costs, especially in transportation.

Construction logistics is often launched around a construction project, which is long in period and complicated in materials required (some common materials like fly ash, steel, cement,etc and the urgently needed materials like heavy and large cargoes), and there are many subjects involved in the project (such as manufacturers, wholesaler, proprietors, supervising units, supervisors, designing institutions, general contractor, sub-contractors, suppliers, etc.). In order to ensure the implementation of the project, schedule must be strictly controlled. Once the schedule delays, it will bring huge losses, so the material supply of the construction is very important. Only the material is supplied effectively, timely and orderly, schedule of construction can be able to carried on smoothly. Different from the general logistics project, construction project materials usually are special large equipment (such as ultra-long, ultra-large, over-weight cargoes, etc.), so the process of transport and handing is with high difficulty and high risk, therefore there is a potential risk of inducing all kinds of accidents. And ultra-large, ultra-long and over-heavy transportation equipment (such as transformer, shield machine, generator sets, etc.) involved in these large-scale construction projects, which are often the key equipment of the national key construction projects and national defense construction invested several hundreds of millions Yuan or even tens of billions Yuan, which contains many restrictive factors, high risks and great difficulties in transportation. It is very important to ensure the safety and timely arrival of the cargoes for the whole construction project.

Many researches have been performed on the construction logistics transportation. Vidalakis C. [1] assessed the performance and explores the relationship between response capability and cost efficiency of transportation based on a range of performance indicators. W., A. Ross uses radio frequency technology to identify and track traffic construction and transportation materials. Xu, Jiuping [2-4] formulated a fuzzy, stochastic multi-objective bi-level optimization model with the higher criterion of minimizing the total transportation cost and time, and used adaptive particle swarm optimization algorithm to solve the model, selected transport routes for transportation agencies at a minimum level of travel costs. At the same time, a travel time mathematical model with soft time windows is built by constraints of fully improving the satisfaction level of customers, and the model for its solution is proposed by him, and finally the feasibility of the proposed model has been validated by means of instances. L. Gan [5] focuses on how to avoid seismic risk problems in the large-scale construction projects and transportation systems. The research of logistics transportation in China mainly concentrates on the selection of transportation modes, the optimization of transport plans, the research of transportation systems and the risk control during transportation. It can be seen that, from transportation problems in heavy constructions, many studies focused the cost, time and vehicle routing problems in transport. Also, most models have the characteristics of limitation and specificity without taking account of transport network from the perspective of systems, while transport network is extremely important for the project. This paper is aimed to study the topology characteristics of large-cargo transport network by using complex network theories and focus on large-cargo transport problems from a system point of view.

II. LARGE-CARGO TRANSPORTATION NETWORK

With the increasing of large-cargo transportation, the complexity of its transport network is more prominent. Difference from general cargo transport, objects of large-cargo transport generally are extra heavy, extra long and extra large cargo, which have higher requirements for roads and ports during transportation, such as the clear width of lines, the minimum turning radius and the rated load strength. The nodes of large-cargo transportation network in construction logistics include not only the real road intersection, but the storage facility and enterprise (such as production enterprises, suppliers, transit stations, warehouses, construction sites, etc.) in logistics activities, as well. The corresponding edges include the road edges and the delivery of goods and information between manufacturers and service providers. So large-cargo transport network in construction is a complex network that includes physical network and service network.

A. Complex Network

The complex network is a way to study complex system, it focuses on topological structure in which factors in system work in conjunction with each other, and it is the basis of understanding the nature and function of a complex system. Watts published a small- world network model in *Nature* in 1998 [6], Barabási and Albert [7] published a complex paper on scale-free network in 1999, since then the research on the structure and properties of complex networks has attracted much more attention in various fields, such as formation network (World Wide Web, citations network, computer sharing network), technology network (power network, telephone network), biological network (food webs, neural network, gene network), social network (scientific collaboration networks [8], movie actor collaboration network) [9] and the transportation network (route network, railway network, highway network, natural river network) and so on. WS and BA is the two most classical network models, other common models include local-world evolving model, multi-local-world evolving model, generalized scale-free dynamical network model, mixed preferential model as well as the wireless sensor network evolving model and so on [10-15]. The construction of these models provides the necessary technological means for the study of the related network systems. However, the research on the evolution model of the transport service network is rarely involved.

