# Empirical topological investigation of practical supply chains based on complex networks*

Hao Liao(廖好)[1], Jing Shen(沈婧)[1], Xing-Tong Wu(吴兴桐)[1], Bo-Kui Chen(陈博奎)[2], and Mingyang Zhou(周明洋)[1,†]

[1] National Engineering Laboratory for Big Data Computing Systems, Guangdong Province Key Laboratory of Popular High Performance Computers, College of Computer Science and Software Engineering, Shenzhen University, Shenzhen 518060, China

[2] Department of Computer Science, School of Computing, National University of Singapore, Singapore 117417, Singapore

(Received 14 June 2017; revised manuscript received 19 July 2017; published online 30 September 2017)

The industrial supply chain networks basically capture the circulation of social resource, dominating the stability and efficiency of the industrial system. In this paper, we provide an empirical study of the topology of smartphone supply chain network. The supply chain network is constructed using open online data. Our experimental results show that the smartphone supply chain network has small-world feature with scale-free degree distribution, in which a few high degree nodes play a key role in the function and can effectively reduce the communication cost. We also detect the community structure to find the basic functional unit. It shows that information communication between nodes is crucial to improve the resource utilization. We should pay attention to the global resource configuration for such electronic production management.

**Keywords:** China supply chain networks, complex networks, data science, network science

**PACS:** 05.65.+b, 05.45.–a, 05.10.Gg **DOI:** 10.1088/1674-1056/26/11/110505

## 1. Introduction

The global economy continues to slump, industrial production has encountered unprecedented bottlenecks since the 2008 economic crisis.[1] For this reason, the Chinese government took the lead in giving priority to the development of strategy "Silk Road Economic Belt and the 21st-Century Maritime Silk Road", hoping a new revolutionary global resource configuration way to stimulate productivity, and reshape the manufacturing industry with the rising "industrial Internet". This strategy shows big ambition to change the current trade pattern and increase the current global economic concession.

Plenty of studies, analysis, and application for the great value of global supply chain are increasingly proposed. Maritime logistics analysis for global supply chain recently has attracted much attention from academics.[2–6] Apart from maritime logistics in global supply chain, business models are proposed to improve the supply chain management through understanding European container terminals.[7] Crossing docking is proposed as a method to enhance the fashion supply chain efficiency.[8] In addition, the information sharing and communication tool in enhancing supply chain efficiency is crucial, which increases the supply chain efficiency by reducing inventories and smoothing production.[9] An analytical network process with fuzzy logic can model the supply chain process and rank potential suppliers.[10] It is an appropriate tool to explicitly handle vague, ambiguous, and imprecise data.[11]

Complex networks theory applied to global supply chain research is raising interest from academics.[12–14] Reference [15] reveals that the efficient supply chains follow complexity and adaptive phenomena.[16] However, studying the supply chain network from the complex network perspective not only shows the characteristics but also needs to understand deeply about the supply chain network itself from complex metrics and its community structure. There is relatively little systematical research from a network perspective. The existing network analysis focuses on the solutions of scene application-oriented (hardware-based design and application software, such as radio frequency identification (RFID), communication protocols, storage technology, personalized recommendation, etc.[17–19]). At present, the network research on the macro structure and analysis of supply chain is not enough, especially the relationship among the topology design, structure, and function of global supply chain.

In this paper, the characteristics of the advanced manufacturing supply chain structure are studied from the perspective of complex network, the suppliers in the supply chain are abstracted into a network which is composed of nodes and edges. The influence of the small-world feature of the supply chain network is explored. Self-organizing characteristics of the network, scale-free characteristics, and community characteristics are analyzed. It is of great value to the whole network of

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11547040 and 61703281), Guangdong Province Natural Science Foundation, China (Grant Nos. 2016A030310051 and 2015KONCX143), Shenzhen Fundamental Research Foundation, China (Grant Nos. JCYJ20150625101524056 and JCYJ20160520162743717), SZU Student Innovation Fund, China, the PhD Start-up Fund of Natural Science Foundation of Guangdong Province, China (Grant No. 2017A030310374), the Young Teachers Start-up Fund of Natural Science Foundation of Shenzhen University, China, the Natural Science Foundation of SZU, China (Grant No. 2016-24), and the Singapore Ministry of Education Academic Research Fund Tier 2 (Grant No. MOE 2013-T2-2-033).

