Social Network Analysis of the Collaboration Networks within National Quality Award Projects of China

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Abstract

In recent years, the investment has continued to expand in the field of engineering infrastructure in China, prompting more and more construction organizations to cooperate, in order to achieve risk sharing, resource allocation and complementary advantages. Based on the social network analysis method, the contractor collaboration network is constructed based on the National Quality Award Project of China (NQAPC) from 2003 to 2012. Using the selected 7 network-level measurement parameters and 5 Node-level measures, the global structural characteristics of the contractors' collaboration network are systematically analyzed, and the location attributes and capability differences of individual contractors in the network are identified. The research shows that the contractors' collaboration network within NQAPC has the small-world and scale-free, and contractors with high centrality have strong communication, control or dependence in the network. The research can provide theoretical basis and practical guidance for the sustainable development of the engineering industry.

Keywords

National Quality Award Project of China (NQAPC); Contractors' Collaboration Network; Project Management; Social Network Analysis.

1. Introduction

The system containing multiple individuals and their interactions in nature can be abstracted into a complex network, where individuals correspond to the nodes of the network, and the interactions between individuals correspond to the edges of the network. As a way and method to explore and evaluate the complexity of the system, complex networks focus on the topological structure of the interaction network of individual units in the system, which is the basis for understanding the behavior and functions of complex systems [1]. Since Watts and Strogatz [2] proposed small world networks in 1998, and Barabási studied scale-free networks in 1999 [3], complex networks have become an important field of complexity science research.

In the past ten years, the empirical analysis and model simulations on the macro-scale structure and evolution of complex networks have achieved remarkable results. For example, by analyzing the topology of scientific research collaboration networks to study the citation relationship between scientific papers or the collaboration relationship between scientists [4, 5]. Based on social networks, scholars in the engineering field have studied the interrelationships of engineering project stakeholders [6], project performance goal setting [7], and project governance [8]. The research is mostly aimed at a single engineering project, and its network scale is relatively small.

With the continuous development of China's economy and society, the planning and construction of major engineering projects are vigorously developing. The major engineering program is composed of a number of large-scale, long-period, and technically complex engineering projects [9], and it is a complex giant system. However, due to limitations in technology, capital, and management capabilities, it is difficult for a single or a small number of engineering project organizations to independently undertake and implement the above-mentioned program. And in the actual construction and operation process, major engineering project groups are faced with pressures and challenges such as high operating costs, low efficiency of comprehensive management and control, and poor organizational relationship governance [10].

In fact, in the long-term interactive collaboration, many program organizations with related interests and diverse specialties have formed an autonomous but interdependent organizational network system dedicated to achieving the strategic goals of major program [11]. In this system, organizations can be abstracted into nodes, and a series of collaboration relationships based on resource, information, and technical collaboration correspond to the edges of the network. The network structure mode of contractors of engineering program is a comprehensive reflection of their own behavior attributes and network environment. Based on the complex network theory and social network analysis methods, this paper discusses the basic mode and structural characteristics of their collaboration, and it is possible to give new ideas and methods to promote the governance of major engineering program [12].

Taking the NQAPC as the prototype, this paper establishes the engineering contractors' collaboration network model, and systematically analyzes its structural characteristics and the position of key contractors in the network based on the global and individual scales of the social network. The research conclusion is helpful to supplement and develop the current program management theory and method, and provide practical guidance and policy choice for the selection of individual organization partners. At the same time, these findings may be of universal value to readers in other developing countries.

2. Literature Review

2.1. Organizational Relationship and Structure of the Program

As a key factor for the success of engineering program, the projects organization management has received extensive attention from many scholars. Relevant research mainly focuses on the organizational structure, organizational collaboration models, and application of program management. Turner [13] earlier defined the program management, believing that it refers to a number of projects with internal connections, in order to realize the increase of benefits and adopt unified and coordinated management. Naoum [14] proposed that partnership is a kind of collaboration strategy in the future, and explored its relationship with organizational growth and improvement of competitiveness. Some studies have investigated the key success factors of partnerships, which are summarized as adequate resources, mutual trust, long-term goals, etc. [15, 16].