B. The Characteristics of Large-cargo Transportation Network

Compared with other transportation networks, the transportation network of large-cargo in construction is a special kind of traffic network, which is mainly reflected in the following four respects:

(i) The requirements of network planning are different. For general cargo transport, the goal of road network planning is to reduce the cost of transport or to shorten the distance between the two places. Due to the particularity of large-cargo in construction, the clear width of lines, the minimum turning radius and the rated load strength are required, the passing ability of transport must be fully improved and the transportation risk must be reduced, so the basic principle of large-cargo transport network planning is to find a practicable route with minimum risk, which is different from other road transport network.

(ii) The morphological structure of network is different. The links and nodes of large-cargo transportation network in general should try to avoid bridges, culverts or roads which with weak bearing capacity and in the sections of small turning radius, which then lead to the morphological structure is different from that of other transportation network.

(iii) The complexity of network is varying. The nodes and edges of large-cargo transportation network are composed of the main roads and intersections, which is a part of the urban road network, but is different from the urban road network. It also includes the transport related services organization, which is a multilayer complex network consists of the physical network and service network.

(iv) The transport mode of network design is complex. For large-scale projects, due to the long transport distance, waterway, highway and other multimodal transport modes are usually used when it comes to international transportation. And the loading and unloading technical of large-cargo requirements is high, the places of transhipment in the process of transportation should have the required handling technique.

All these above factors considered, large-cargo transportation network in construction inevitably presents different topology property from other transportation networks. The application of the complex network theory in the research about the topology property of large-cargo transportation network is helpful to improve the understanding of the network characteristics and to reduce the damage for the unknown risk of the network function, and to ensure the smooth delivery of construction materials in construction sites without delaying the construction period.

III. TOPOLOGICAL STRUCTURE OF LARGE-CARGO TRANSPORTATION NETWORK

In this paper, the network model is described by analyzing the characteristics of the large-cargo transportation network and the statistical characteristic value of network is calculated, finally numerical simulation of the network is performed.

A. Network Model

Construction large-cargo transportation network consists of two major layer networks which are physical network and service network.

The nodes of physical network are the starting point, the ending point and the transition point in the transportation process, the edges of transportation network represent the path between the two nodes. The specific location of nodes and the route alignment are not considered in the construction logistics transportation network, but the node degree and degree distribution are mainly considered. According to the method of graph theory, $G=(V,E)$ can be used to represent the transportation network of large-cargo in construction, where V is the node collection of the network G, represents the physical location such as the starting point, the ending point, the intersection and the transition point, and so on in the transportation process. If there are M Mnodes in the network, then $V=\{v_{1,}v_2,\cdots,v_m\}$, E is a set of edges of construction logistics transportation network, represents the set of the roads which connecting the two places, including waterways, highways and railways, if there are N edges, then $E=\{e_{1,}e_2,\cdots,e_n\}$, the distances of large-cargo transport is long, the requirement for transport lines is high, so the mode of transport is always multi-modal transport, involving roads, waterways, railways and other different transportation modes, there are many modes of transport can be selected from V_1 to V_2 as shown in Fig.1.