†Corresponding author. E-mail: zmy@szu.edu.cn

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supply chain and the robustness analysis of network function, which provides the basis for the design of current supply chain macroscopic structure.

## 2. Material

In this paper, we use two data sets:[20] the smartphone's supply network (154 nodes, 963 edges) including the major smartphone brands (such as MI, Samsung, Huawei) and iPhone supply chain network (78 nodes, 172 edges).

With the increasing popularity of mobile communication, the major smartphone providers account for a certain share in the mobile market. Most of the smartphone brands have their own relatively complete supply chain systems to enhance their core competitiveness. Lately, smartphone brand companies (such as Apple, MI, Samsung, Huawei) have created a good supply chain system. Most of the smartphone companies do not produce the components directly, it seems that they have a weak control of the production, but through the flat management and global procurement, the control of the product compared to the traditional company is greatly improved. These companies around the world and in different industries can cooperate with each other effectively, so their structural characteristic is of great significance for Internet industry construction. We collect relevant data of brand smartphone components and suppliers. It is necessary to analyze the key suppliers of smartphone from the perspective of complex network, we also measure the complexity of the supply chain network of smartphone. We collect the smartphone data from online manually. The data of the smartphone supply chain involves 154 suppliers who supply 46 major components including power, flash, panel, touch ID, and so on. It will create edges between the different suppliers who supply the same component. In order to simplify the suppliers' names, this paper replaces the 154 suppliers' names with the nodes number.

It should be noted that we use the main components of the smartphone corresponding suppliers to determine the edges, create the supply relationship by identifying the suppliers of the same components, and build 963 edges. Take the memory DRAM as an example. The memory DRAM is supplied by four suppliers, i.e., Hynix, Micron, SanDisk, Apple, and we can set up the supply edges between the four suppliers (see Fig. 1). The direction and weight of the edges are not taken into account in this work. Figure 2(a) shows the smartphone components supply network topology.

Apple stands out in the smartphone international market. It has more than 590 suppliers around the world, the seamless control of the supply chain and the rigorous review of the cost are the real source of Apple's profit. So Apple has been named the world's best supply chain manufacturers for many years. This paper extracts the suppliers for iPhone from the data we gained, and based on the components supply chain system of iPhone, which serves as the second example, and measures the complexity of iPhone's supply chain network system. We select the iPhone's 44 kinds of important components of the 78 suppliers to build the main nodes. According to the relationship between the iPhone suppliers that supply the same components, we build 172 edges, and finally obtain the iPhone component supply network (see Fig. 2(b)). Note that the Apple company (node 1) is connected to all the other nodes in the network and plays a crucial role in network connectivity.[39]