For the research on the organizational structure of the program, the Project Management Institute [17] proposed the standards and organizational structure of program management, which is composed of the program committee, the program office and the program manager. Later, Anderson [18] pointed out that the core of the program management organization structure is the program management office, which is responsible for reflecting the strategy into the program. Cheng [19] proposed an evaluation model for the degree of collaboration and efficiency within the project organization structure, and spent its optimization choices.

2.2. Social Network Analysis of the Program Organization Network

The past two decades have witnessed the rapid development of the research on the network relationship structure of project organization based on SNA. Pryke [20] divided the internal relationship network of project organization into information network, contract network and incentive network, and pointed out that SNA provides a new quantitative model and method of joint project management. Loosemore [21] applied SNA to study the individual communication network in construction projects under the crisis conditions of the British construction industry through the quantitative analysis of their communication network with the help of SNA. Zheng et al [22] reviewed the application of SNA from the aspects of organizational and personal contributions, covered topics, research methods, research citations of construction project management.

Recently, Pryke et al. [23] discussed the usefulness of social network theory and SNA as a conceptual and methodological perspective for exploring major issues in construction project management. Based on complex global parameters and social network centrality indicators, Liu et al. [11] discussed the change trend of macro-scale structural parameters of the contractors' collaboration network in NQAPC. In summary, SNA provides a powerful example for the expression and quantification of the relationship pattern between project organizations.

3. Method and Data

3.1. Social Network Analysis Indexes

In order to analyze the topological characteristics of the NQAPC organization collaboration network, we used 7 selected network-level global parameters (namely, density, diameter, average degree, degree distribution, heterogeneity, clustering coefficient, average path length, etc.) and six Node-level metrics (including degree, betweenness, closeness, eigenvector, shortest path length and structural holes, etc.), the theoretical definitions and practical meanings of related parameters are shown in Table 1 and Table 2.

Table 1. Theoretical definition and practical significance of network-level parameters

Name	Theoretical definition	Practical significance
Density	The ratio of actual connections in the network to the maximum number of possible connections.	Describe how closely the nodes in the network are related. The higher the density, the closer the connection between network members.
Diameter	The maximum value of the geodesic distance between all pairs of nodes.	The larger the diameter, the more difficult the communication between these contractors.
Average degree	The average degree of all nodes in the network.	The higher the value, the larger the scale of the network and the closer the connection.
Degree distribution	Representing the probability that a randomly selected contractors has k directly correlated.	The most basic topological characteristics of graph G, which determines the statistical properties of non-associated networks
Heterogeneity	A measure of the degree of uniformity of node distribution.	Reflect certain tendency and disorder of the network structure caused by the uneven distribution of contractors characteristics
Average path length	The average of the shortest path length of all nodes in the network.	Reflect the capacity of the network and the efficiency of information transmission.
Average clustering coefficient	The average clustering coefficient of the network is the average of the clustering coefficients of all nodes.	Explain the homology of contractors and the transferability of collaboration between contractors.

Table 2. Theoretical definition and practical significance of Node-level parameters