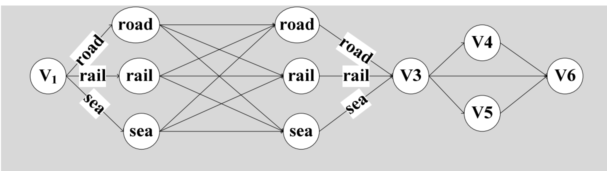


Fig. 1. Large-cargo transportation physical network in construction

The service subject of large-cargo transportation service network in construction includes raw material producers, suppliers, contractors, delivery centers and carriers who are responsible for the sending and receiving of the supply and demand information, the selection of transport mode and route, and the transportation cost reduction under the premise of ensuring safety and within the schedule. The object is the construction large-cargo, $G=(V,E)$ can also be used to represent the large-cargo service network, of which V denotes the set of nodes in the large-cargo service network G and it represents the raw material manufacturers, suppliers, contractors, and organizations like delivery centers and demand centers during transport. E is the set of network edges and represents a demanding relationship or an information exchange relationship between the two nodes.

This paper mainly focuses on the service network, which means the network nodes are the storage sites of logistics activities or enterprises and edges are large-cargo transportation and information exchange between the storage sites and enterprises.

B. Construction of Topological Structure

In traditional construction large-cargo transportation, it is usually considered only from an individual customer perspective that it is enough to transport the large-cargo to the construction site safely and punctually, without considering how to effectively integrate all the resources throughout the transportation process to meet the needs of many customers from the viewpoints of logistics service providers. So this article discusses the large-cargo service network in construction with the complex network theory, which is a complex network composed of many *OD* for the formation of cross-cutting, which reflects the connection between different nodes, and it is a good indication of the characteristics of the large-cargo transportation network in construction. In order to establish a complex network model of large-cargo transportation in construction, which is based on adjacent nodes, the basic definitions and assumptions about network topology have been made as follow:

(i) The nodes of the network are the raw material manufacturers, suppliers, transfer centers, contractors, construction sites, etc. The edges of the network are the distribution routes and information transfer between adjacent nodes.

(ii) The network is regarded as an un-weighted network when the times that the transport vehicle passes through the sides and the frequency of information transmission are not considered.

(iii) In order to save time in the process of reloading.

(iv) The transportation network in construction logistics is an undirected graphical network without considering the road directions.

(v) Supplier of materials can fully meet the needs of the construction sites.

Therefore, the large-cargo service network model in construction has the following characteristics:

(i) The network node is a part of the physical network, which has an accurate geographical location and space information.

(ii) The structure of the network is subject to the physical network.

(iii) The node degree of network is the most obvious symbol of the service network, and the change of traffic assignment and traffic flow will directly affect the degree distribution of the network.

(iv)The path capacity, risk, cost and time need to be considered in the path choice of the network distribution, which also directly affect the characteristics of complex network.

C. Model Description

According to the description of the network, driven by the benefits in large-cargo transport service network, new nodes such as new suppliers, logistics service providers and construction parties are emerging, as well existing nodes are dropping out for competitive reasons, similarly there are new edges entry and exit between nodes.

For simulation, we generated a network by the following Algorithm:

(i) Initial state. There are m_0 nodes in the network.

(ii) We add a new node which have m_1 edges to the network with the probability $p(0 \le p < 1)$, the probability $\prod_1$ that a new node will be connected to node i depends on the degree k_i of node i and attraction α ,such that

$$\prod(k_i) = \frac{k_i + \alpha}{\sum_j k_j + \alpha} \tag{1}$$

(iii) We add m_2 edges to the network with the probability $q(0 \le q < 1)$, one end of the new edges is added to the network with random connection, the other end is added to network with the probability $\prod_1$.

(iv) We remove the m_3 edges with the probability $r(0 \le r < 1)$, one end of the edges is chosen randomly, the other end is selected with following probability:

$$\prod_2(k_i) = \frac{1}{N(t)-1}\left(1-\prod_1(k_i)\right) \tag{2}$$

(v) We randomly remove a node with the probability $s(0 \le s < 1)$, then m_4 sides of the node are also removed, where $p+q+r+s=1$。

$$\left(\frac{\partial k_i}{\partial t}\right)_1 = m_1 p \frac{k_i + \alpha}{\sum_j k_j + \alpha} \tag{3}$$

IV. ANALYSIS OF NETWORK CHARACTERISTICS

A. Degree Distribution

We can obtain the degree distribution of the network node i based on mean field theory.