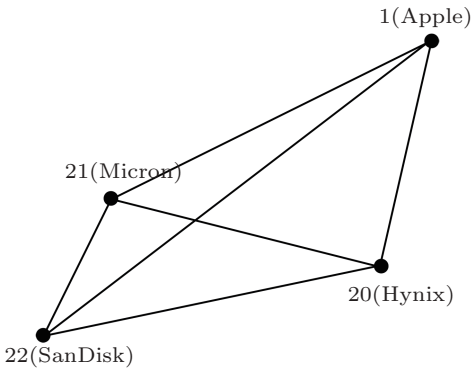



**Fig. 1.** Topology of DRAM supplier relationships.

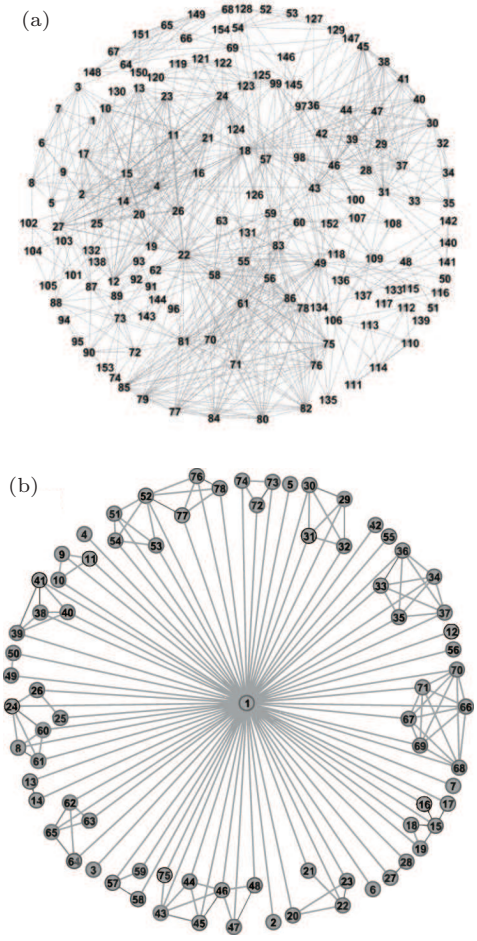



**Fig. 2.** (color online) (a) Smartphone's supply chain network topology and (b) iPhone's supply chain network topology.

## 3. Methods

The real network can be represented by nodes and edges. The nodes represent the entity, such as the supplier, the company, and so on. The edges represent the relationship between the nodes. We analyze the relationship between structure and function through this simplified network model. Firstly, the common statistical indicators are introduced, including the average degree, network density, average path length, and clustering coefficient.

### 3.1. Theoretical basic features

#### 3.1.1. Degree and average degree

Degree[21] is one of the important concepts that characterize a single node. The degree $k_i$ of node $i$ in an undirected network is defined as the number of edges which are directly connected to the node. For simple graphs without loops and overlapping edges, the degree $k_i$ is also the number of other nodes that are directly connected to this node. The average of the degrees of all nodes in the network is called the average degree, denoted as $\langle k \rangle$.

#### 3.1.2. Network density

The density[22] $\rho$ of a network which contains $N$ nodes and $M$ links is defined as the ratio of the actual number of edges in the network to the maximum possible number of edges. Therefore, for the undirected network, there is

$$\rho = \frac{2M}{N(N-1)}. \tag{1}$$

For the directed network, the denominator 2 can be removed. The density indicates the degree of sparseness in the real network.

#### 3.1.3. Average path length

The average path length of the network indicates that any two nodes in the network need to pass the average length of the path in the information transmission, which reflects the separation level among the nodes in the network. The shortest path between two nodes in the network is the path with the least number of edges connecting the two nodes. The distance between node $i$ and node $j$ is defined as $d_{ij}$, which is the number of edges on the shortest path connecting these two nodes. The average path length of the network is also called the characteristic path length or the average distance of the network, i.e.,

$$L = \frac{2}{N(N-1)} \sum_{i \geq j} d_{ij}. \tag{2}$$

### 3.2. Verification of small-world feature

Large size networks may have small diameter, such as WWW. It is well known as the small-world effect, an ubiquitous feature of real-world networks. Mathematically, the small-world feature[23] is described by the slow growth of average distance

$$L \sim \ln N. \tag{3}$$

We compare the average path length $L_{\text{actual}}$ of the real network with that of its random counterpart $L_{\text{random}}$, which has small-world property with the same numbers of nodes and edges. If $L_{\text{actual}}$ is close to $L_{\text{random}}$, we could say that the real-world network also has the small-world feature.

