Research on a regional innovation system: viewed from the degree distribution of complex networks theory

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Abstract

A Regional Innovation Systems is viewed as a special type of complex network in this paper, and the complex features of the entities in the system as well as the interactions between the entities are discussed in detail. Based on the Degree Distribution of Complex Networks theory, firstly this paper proves the feasible degree distributions in practical networks through mathematical reasoning and analysing. Then, an empirical case of degree distribution characteristics for the Regional Innovation System is tested by mean of calculating the Correlation Coefficient with the statistical data of Guangdong Province. Coupling Complex Networks Theory with these data and the practical conditions of Guangdong province, this paper sheds light on the insight of the calculating results. Such research shows that the methodologies and conclusions of this paper are proper.

Keywords: regional innovation system, degree distribution, complex networks, data calculation, Pearson correlation coefficient

1. Introduction

Since the early 1990s, the concept of regional innovation systems has obtained considerable attention for advancing the understanding of the innovation process in regional economies. The increasing popularity of this concept has been impelled partly by the intense international competition in globalizing environment, as well as the deficiencies of traditional regional development models and policies in many regions around the world. Although it is typically understood to be a set of interacting private and public institutions or organizations that function according to organizational arrangements and relationships conducive to the generation, use, and dissemination of knowledge, the concept of regional innovation systems has no generally accepted definitions. The basic argument is that such a set of actors produce pervasive and systemic effects that encourage firms within the region to develop specific forms of capital that are derived from social relations, norms, values, and interactions within the community in order to reinforce regional innovative capability and competitiveness [1].

The original concept can be found in two main bodies of relative research. The first is systems of innovation. Built on evolutionary theories of economic and technological change, the literature [2] conceptualizes innovation as an evolutionary and social process. In the literature [3], innovation is stimulated and influenced by many actors and factors, both internal and external to the firm. In the literature [4], the social aspect of innovation refers to the collective learning process between several departments of a company (for example, R&D, production, marketing, commercialization, etc.) as well as to external collaborations with other firms, knowledge providers, financing, training, etc. The second body is regional science and its explanations about the social environment from which innovations emerge. From this point of view, innovation is localized and a locally embedded, not placeless, process [5, 6]. Namely, a regional innovation system is characterized by cooperative innovation activities for knowledge creation and diffusion between firms and organizations, such as universities, training organizations, R&D institutes, technology transfer agencies, and so forth.

A fundamental problem in all studies of regional innovation systems is that we cannot yet determine how a regional innovation system might appear in reality [7]. For instance, how much and what type of innovation must occur within a region for it to be considered a regional innovation system? Do all regions that aspire to take a lead in organizing and innovating become regional innovation systems by default? If something like a regional innovation system already exists, but the extant literatures on the subject are not clear. We contend that the interactions between actors in regional innovation systems have not been sufficiently explored, while the institutional context of these interactions has been largely overlooked. As a result, the validity of recommendations for innovation policy making based on the current analyses of regional innovation systems is somewhat questionable. Therefore, it is very necessary to analyse a regional innovation system from new viewpoint to obtain substantial insight.

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2 The definition of a regional innovation system in the sight of network

The innovation theory initially emphasizes on the technological innovation within corporations. For instance, American economist Joseph Alois Schumpeter's book The Theory of Economic Development: An inquiry into profits, capital, credit, interest and the business cycle pointed out that technological innovation is a linear process including developing, designing, manufacturing and selling [8]. However, as researches deepened, innovation was no longer confined to a linear model within corporations or between corporations. People generally consider it in a higher level--regional innovation system. In 1987, British economist Christopher Freeman introduced the concept of "National Innovation System" [9]: the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies. The OECD report "Managing National Innovation Systems" [10] in 1999 pointed out: "Innovation performance depends on the way in which the different components of the 'innovation system' -- businesses, universities and other research bodies - interact with one another at the local, national and international levels, and concludes that the public authorities must change their approach to the promotion of innovation." Throughout the researches published, although regional innovation systems have drawn great attention in the academic fields, there is no plausible explanation about it given by mainstream Economics, Industrial Economics, or Evolutionary Economics [11]. The researches in managerial fields are even in a worse situation.