Name	Theoretical definition	Practical significance
Degree centrality	The number of nodes directly adjacent to the node. $k_i = \sum_{j=1}^{n} a_{ij}$.	Represents the direct influence of a node on other nodes in the network, and contractors with greater degrees have greater "activity" in the network.
Closeness centrality	For fully connected networks, CC(i) $=\frac{n-1}{\sum_{j\neq i} d_{ij}}$, defined as the reciprocal of the average geodesic distance from i to all other nodes.	A measure of how close a participant is to all other participants in the network. The larger the value, the more it is in the center of the network.
Betweenness centrality	The number of nodes i through all the shortest paths in the network, BC (i) $=\sum_{i\neq s,i\neq t,s\neq t} \frac{g_{st}^{i}}{g_{st}}$.	A measure of the extent to which a participant is on the shortest path of all other participants in the network. The larger the value, the stronger the resource control ability.
Eigenvector centrality	The eigenvector of the largest eigenvalue corresponding to the network adjacency matrix, x_i=c $\sum_{j=1}^{n} a_{ij}\, x_j$, j≠i.	Measure the indirect influence of neighboring high-value nodes. A node with a high value indicates that it is close to the core object of the network.
Shortest path length	L (i) $=\frac{\sum_{j\neq i} d_{ij}}{n-1}$, d_{ij} is the shortest distance between node i and node j.	The shortest path provides an optimal path so that it can be transmitted quickly and save system resources.
Structural hole	A structure in which one contractor cooperates with the other two contractors and the other two contractors do not cooperate. Considering Four aspects of structural hole: effective size, efficiency, constraint and hierarchy.	It pays attention to the structural level of the relationship between at least three actors, and points out the intermediary in this structure has information advantage and control advantage and will become a kind of social capital.

3.2. The Contractors' Collaboration Network Model within NQAPC

As the highest honor award for the quality of China's engineering construction, the selection scope of the NQAPC [24] covers ten types of engineering professional fields including housing construction, municipal administration, railways, highways, electric power, chemical industry, smelting, ports, water conservancy and communications. The award objects include construction, design and consulting companies. The data used in this study is the construction contractor data in the list of the NQAPC, which comes from the China Construction Enterprise Management Association [25].

The study adopts the bipartite network and its single projection network modeling method [26]. First, the bipartite network is established based on the 2003-2012 NQAPC and their contractor relations as an example. The upper nodes are regarded as the winning program. The lower node is the contractor organization group (see Figure 1). Then, based on the complex network modeling and analysis method, with the help of Cytoscape software, this bipartite network is projected to the lower nodes, and the largest cluster topology of the contractors' collaboration network within NQAPC accumulated to 2012 is obtained, as shown in Figure 2.

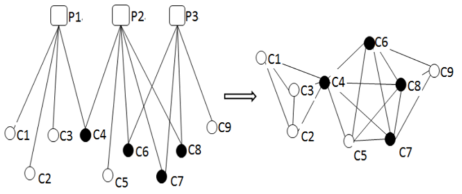


Figure 1. Project-contractor binary network and contractors' organization network construction

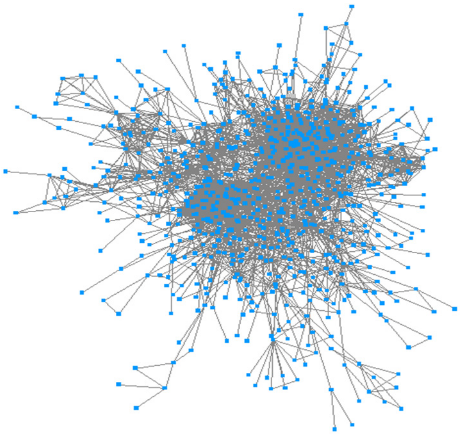
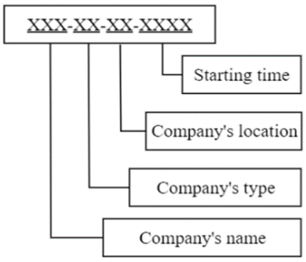


Figure 2. The largest cluster topology of the contractors' collaboration network up to 2012

For the convenience of research, we have numbered all contractors in the NQAPC contractors' collaboration network, according to "name abbreviation-contractor type-province-year of appearance". The explanation of the numbers is shown in Table 3.

Table 3. Contractor number and its interpretation

	Contractors	Code Instruction	
Example			**Company's name:** The name of the contractor who have taken part in the construction of one project. **Company's type:** shows the contractor's profession and the field the company is focus on, such as housing(HC), electric power(EP), Railway endgneering(RA). **Company's location:** represents the enterprise region, eg, Shanghai(SH), Beijing(BJ), Guangdong(GD). **Starting time:** represents the year the contractor first participated in the construction of one project.