### 3.3. Network degree distribution

Different types of empirical data show that most of the real network's degree distributions are subject to the power-law distribution or approximate power-law distribution. The feature of scale-free networks[16] can be expressed as $p(k) \sim k^{-\gamma}$, where $k$ is the nodes degree, i.e., the number of links that a node has, and $p(k)$ represents the probability of finding a node with degree $k$ in the network.[24]

### 3.4. Community structure

The community structure represents the basic functional activity unit in the network, which shows the characteristics of "clustering and grouping". The edges within the community are thicker, while the edges between different communities are sparse. In the real network evolution process, nodes with similar functions will gradually self-organize into a community. As the nodes in the community have similar function, different nodes can be replaced with each other in the production management. It is conducive to improve network reliability. At the same time, the detection of the community is also conducive to analyze communication differences of different communities, and also facilitate the production management.[25]

The community testing continues to receive attention.[26] Traditional approaches to community detection include spectral analysis,[27–29] modularity based methods,[30] edge clustering,[31,32] clique percolation,[33] and so on.[43–45] In this work, we extend the spectral analysis methods to the analysis of networks of industrial Internet.

Spectral analysis methods mainly include Laplace matrix decomposition[34,45] and normal matrix decomposition methods.[35,36] Laplace matrix $\boldsymbol{L} = \boldsymbol{K} - \boldsymbol{A}$, in which $\boldsymbol{K}$ is the degree of network diagonal matrix. The diagonal elements are the degrees of the nodes. The non-diagonal elements are zero. The matrix $\boldsymbol{A}$ is the connection matrix. If nodes $i$ and $j$ have direct edges of connection, $a_{ij} = 1$. Otherwise, $a_{ij} = 0$. The normal matrix is defined as $\boldsymbol{N} = \boldsymbol{K}^{-1}\boldsymbol{A}$.

The matrix $\boldsymbol{L}$ has a trivial eigenvalue 0, with the corresponding eigenvector $\mathbf{1}_{N\times 1}$. The nodes of the same community are approximately equal in the eigenvector of the nonzero eigenvalue. If there are $g$ communities, then there are $g-1$ eigenvalues closed to zero, and the corresponding eigenvectors

can be used as a basis for community division. Then, similar to matrix $\boldsymbol{L}$, the normal matrix $\boldsymbol{N}$ has a trivial eigenvalue 1, with the corresponding eigenvector being $\mathbf{1}_{N\times 1}$. If there are $g$ communities, there will be $g-1$ eigenvalues closed to 1, and the nodes of the same community are approximately equal in the corresponding eigenvector. The principles of spectral analysis for Laplace matrix and normal matrix are similar.

In order to improve the detection accuracy and be more likely to form a joint relationship in the real network between the nodes, we often introduce weights to the unweighted network, and make the weight of the edge inversely proportional to the degree of the vertex.[37,38] In this way, we introduce parameter $\alpha$,

$$\boldsymbol{L}_\alpha = \boldsymbol{K}^{-\alpha}\cdot\boldsymbol{L}\cdot\boldsymbol{K}^{-\alpha}, \tag{4}$$

$$\boldsymbol{N}_\alpha = \boldsymbol{K}^{-\alpha}\cdot\boldsymbol{A}\cdot\boldsymbol{K}^{-\alpha}. \tag{5}$$

When $\alpha \approx 0$, $\boldsymbol{L}_\alpha$ degenerates into Laplace matrix. $\boldsymbol{N}_\alpha$ cannot degrade into $\boldsymbol{N}$, we introduce a symmetric matrix to avoid the appearance of complex elements in the eigenvectors.