The world-famed physicist Stephen Hawking once said that the 21st century would be the Century of Complexity. This statement is widely recognized, and the researches on complexity have been carried out in many fields in recent years. Among many new researches on complexity science, one of the most representative theories is Complex Networks Theory. According to this theory, a complex network is a highly abstract complex system. In fact, complex networks can be found in natural, engineering, and even our social fields [12,13]. For instance, the metabolism in cells, neural networks in brains, food chain networks forming the ecological system, social relationship networks, science research cooperation networks, trade networks, internet, and electric power networks, etc [14-19]. Recent years, with the rapid development of network and computer technologies, researchers are able to obtain abundant data from major real networks to conduct statistical analysis. Such results show that complex networks are not homogeneous; on the contrary, they are heterogeneous. Their degree distribution does not follow Poisson distribution, but power-law distribution. A network that follows power-law distribution is called a scale-free network [20]. Because of the scale-free feature possessed by complex networks, its degree distribution is completely determined by its power-law index (degree distribution index). For instance, the degree distribution indexes of most artificial networks are between 2 and 3. And some key natures (like transmission threshold) of network dynamics (like transmission of infectious disease or virus) are directly related with degree distribution index.

All of the achievements have shown the successful application of complex networks theory. However, there are not yet specific researches utilizing this theory into the important academic field-regional innovation. Based on the previous researches, this paper defines a regional innovation system as a complex network constituted by corporations, research institutions, universities and colleges, government and institutions with intermediary functions within a given region, which develop the ability of regional innovation by interacting with each other. Based on the definition, this paper first analyses the connotation of the degree distribution based on complex networks theory. Then, taking Guangdong Province of China as the object of demonstration, this paper calculates the degree distribution with the related data and tries to explain the calculation results. It is believed that this paper will offer important reference for future research related to regional innovation.

3 The complex network's features of a regional innovation network

Based on the complex networks theory, both the characteristics of the subjects in regional innovation networks and interactions between subjects have embodied complex network features.

3.1 FEATURES OF THE SUBJECTS

There are many categories of subjects building a regional innovation system. These subjects have different forms and abilities. Furthermore, each type subject can be described in different accurate degrees. Such subjects have different layers and scales, and play different roles in the innovation systems. This paper has classified subjects into 4 following categories.

Creative Subjects: this paper considers that the sources of innovation are ideas, which produce new knowledge. In a regional innovation network the subjects that produce new knowledge are research institutions, universities, R&D departments of enterprises. They are in the one edge of the frontier in the innovation network. And the aggregates of these subjects are creative ones. These subjects should be depicted according to the layer of the network studied or the particular characteristics of data.

Supportive Subjects: if creative, informational new knowledge can be transformed into economic interests, it has to gain support and coordination from material elements. That is why we think governments (political supports), banks (financial credits), venture capitals, etc. are on the other edge of the frontier in the innovation network. They are supportive subjects.

Flowing Subjects: in an innovation network system, the combinations and flows from source boundary (inputs of economic interests) to department boundary (outputs of economic interests) of every elements related to innovation cannot fulfil the transmission function. They need corresponding channels, patterns and drivers as inter-mediums. We see intermediaries in technical markets and related government sectors that perform communicative functions and resource allocation are in the middle area of the innovation network. They are flowing subjects.

Productive Subjects: in an innovation network, many innovation elements finally come together and transform into economic interests. This process need to be performed by a specific category of subjects. In this paper I view corporations as the elements that produce outputs of innovation networks. They are in the last area of an innovation network and can be defined as productive subjects.

As *we* can see, different kinds of subjects in a regional innovation network not only have important effects on themselves, but also have corresponding attributes and features that can directly affect the whole innovation network. Based on the description of different accurate degree, therefore, if we see the subjects in an innovation network as nodes in the network, they have obviously embodied the features of nodes in the complex network.