4. Empirical Results

4.1. Basic Global Parameter Analysis

The basic statistics of the network are shown in Table 4. The largest component in the table is the largest connected node group in the contractors' collaboration network within NQAPC. It has gradually increased in absolute and relative scale over time, representing the core group of the NQAPC contractors. It can be seen from Table 4 that as of 2012, the largest cooperative cluster has covered 79.3% of contractors, the largest number of cooperative contractors is 948, and the number of cooperative sides is 4713.

Firstly, the study interprets the global topological characteristics of the contractors' collaboration network within NQAPC accumulated to 2012. The main analysis and conclusions are as follows: Table 5 shows that as of 2012, the density of the contractors' collaboration network is only 0.017, and it is very sparse, indicating that the newly added contractors only cooperate with a few existing contractors in the network. The average degree is 12.535, which means that each contractor works with more than 12 contractors on average, the collaboration between NQAPC contractors is getting closer.

Analysis shows that the diameter of the contractors' collaboration network within NQAPC was 10 in 2012 (we set the distance between two adjacent nodes as 1), indicating that any two contractors in the network can establish contact with other contractors within 10 steps. It shows that the network has greater technical relevance. Contractors with multiple qualifications have participated in different types of projects, and few of key contractors have participated in many projects, forming a bridge point of the network, leading to "ten Degree relational space". It can also be seen from Table 5 that the heterogeneity of the network reached 1.228 in 2012, indicating that the contractors in the NQAPC have large differences in professionalism, qualifications, influence, etc., making the network structure dependent on the bridging of some important contractors, and their activity ability in the network is high.

Table 4. Fundamental statistics of the contractors' collaboration network for the period 2003-2012

Quantity/year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Number of projects each year	54	74	86	116	155	138	149	145	191	199
Number of contractors each year	91	142	158	201	237	210	296	273	333	281
Number of projects up to a given year	54	128	214	330	485	623	772	917	1108	1307
Number of contractors to a given year	91	207	296	400	500	590	680	767	863	948
Number of nodes in the largest component up to the given year (as a percentage %)	7 7.7	47 22.7	77 26%	198 49.5%	334 66.8%	434 73.6%	509 74.9%	599 78.1%	695 80.5%	752 79.3%
Number of edges in the largest component up to the given year	10	285	417	1228	1903	2354	2847	3359	4336	4713

The average path length of the contractors' collaboration network within NQAPC is 3.635, the proper term for the typical distance between a pair of nodes may be "four degrees of separation". Any two contractors can get in touch within four steps on average. The small "average path length" between contractors allows members to quickly disseminate new ideas, technologies and resources as they participate in the project, which helps contractors learn advanced experience from successful projects and improve project performance. In addition, the clustering coefficient of the contractors' collaboration network is as high as 0.606 in 2012, indicating that at least two of every three contractors have cooperated, and the network members are familiar with each other. The smaller average path length and larger clustering coefficient reveal the small world effect of the contractors' collaboration network.

Table 5. Fundamental statistics of the contractors' collaboration network within NQAPC up to 2012

Year	Density	Average degree	Diameter	Heterogeneity	Average path length	Clustering coefficient
2012	0.017	12.535	10	1.228	3.635	0.606

In addition, as of 2012, the distribution characteristics of the contractors' collaboration network within NQAPC are mainly reflected in the number of nodes with low degrees and fewer nodes with high degrees. Figure 3 shows, the degree ranges from 1~108, there are only 3 nodes with a degree greater than 80, and the number of nodes with a degree between 1 ~ 20 accounts for more than 80% of the total number of nodes, indicating that the degree distribution of the network approximately obeys the power-law distribution. This means the average nature of the contractors' collaboration network is dominated by a small number of contractors with more collaborators.