(i) New nodes are added with the probability $p(0 \le p < 1)$:

(ii) m_2 nodes are added with the probability q :

$$\left(\frac{\partial k_i}{\partial t}\right)_2 = m_2 q \frac{1}{N(t)} + m_2 q(1-\frac{1}{N(t)})\frac{k_i + \alpha}{\sum_j k_j + \alpha} \tag{4}$$

(iii) m_3 nodes are removed with the probability r :

$$\left(\frac{\partial k_i}{\partial t}\right)_3 = -m_3 r \frac{1}{N(t)} - m_3 r(1-\frac{1}{N(t)})\frac{1}{N(t)-1}(1-\prod_1(k_i)) \tag{5}$$

(iv) A node is removed with the probability s, then:

$$\left(\frac{\partial k_i}{\partial t}\right)_4 = -\frac{sm_4}{N(t)} \tag{6}$$

In t step, the sum of degree in the network and the sum of nodes are:

$$\frac{\partial k_i}{\partial t} = m_1 p \frac{k_i + \alpha}{\sum_j k_j + \alpha} + m_2 q \frac{1}{N(t)} + m_2 q(1-\frac{1}{N(t)})\frac{k_i + \alpha}{\sum_j k_j + \alpha}$$
$$-m_3 r \frac{1}{N(t)} - m_3 r(1-\frac{1}{N(t)})\frac{1}{N(t)-1}(1-\prod_1(k_i)) - \frac{sm_4}{N(t)}$$

The initial conditions are: $k_{id}(t_i) = m_1$, we can get

$$k_i(t) = \left(m_1 + \frac{B}{A}\right)(\frac{t}{t_i})^A - \frac{A}{B}$$

Where

$$A = \frac{m_1 p + m_2 q}{2(pm_1 + qm_2 - rm_3 - sm_4) + p\alpha},$$

And

$$B = \frac{(pm_1 + qm_2)}{2(pm_1 + qm_2 - rm_3 - sm_4) + p\alpha}\alpha + \frac{m_2 q - 2rm_3 - sm_4}{p - s}$$

The probability $P(k_i(t) < k)$ that the degree $k_i(t)$ less than k can be given:

$$P(k_i(t) < k) = P\left[t_i > \left(\frac{m_1 + B/A}{k + B/A}\right)^{1/a} t\right] = 1 - \frac{t}{m_0 + (P-S)t}\left(\frac{m_1 + B/A}{k + B/A}\right)^{1/A}$$

Assume that $P(k) = \frac{\partial\{P[k_i(t) < k]\}}{\partial k}$, we can get

$$P(k) \propto \left(m_1 + B/A\right)^{1/A} \left(k + B/A\right)^{-\gamma} \quad (7)$$

Where $\gamma = 1 + 1/A$.

B. *Clustering Coefficient*

In networks, if the node i is connected to the node j, the node j is connected to the node k, then the node k is likely to be connected to the node i. This phenomenon reflects the nature of the dense connections between some of the nodes, which can be shown by the clustering coefficient CC , in the undirected network, clustering coefficient is defined as：

$$C_i = \left(\frac{2E_i}{k_i(k_i - 1)}\right) \quad (8)$$

And the average cluster coefficient is：

$$C_i = \frac{1}{N}\sum_{i=1}^{N} C_i \quad (9)$$

In the formula (9), E_i represents the number of edges among all the neighbors of the node.

C. *Average Path Length*

The distance d_{ij} between node i and j in the network is defined as the edges connecting the two nodes in the shortest path, then the average path length L in the network is the average value of the distance between any two nodes. The formula is:

$$L = \frac{2}{N(N-1)} \sum_{1 \le i < j \le N} d_{ij} \quad (10)$$

For the construction service network, the average path length manifests the transport distance and the efficiency of information transmission, in order to meet customers' needs and enhance their own competitiveness, suppliers, logistics providers, transit stations should accelerate the speed of transmitting information, reduce the transportation time, and deliver the materials in time without construction delay. Prompt delivery of materials and information transfer reaction of the transport service network has a small average path, which reflects the characteristics of a small- world.