3.2 FEATURES OF THE INTERACTIONS BETWEEN SUBJECTS

In a regional innovation network, interactions between subjects substantially reflect the interactive relations between material, energy and information. These interactions are non-linear synergistic actions. With these interactions, subjects can modify their behaviors to response to the changes of environment. In other words, every subject can gain innovative ability through information sharing, mutual complementarities of abilities, diffusion effect of knowledge and cumulative effect of innovation accumulation. Therefore, theoretically speaking, the interactions between subjects have features like direction and intensity (or weight). In practice, of course, they can be dealt as undirected and weightless interactions.

The Directions of the Interactions: almost every interaction between subjects specifically directs from one to another. For example, an action which directs to a corporation from a research institute means that the researches flow from the latter to the former, while an action directing to universities from government financial sectors means the flows of financial expenses to the universities. Therefore, the in-degree and out-degree of every subject should be considered respectively. And also we can study the ratio of input to output (like innovation effectiveness), the proportion of patent, etc. about the corresponding innovative behavior.

The Multiple-characteristics of the Interactions: the interactions between subjects in an innovation network have different characteristics. Take universities as an example, an action directing the university from government means the government supports the university financially; an action from a corporation means it supports the university financially as well. The former is much more policy behavior, while the latter is more business cooperation.

The Weights of the Interactions: in innovation networks, the interactions not only differ in quality, but also in quantity - it means that the interactions have weights. Furthermore, in this paper weight means the intensity of *interactions* between subjects.

The Dynamics of the Interactions: the interactions between subjects in innovation networks are not static, but dynamic. In other words, every action happens only in a specific time, being a function of time.

Therefore, if we see the interactions between different subjects in an innovation network as the "edges", they will obviously reflect the features of edges in complex networks.

4 Theoretical analyses on degree distribution

Based on the principles of complex networks, the degree of a node refers to the number of the edges to which link the node. Suppose that there is no isolated node in a network, no self-circled phenomenon, and there is at most one edge between any two given nodes, then the definition of degree distribution should be:

$$P(k)=\frac{\text{the number of nodes whose degrees are k}}{\text{the total number of nodes}}$$

($\forall$ positive integer k).

Set the total number of nodes as N, and the total number of edges as W. Then the minimum degree of every node is 1, the maximum is N-1. So the relationship of degree distribution can be expressed as Equation (1) which is called completeness:

$$\sum_{k=1}^{N-1} P(k)=1\,. \tag{1}$$

For a scale-free network [12~13], $P(k)$ is a power function, namely $\gamma>0$ and $C_N>0$, making:

$$P(k)=C_N\cdot k^{-\gamma}\,. \tag{2}$$

In the equation above, γ is called degree exponent; C_N is a Power law coefficient, whose value can be calculated according to the completeness of degree distribution in Equation (3).

$$C_N=1\Big/\sum_{k=1}^{N-1} k^{-\gamma}\,. \tag{3}$$

In order to further discuss degree distribution, set the fist moment and second moment of degree distribution as d_{M1} and d_{M2} respectively, expressed as followed:

$$d_{M1} = \sum_{k=1}^{N-1} k \cdot P(k) = C_N \cdot \sum_{k=1}^{N-1} k^{1-\gamma} , \quad (4)$$

$$d_{M2} = \sum_{k=1}^{N-1} k^2 \cdot P(k) = C_N \cdot \sum_{k=1}^{N-1} k^{2-\gamma} . \quad (5)$$

Set the average value and standard deviation as μ and σ respectively, let $\mu = d_{M1}$, then:

$$\sigma^2 = d_{M2} - \mu^2 = d_{M2} - d_{M1}^2 . \quad (6)$$

Obviously, with γ increasing, both d_{M1} and d_{M2} will decrease. When reflecting on network topology, that means the network transits from heterogeneity to homogeneity. When $\gamma \to +\infty$, there would be $\mu \to 1$, $\sigma \to 0$, which means the network is completely homogeneous. Since the length of this paper is limited, only one situation is discussed to demonstrate the relations between the range of γ and network topology.