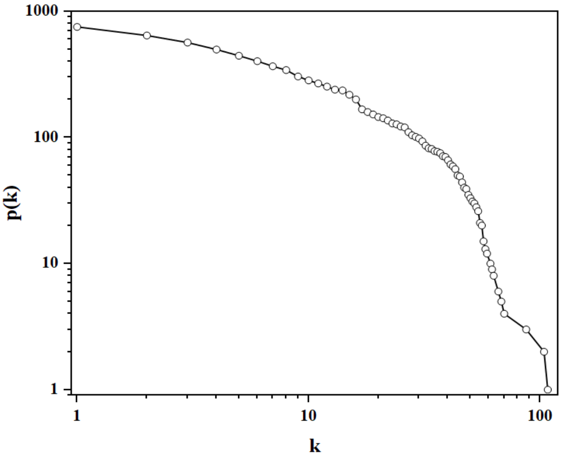


Figure 3. The cumulative degree distribution of the largest component up to 2012

4.2. Individual Characteristics based on Node-level Network Parameters

This paper introduces the number of NQAPC contractors from 2003 to 2012 into Cytoscape 3.7.2, and outputs four centralities (degree, betweenness, closeness, eigenvector), shortest path length and structural holes, etc., the top 20 contractors in the entire network based on the above indexes are obtained, as shown in Table 6.

In the engineering collaboration network, the contractor's degree reflects the size of its social capital in the network, and is a symbol of industry status and prestige. Table 6 shows that under the degree centrality, the top three contractors in the top 20 belong to the fields of railway, electric power and housing construction sectors. All of them are large state-owned enterprise holding companies, indicating that such engineering contractors can obtain more resources and participate in more projects in the industry, which is the basis for the existence of the industry. Under the betweenness centrality index, the industries (including railways, housing construction, highways, metallurgy, electric power, ports, etc.) and regions of the top-ranked engineering contractors are relatively scattered. The reason is that the betweenness reflects the intermediary relationship of contractors in different industries and regions, and there are more intermediary contractors in each industry and region.

Similar degree centrality, under the shortest path length and closeness index, more than half of the top 20 contractors have railway, power and highway qualifications, indicating that compared with contractors in other fields, such contractors who are good at contracting large-scale linear engineering projects are at the core of the network and have greater "search ability" in the network, easier access to resources, and more competitive advantages in seeking more capable partners.

It is worth noting that all the top 20 contractors under the eigenvector index belong to the electric power industry. The reason may be that the electric power industry is a knowledge-intensive industry with strong market access and industry barriers. In recent years, China has carried out many electric power infrastructure projects across the country. They are typical linear projects involving a wide range of engineering regions. Contractors in the industry have high relevance and close collaboration.

In order to more accurately express the contractor's ability difference, the study selects the most typical characteristic index (structure hole) in the individual network for calculation and analysis. In general, structural holes can be understood as the degree to which individuals are restricted by others in the network. Table 6 shows that the top 20 contractors under the structural hole index are least constrained by other contractors in the network are the railway industry, followed by the housing construction and power industries. This type of contractor has more alternative partners in the network, has a wider channel for obtaining resources, and is the middleman or occupant of the structural hole in the network.

From an engineering perspective, structural holes can provide opportunities for contractors to obtain "information benefits" and "control benefits", thus having a competitive advantage over members in other positions in the network. For example, a contractor who occupies a structural hole can obtain non-redundant information that other competitors cannot obtain (such as a competitor's bidding quotation), thereby gaining development opportunities for high-quality projects for themselves, thereby achieving an increase in reputation.

In summary, railway, electric power, highway, and housing construction qualified contractors account for more than 2/3 of the top 30 of the entire contractors' collaboration network under various indicators, and they are all in the forefront. In particular, China Railway and China Construction System engineering contractors have high centrality in the network, and they have high activity, control or dependence in the network.