## 4. Result analysis

### 4.1. The basic statistical characteristics

The smartphone supply chain network and iPhone supply chain network are described in Table 1. After investigating the basic feature of the major brands of smartphone supply chain network and iPhone supply network, we can conclude that the characteristics of these two networks are similar. From Table 1, we can see that the edge density is very low in the network, both of them are a sparse network, and the average distances between the nodes are relatively short. In the real world, there is a famous concept of "six degrees of separation", which means that the average distance between any two nodes is less than 6, to describe the small-world feature of real networks. It indicates that the average distances between nodes of the smartphone supply chain network and the iPhone supply chain network also meet the small-world feature. On one hand, it is noted that Apple as the core of the entire network has an absolute influence on the average distance, which indirectly shows Apple's controllability to the supply chain system. On the other hand, the clustering coefficients of these two networks are very high, which indicates that the aggregation of nodes is high. Through the network topology, we can find that the high aggregation is mainly due to the same kind of components from the multiple suppliers, there is an intensive cooperation among them, and they can be replaced by each other, so high aggregation also leads to the robustness of the entire supply chain system. Thus, if one supplier has an unexpected accident, it will not affect the entire product chain.

In order to further analyze the characteristics of small-world, we analyze the degree distribution, community, and other features to verify the efficiency of the network.[42]

**Table 1.** Basic features of the two supply chain networks: network size $N$, average degree $\langle k\rangle$, edge density $\rho$, average distance $L$, and cluster coefficient $C$.

| Network | $N$ | $\langle k\rangle$ | $\rho$ | $L$ | $C$ |
|---|---|---|---|---|---|
| Smartphone | 154 | 12.506 | 0.082 | 3.1792 | 0.7772 |
| iPhone | 78 | 4.41 | 0.057 | 1.9427 | 0.8248 |

### 4.2. Small-world feature

The network statistics are shown in Table 2. The results show that the smartphone component supply chain network and the iPhone component supply chain network have large clustering coefficients of regular networks, and also have small average path lengths of random networks. By comparing with the corresponding random network, satisfying Eq. (3), it shows that the supply relationship in the supply chain network of these two parts has significant small-world feature.

**Table 2.** Comparison of smartphone and iPhone supply chain networks and random networks.

| Network | $C_{\text{actual}}$ | $C_{\text{random}}$ | $L_{\text{actual}}$ | $L_{\text{random}}$ |
|---|---|---|---|---|
| Smartphone | 0.7772 | 0.042 | 3.1792 | 2.489 |
| iPhone | 0.8248 | 0.065 | 1.9427 | 3.031 |

The existence of small-world feature suggests that the suppliers in the supply chain network can easily communicate and cooperate with each other. A higher clustering coefficient indicates a tighter connection among the nodes in the supply chain network. With the rapid development of information technology, more and more enterprises use information technology and Internet media to establish a connection with each other. Enterprises can establish a closer relationship among various suppliers, and more frequently exchange information. In this way, a high coefficient clustering of suppliers can be selected as the core suppliers to focus on cooperation and development in component supply chain management. The average path length can represent the delivery time of the product in the supply chain network. The smaller the average path length in the component supply chain network, the higher the efficiency of the exchange and cooperation between the suppliers, thus, it can be used to determine the close relationship between two suppliers (nodes). In order to maintain the advantages in the competitive environment, suppliers should take the following measures: portfolio rebalancing, speed up the information exchange, improve ability to respond and adapt to change.

### 4.3. Network degree distribution

Figure 3(a) shows the degree distribution of smartphone components supply chain network. The degree distribution of iPhone components supply chain network is shown in Fig. 3(b). From Fig. 3, it is found that most of the nodes' degrees are very small, in other words, most of the nodes have few neighbors, and it is noted that the distribution has a long tail. That is heterogeneity of the scale-free network. So it can be seen from the figure that the two networks approximately follow the power-law distribution.