When $0 \le \gamma < 1$, there is:

$$\sum_{k=1}^{N-1} k^{-\gamma} = O\left(N^{1-\gamma}\right), \sum_{k=1}^{N-1} k^{1-\gamma} = O\left(N^{2-\gamma}\right), \quad (7)$$

$$d_{M1} = O\left(N^{2-\gamma} / N^{1-\gamma}\right) = O(N) . \quad (8)$$

Obviously, when N is abundantly large, d_{M1} is divergent. The same:

$$d_{M1} = O\left(N^{3-\gamma} / N^{1-\gamma}\right) = O\left(N^2\right) \quad (9)$$

So d_{M2} is also divergent. Therefore based on the Equation (6), it can be proved that the average and variance of degree distribution are divergent. The total number of edges in the network is:

$$W = N \cdot \mu = N \cdot d_{M1} = O\left(N^2\right). \quad (10)$$

The Equation (10) shows that the number of edges in the network is of the same magnitude with $N \cdot (N-1)/2$, the number of edges in a complete network. The calculation does not quite fit the real evidence obtained by other researchers since many researches with real evidence show that large networks are almost sparse networks, therefore the network where γ is in the range of [0,1] does not exist in the real world.

Specially, when $\gamma = 1$, there will be:

$$\sum_{k=1}^{N-1} k^{-\gamma} = O[\ln(N)], \sum_{k=1}^{N-1} k^{1-\gamma} = O(N), \sum_{k=1}^{N-1} k^{2-\gamma} = O\left(N^2\right)$$

and we can yield:

$$d_{M1} = O\left[N / \ln(N)\right], \; d_{M2} = O\left[N^2 / \ln(N)\right], \quad (11)$$

$$W = N \cdot \mu = N \cdot d_{M1} = O\left[N^2 / \ln(N)\right]. \quad (12)$$

Based on the principles above, a large network with $\gamma = 1$ does not exist in the real world either.

5 Demonstration and analyses based on data calculation

According to the complex networks theory, different types of degree distribution of networks can reflect the nature of the whole structure. Moreover, nodes with different degrees have different status and functions within the network. Besides, the degree distribution of complex network theory is built on the hypothesis that edges and weights are equal. But in practice, what matters is the overall weight. In examining the degree distribution, we can ignore the source of the edges (in the case of in-degree) and the direction of the edges (in the case of out-degree), just focus on the calculation of input and output distribution of nodes.

5.1 DEFINITION OF NODES AND EDGES IN THE NETWORK

Ideally speaking, universities, corporations and government sectors can be identified as the innovation subjects in a region because these subjects meet with the requirements of complex network theory well. But since data that completely fits theoretical requirements is unavailable, we instead employ rough method to define nodes. That is, to view Guangdong Province as an innovation network and the 21 cities of Guangdong as nodes.

Some other measuring methods are often subjective when defining whether there are relationships between nodes or not. In general, those arbitrary weights will affect the result of the measurement. To eliminate the subjectivity in defining the edges, this paper applies Pearson Correlation Coefficient as an objective indicator to measure the relationship between nodes. Pearson correlation coefficient is a statistical measure of the degree of linear dependence between two variables, explaining the strength of linear relationship between two phenomena (X and Y). Sample correlation coefficient is commonly represented by the letter R, giving a value between -1 to 1 inclusive, where $R>0$ indicates positive correlation, $R<0$ indicates negative correlation, and $R=0$ is no correlation. The Equation is:

$$R = \frac{\sum (X-\overline{X})(Y-\overline{Y})}{\sqrt{\sum (X-\overline{X})^2 \sum (Y-\overline{Y})^2}} = \frac{\sum XY - \frac{\sum X \cdot \sum Y}{n}}{\sqrt{[\sum X^2 - \frac{(\sum X)^2}{n}][\sum Y^2 - \frac{(\sum Y)^2}{n}]}} . \quad (13)$$