Table 6. The ranking of the top 20 contractors in the collaboration network within NQAPC based on various network parameters up to 2012

Rank	Degree	Contractor	Betweenness	Contractor	Closeness	Contractor	Eigenvector	Contractor
1	108	CRC18-RA-TJ-2005	0.110	CRC19-RA-BJ-2004	0.420	CRC18-RA-TJ-2005	0.169	HBPTTE-EP-HB-2004
2	104	CRC19-RA-BJ-2004	0.106	CRC18-RA-TJ-2005	0.412	CRG1-RA-SA-2006	0.169	SDPTTE-EP-SD-2003
3	87	CRG1-RA-SA-2006	0.082	SCG-HC-SH-2003	0.408	CRC19-RA-BJ-2004	0.168	HPTTE-EP-HLJ-2005
4	70	CRGT-RA-GD-2005	0.069	CSCE8-HC-SH-2003	0.396	CRGT-RA-GD-2005	0.167	JHEB-EP-JX-2006
5	68	CRC12-RA-SX-2003	0.065	CRG1-RA-SA-2006	0.389	TEPC-EP-TJ-2003	0.167	SXPTTE-EP-SA-2004
6	66	SUCG-HC-SH-2003	0.062	CPECPB-CH-HE-2005	0.385	CMGC15-SM-HB-2006	0.166	GSPTTE-EP-GS-2005
7	63	JHEB-EP-JX-2006	0.058	CSCE3-HC-HB-2003	0.384	ZECG-HC-ZJ-2003	0.165	BPTTE-EP-BJ-2005
8	63	ZECG-HC-ZJ-2003	0.057	ZECG-HC-ZJ-2003	0.382	SCG-HC-SH-2003	0.164	JLPTTE-EP-JL-2004
9	62	CGG-WC-HB-2009	0.053	CMGC15-SM-HB-2006	0.380	CCCG2HEB-PO-BJ-2008	0.163	HETTC-EP-HA-2003
10	61	CRGBBG-RA-HB-2007	0.048	TEPC-EP-TJ-2003	0.375	CRGBBG-RA-HB-2007	0.160	ECPTTE-EP-SH-2005
11	59	SCG-HC-SH-2003	0.045	CGG-WC-HB-2009	0.375	CGG-WC-HB-2009	0.159	APTTE-EP-AH-2004
12	59	YHBE1-HW-YN-2005	0.041	SBCG-SM-SH-2005	0.373	YHBE1-HW-YN-2005	0.159	GZPTTE-EP-GZ-2004
13	58	JLPTTE-EP-JL-2004	0.040	GGCG-HC-GD-2004	0.372	CRC12-RA-SX-2003	0.159	NCPBTTE-EP-LN-2003

14	57	IMPTT-EP-NMG-2004	0.037	CMGC6-SM-HA-2004	0.372	CCCG1HEB-PO-TJ-2007	0.158	QTTE-EP-QH-2004
15	57	CRC13-RA-TJ-2007	0.036	BEPC-EP-BJ-2004	0.372	YHBE2-HW-YN-2005	0.156	GPTTC-EP-GX-2004
16	56	YHBE2-HW-YN-2005	0.035	SUCG-HC-SH-2003	0.372	CRG3-RA-SX-2003	0.154	XTTE-EP-XJ-2005
17	56	CCCG2HEB-PO-BJ-2008	0.033	CSCE7-HC-HA-2003	0.370	CCCG3HEB-PO-JS-2007	0.153	IMPTT-EP-NMG-2004
18	56	CRC14-RA-SD-2004	0.032	CCCG1HEB-PO-TJ-2007	0.370	YHB-HW-YN-2005	0.152	SPTTE-EP-SH-2006
19	56	CRC15-RA-SH-2004	0.030	CRGT-RA-GD-2005	0.368	CRC11-RA-HB-2004	0.151	GDPTTE-EP-GD-2006
20	56	CRG4-RA-AH-2003	0.029	ZCE-HC-ZJ-2003	0.368	SACEG-HC-SA-2006	0.150	JXPTTE-EP-JX-2004