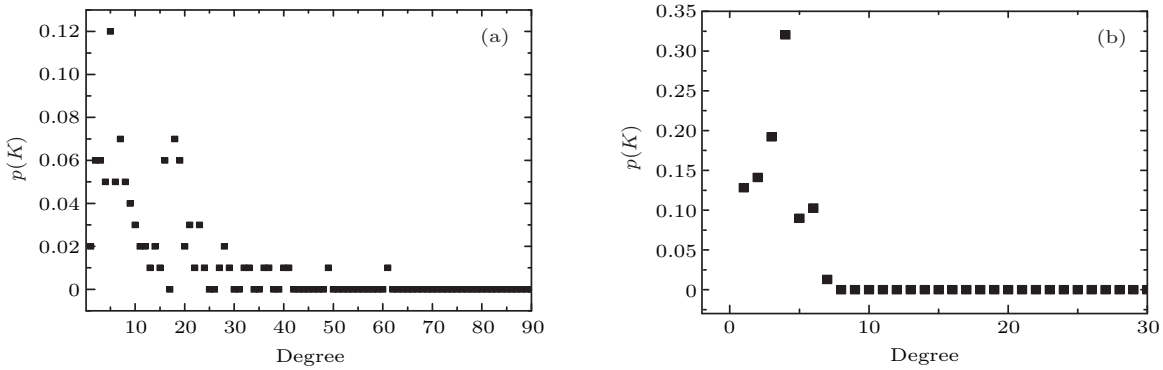



**Fig. 3.** Degree distributions of (a) the smartphone's and (b) iPhone's supply chain networks.

The component supply chain network describes the connection between the main suppliers, and we analyze the basic characteristics of the supply chain network from the network point of view. The supply chain networks have a few nodes with a lot of links. That is to say, there is a lot of cooperation and information exchange channel. In the supply chain network, due to the priority of the connection, the core suppliers have a greater degree of connectivity. Therefore, to a certain extent, the core suppliers directly affect the overall size of the supply chain system. It is particularly important to enhance the core suppliers' connection channels to value creation for the whole supply chain system.

At the same time, in the complex network research, it is found that the scale-free network has high communication efficiency and high survivability or robustness. The high communication efficiency is attributed to the large degree nodes as the information transit center, it is conducive to production management and information communication between the various suppliers, and to reduce storage costs and product backlog. The high survivability refers to that the network can still keep connectivity under random failure of the nodes, maintaining the good functional activity. In the real production, if a supplier who supplies problematic components, there will soon be an alternative plan immediately which can ensure production is orderly. However, if the large degree nodes fail, it will have a huge impact on the network function. Thanks to the proportion of large degree nodes being very low, we can focus on protection and special management of supplies with large degree nodes. It is conducive to improve the network survivability.

### 4.4. Community structure

This paper conducts community detection on the iPhone supply chain network. Figures 4 and 5 describe the distribution of the network nodes location through the eigenvectors.