D. *Numerical Simulation and Analysis of Results*

To further investigate the statistical characteristics of the model, we assume that $p = 0.4$; $q = 0.3$; $r = 0.1$; $s = 0.2$; $N = 1000$; $m_1 = 10$; $m_2 = 10$; $m_3 = 10$; $\gamma = 20$; degree distribution Fig.3 is obtained by numerical simulation. The results show that the topological structure of transportation service network in construction logistics which is generated by the mechanism proposed in this paper has scale-free properties. Figure.3 (a) shows the degree distribution while $p = s = 0$, then there are no changes in the amount of the network nodes, only changes in degree distribution of networks when edges increased or decreased, which means that there are no nodes such as new manufacturers and suppliers, joining and exiting in a certain period of large cargo transportation network in construction, only fluctuation of transport service and information transfer between nodes. Fig.3 (b) shows the degree distribution while $q = r = 0$, it only takes into account of the node's fluctuation, not the particular degree distribution of networks when edges have no changes. From the Fig.4 the relations between node degree distribution and node numbers, we can see most nodes have a smaller degree, only a few nodes have a higher degree (hub points), which illustrates again that the construction logistics service network is a typical scale-free network.

The Fig.5 shows the regular pattern of the clustering coefficient with the variation of the scale of the network, when the network size is infinite, the clustering coefficient tends to zero, it does not have the obvious characteristics of clustering.

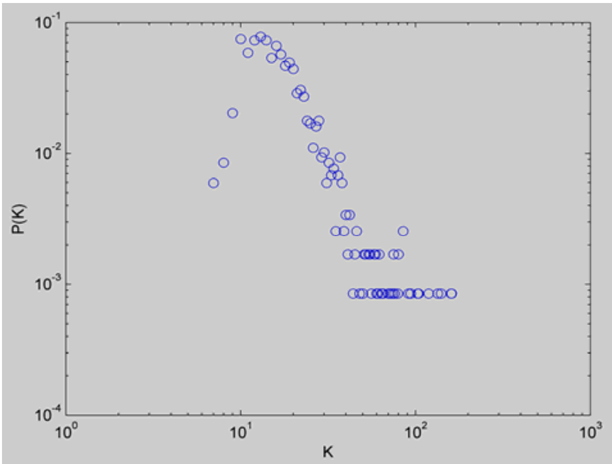
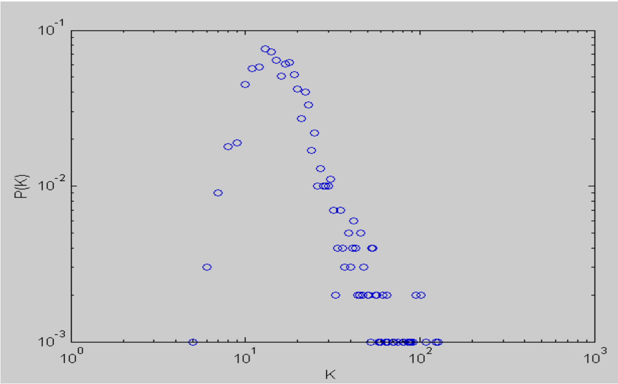
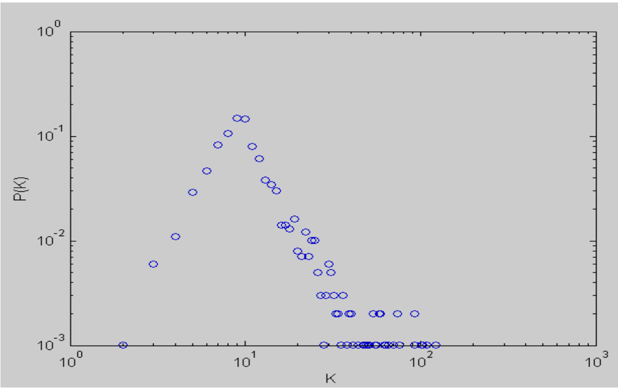


Fig.2. Degree distribution.