Rank	Structural hole					Shortest path length	Contractor
	Effective scale	Efficiency	constraint	hierarchy	Contractor		
1	89.296	0.827	0.027	0.022	CRC18-RA-TJ-2005	2.382	CRC18-RA-TJ-2005
2	88.654	0.852	0.027	0.025	CRC19-RA-BJ-2004	2.425	CRG1-RA-SA-2006
3	67.138	0.772	0.034	0.028	CRG1-RA-SA-2006	2.451	CRC19-RA-BJ-2004
4	53.136	0.901	0.037	0.058	SCG-HC-SH-2003	2.523	CRGT-RA-GD-2005
5	48.629	0.695	0.039	0.016	CRGT-RA-GD-2005	2.570	TEPC-EP-TJ-2003
6	45.762	0.726	0.039	0.009	ZECG-HC-ZJ-2003	2.599	CMGC15-SM-HB-2006
7	41.185	0.763	0.040	0.016	TEPC-EP-TJ-2003	2.607	ZECG-HC-ZJ-2003
8	37.968	0.612	0.040	0.010	CGG-WC-HB-2009	2.621	SCG-HC-SH-2003
9	42.071	0.751	0.041	0.011	CCCG2HEB-PO-BJ-2008	2.628	CCCG2HEB-PO-BJ-2008
10	39.542	0.824	0.042	0.010	CMGC15-SM-HB-2006	2.667	CRGBBG-RA-HB-2007
11	39.787	0.652	0.045	0.008	CRGBBG-RA-HB-2007	2.668	CGG-WC-HB-2009
12	52.970	0.803	0.045	0.031	SUCG-HC-SH-2003	2.684	YHBE1-HW-YN-2005
13	38.571	0.689	0.046	0.022	CRC15-RA-SH-2004	2.686	CRC12-RA-SX-2003
14	43.059	0.633	0.047	0.021	CRC12-RA-SX-2003	2.688	YHBE2-HW-YN-2005
15	41.143	0.735	0.048	0.020	CRC14-RA-SD-2004	2.688	CCCG1HEB-PO-TJ-2007
16	34.393	0.614	0.049	0.013	CRG4-RA-AH-2003	2.690	CRG3-RA-SX-2003
17	35.807	0.628	0.050	0.013	CRC13-RA-TJ-2007	2.700	CCCG3HEB-PO-JS-2007
18	29.681	0.632	0.051	0.019	CRC11-RA-HB-2004	2.703	YHB-HW-YN-2005
19	33.254	0.528	0.052	0.013	JHEB-EP-JX-2006	2.714	CRC11-RA-HB-2004
20	29.415	0.555	0.052	0.012	CRG3-RA-SX-2003	2.718	SACEG-HC-SA-2006

5. Conclusion

With the help of social network analysis methods, this paper abstracts the contractors' collaboration network within NQAPC from 2003 to 2012. Network research mainly focuses on the macro-global scale and individual scale, and analyzes the structural characteristics and collaboration mode of the network. The research results show that: in terms of the overall structure of the contractors' collaboration network within NQAPC, it has the general characteristics of a social network, that is, small-world and scale-free. This shows that the collaboration progress of Chinese contractors can be shown to a certain extent as self-organization based on priority dependency rules and social constraints. In the dimension of individual characteristics, based on the Node-level parameters, it shows that contractors with a large centrality measurement have high social capital, social status and social influence.

The analysis of individual key contractors in the engineering collaboration network based on the social network Node-level measurement is helpful to understand the location priority and privilege of contractors. These interesting findings can not only help relevant personnel identify the unique characteristics of different types of projects, and plan different resource allocation strategies for different projects, but also help contractors better formulate reasonable collaboration strategies by determining network attributes and focusing on the development of network positioning strategies.

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