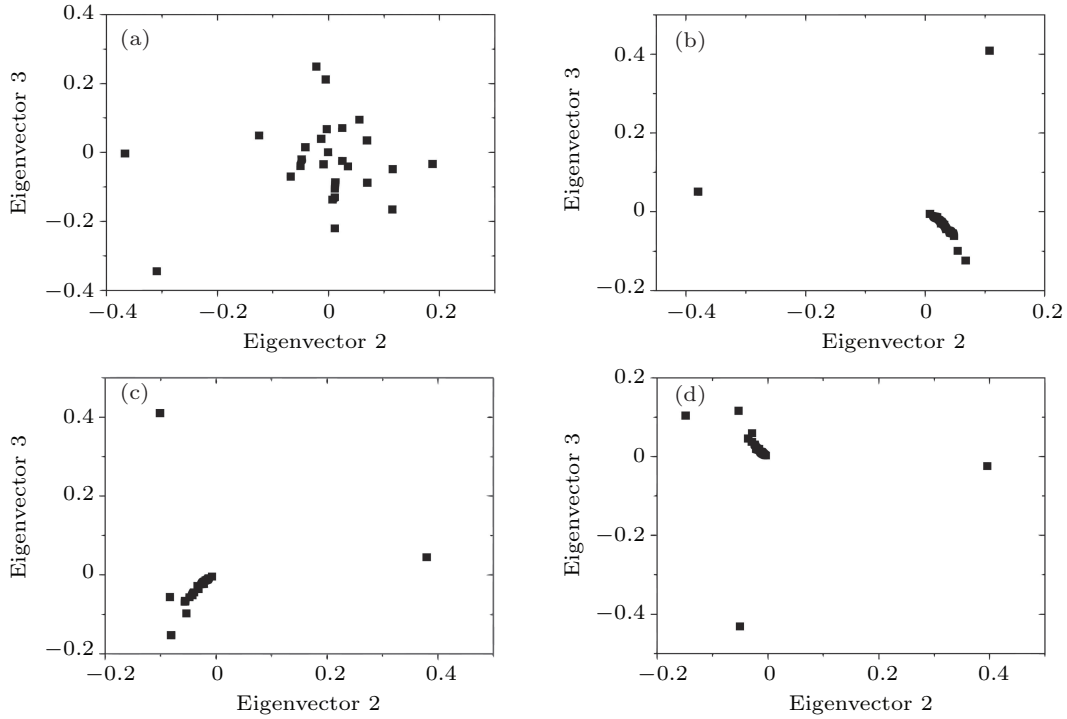



**Fig. 4.** Eigenvector distribution of $\boldsymbol{L}_\alpha$. Eigenvector 2 is the eigenvector corresponding to the second smallest eigenvalue, and eigenvector 3 is the eigenvector corresponding to the third smallest eigenvalue. (a) $\alpha = 0$, (b) $\alpha = 0.3$, (c) $\alpha = 0.6$, (d) $\alpha = 0.9$.