Then we choose some statistics data with temporal continuity of nodes, and calculate its relevance with time, to gauge whether and at what degree they are related. The method is to subjectively define the critical value of the correlation coefficient between any two cities as R_0, then to analyze the correlation between every two different nodes. When the correlation coefficient is larger than R_0, we consider there is a edge between the two nodes. This assumption is built on such theoretical basis: if two cities, at a particular time period, have a relatively consistent development trend, it means that they have similar policies and other internal and external elements. The reason they have such similarities is generally due to communications and interactions between cities (for instance, one city often learns some patents from other cities to promote the experience of development). Therefore, this method avoids subjectivity, as well as better reflecting the connections between cities.

5.2 DATA SELECTION AND CALCULATION RESULTS

Table 1 shows the statistics of the number of patents of 21 cities of Guangdong Province (data from statistics yearbook, only part of the data is shown below), which is calculated to see if an edge is formed between any 2 cities. When the given R_0 =0.97, the degree distribution (by computing programming) is shown in Figure 1.

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In Figure 1, the network built by numbers of patents in Guangdong cities is scale-free. It is found that the degree distribution is negative power law distribution with $2 < \gamma \le 3$. Based on the complex network theory, its network architecture is highly self-similar and divergent, meaning that most nodes' degree have low values, but a minority of nodes are central nodes with pretty high degree values. Therefore, these central nodes with high degree values are obviously of great importance, like Guagzhou, Shenzhen, Zhuhai and Foshan. The results fit the actual situation of Guangdong Province quite well, in a way demonstrating the correctness of our research.

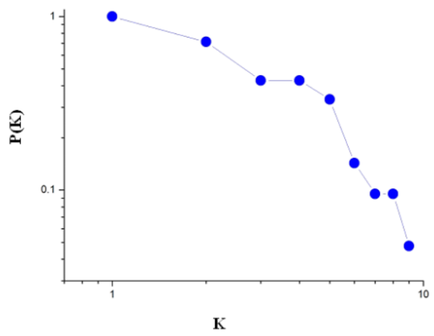

FIGURE 1 Degree distribution of domestic patents application

TABLE 1 Domestic patent application of the main cities in Guangdong province

City/year	2007	2008	2009	2010	2012	2013
Guangzhou	4410	4998	6288	8206	8230	11012
Shenzhen	4447	6177	8337	12344	15088	20943
Zhuhai	594	759	825	989	1220	1830
Shantou	1061	1285	1849	2270	2586	2715
Foshan	4238	5490	6897	7388	10809	17248
Shaoguan	98	106	114	129	169	303
Heyuan	51	28	39	65	133	83
Meizhou	72	87	69	123	148	190
Huizhou	378	331	708	854	1109	1041
Shanwei	51	104	169	182	188	160
Dongguan	1653	2914	3100	3865	4325	6694
Zhongshan	1372	1829	2115	2159	2545	3399
Jiangmen	695	767	1097	1848	2116	2787
Yangjiang	195	283	425	369	499	699
Zhanjiang	217	195	248	235	406	475
Maoming	94	84	157	205	172	314
Zhaoqing	118	179	190	255	343	303
Qingyuan	53	108	169	119	218	167
Chaozhou	746	997	737	805	879	1155
Jieyang	498	346	331	504	539	523
Yunfu	28	43	84	94	152	148

6 Conclusions and future research

The following conclusions can be drawn from the research:

1) A regional innovation system can be considered as a complex network. The definitions of nodes and sides reflect its features as a complex network.

2) The calculations show that the Guangdong Province regional innovation network follows the negative power law distribution and the degree index is between 2 and 3.

3) The calculation results show that degree distribution theory is able to reflect the status of subjects and their relations with one other.

4) The complex networks theory brings new view, new tools and new methodologies for regional innovation researches. Relative researches worth going even further.

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