(a) $p = s = 0$



(b) $q = r = 0$

Fig.3. the p(k) of simulation results with $p = s = 0$ (a); and with $q = r = 0$ (b).

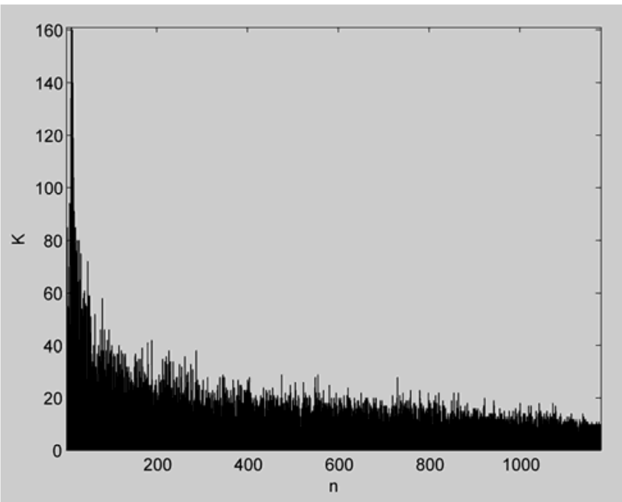


Fig.4. Degree distribution of nodes

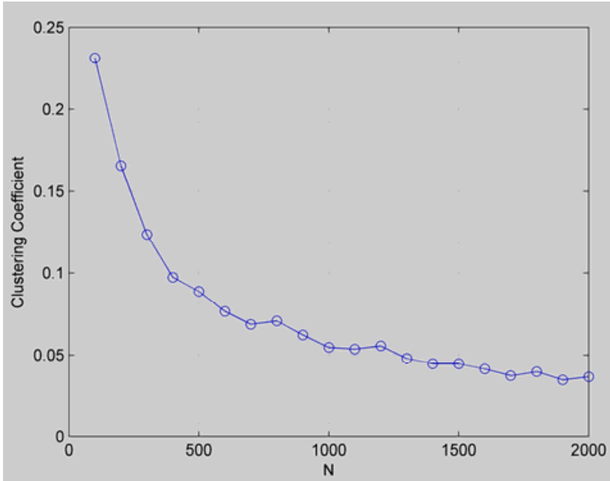


Fig.5. The regular pattern of clustering coefficient with the variation of the scale of the network.

V. CONCLUSION

According to characteristics of the large-cargo transportation network, the paper describes the physical network and service network of large-cargo transportation, analyzes the characteristics of the service transport network in the growth process, and establishes dynamic evolution model with the growth and deletion of edges after synthetically considering the growing and exiting of the network nodes. The paper derives node degree distribution based on mean field theory, then analyzes the topological properties of large-cargo transport service network in construction by using degree distribution parameter. We selects 1000 nodes as the sample data, the degree distribution obeys power-law index distribution P (k) k-γ by simulation analysis, which reveals its scale-free properties; through the analysis of clustering coefficient and average path's changes with the growth of network size, the results show again that the network has scale-free and small-world characteristics.

In the transport process of construction logistics, the transportation and service tasks are usually completed by a few manufacturers, service providers and other companies. If the transport and service of these enterprises once blocked, the entire transport service network will be destroyed. Thus, we should try to share business pressures of key enterprises on the premise of ensuring the smooth of these critical business services and transport, and make the network show a certain degree of modularity and hierarchy so that the invulnerability of the entire network in the face of unexpected events can be enhanced.

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