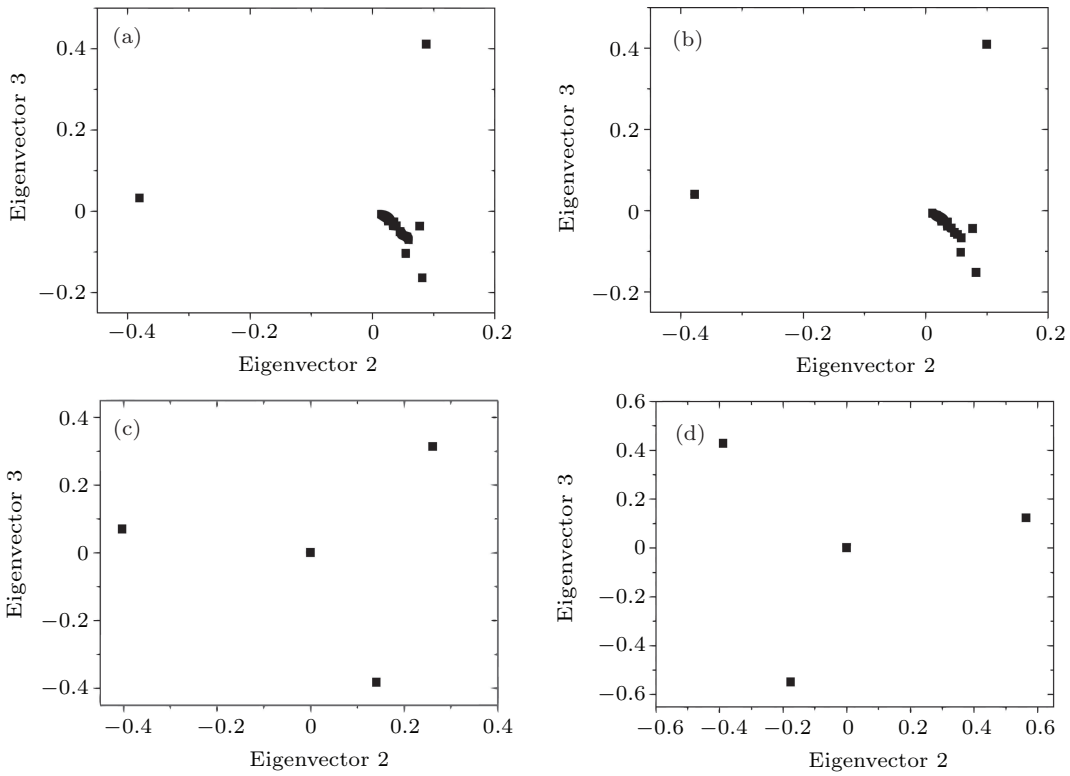



**Fig. 5.** Eigenvector distribution of $\boldsymbol{N}_\alpha$. Eigenvector 2 is the eigenvector corresponding to the second largest eigenvalue, and eigenvector 3 is the eigenvector corresponding to the third largest eigenvalue. (a) $\alpha = 0.1$, (b) $\alpha = 0.4$, (c) $\alpha = 0.7$, (d) $\alpha = 1$.

The nodes position coincidence is high in different $\alpha$, and it has a few similarities. Furthermore, figure 6 depicts the clustering results obtained by $\boldsymbol{L}_\alpha$ and $\boldsymbol{N}_\alpha$, and there is a similar result when $\alpha$ is another value. It is noted that the clustering results of the same method are different when $\alpha$ varies. Meanwhile, the results of various methods are different when $\alpha$ is the same. Because some nodes are isolated nodes, or locate at the boundary of the community, this makes these nodes difficult to detect. However, on the whole, we observe that the network is divided into three large communities that represent the major component suppliers of iPhone. It is noted that nodes within the same community represent suppliers providing the same components. Any failure of a supplier would not influence the production of iPhone, and thus the robustness of the network is improved. Analogously, the process of the industrial Internet evolution will also form the similar pattern: nodes (suppliers) in the same community produce similar components and compete with each other. The growth of one supplier would lead to the decrease of other suppliers, since the total demands are limited. That is to say, suppliers are sensitive to other similar suppliers and the market. Therefore, the industrial network has high efficiency of information communication (the community is relatively dense), which benefits reducing the product backlog and improving the efficiency of the whole social resource. For the smartphone network, the result is similar to Figs. 4 and 5, and we do not show them in the paper.

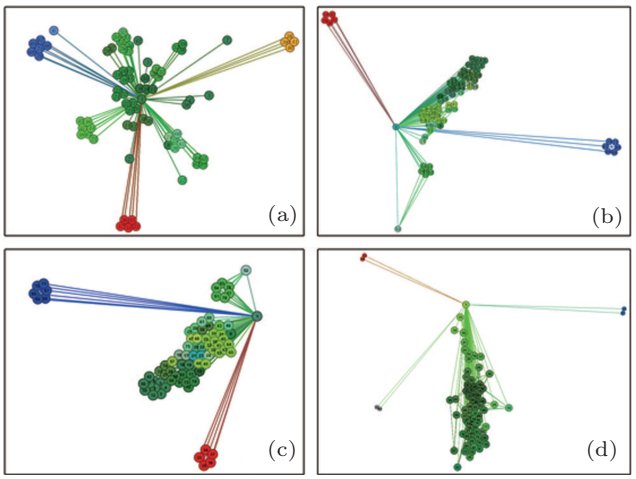



**Fig. 6.** (color online) Clustering results of spectral analysis, the same color represents a category. (a), (b) Clustering results using $\boldsymbol{L}_\alpha$ when $\alpha = 0, 0.6$; (c), (d) clustering results using $\boldsymbol{N}_\alpha$ when $\alpha = 0.4, 1$.

## 5. Conclusion

We adopt the global supply chain data of smartphone to construct the the supply network, and analyze the complexity of the supply chain network. We focus on the practical implications of the small-world and scale-free characteristics demonstrated in the supply chain network. Moreover, the community structure of the network and its applications are also studied. Community structure analysis of the supply chain network may draw interest from the global supply chain community. However, different smartphone supply chains vary in reality, thus even broader research on the elec-

tronic product global supply chain networks can be extended in the future.

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