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Research on Complex Network Models and Characteristics of Building Material Enterprises Based on Competitive Relationships

Likun Zhao, Hui Yuan *, Mengqian An  and Xiaoqing Bao

School of Civil Engineering, North China University of Technology, Beijing 100144, China; zlk@ncut.edu.cn (L.Z.); anmengqianaa@163.com (M.A.); bxq1434040043@163.com (X.B.)

* Correspondence: yuanhui@mail.ncut.edu.cn

Abstract: Based on complex network theory, this paper establishes a Boolean competitive relationship network model and a weighted competitive relationship network model for building material enterprises based on big data and performs empirical analyses with construction prefabricated component (PC) enterprises in the Beijing–Tianjin–Hebei region as research samples. Results show the competitive relationship network of PC enterprises in the Beijing–Tianjin–Hebei region is characterised by the development of a small-world network, and its cumulative degree and out-degree (in-degree) intensity distributions are single-scale networks with fast-decaying tails. The network has strong network clustering and assortativity, and it can truly reflect the competitive status and dynamics of the enterprises.

Keywords: complex network; building material enterprises; competitive relationship; network model



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1. Introduction

The construction supply chain involves the flow of materials, information, and capital through various components of a construction project. The construction supply chain is a complex, large system that includes multiple participants such as building material suppliers, manufacturers, contractors, distributors, and logistics companies [1]. In the new digital era of escalating demand from construction clients, the building material enterprises are increasingly characterised by competition [2]. In addition, according to China's Statistical Analysis of the Development of the Construction Industry 2022, the number of construction enterprises has continued to increase yearly; by the end of 2022, the total of number of construction enterprises nationwide is 143,621, with fierce competition amongst them. Although the building material enterprises feel strong competitive pressure in practice, they are not clear about who their competitors are, and they lack a basic understanding of how to cope with the fierce competitive environment and develop.

A complex network is an abstract model for understanding real-world complex systems. A complex network abstracts entities in complex systems as nodes and relationships between entities as connectivity. Since 2000, complex network research has been rapidly applied to practical areas such as computer networks [3–5], biological networks [6–8], technological networks [9–11], brain networks [12–14], climate networks [15–17] and social networks [18–20]. Competitive relationships are pervasive in the real world, such as species competition in ecosystems, corporate competition in economic markets and individual competition in social networks. The study of competitive relationships can improve the understanding and explain the behavioural evolution of these complex systems, predict and manage competitive behaviour in complex systems, and optimise resource allocation and decision making. In existing studies, the research on complex networks based on competitive relationships is mainly conducted for industries such as logistics [21–23], manufacturing [24,25], and software [26,27], and they mostly use enterprises as nodes and competitive relationships between enterprises as edges to construct complex network

models. Furthermore, some scholars construct complex networks with countries as nodes and trade rivalries as edges, such as Long et al. [28] and Wang et al. [29].

The competitive relationship between enterprises is primarily defined the derivation of the concept of niche overlap [30], which states that competition exists between enterprises when they compete for limited market resources, human resources, and capital resources. Thus, firms' competitive relationships can be defined as follows: (a) Competitive relationships arise when firms have similar products, which follows Watts et al.'s [31] definition, namely, to take a dichotomous network model of component firms and products, and then convert it into a model of competitive network relationships between firms [32,33]. (b) The competitive relationship between firms is defined in terms of two dimensions: homogeneous products and the geographic location of firms. For example, Hou et al. [34] defined the competitive relationship between logistics firms based on two dimensions: the type of service and the geographical location of the logistics service provided by the logistics firms. Gao et al. [35] argued that a competitive relationship exists between the community of logistics enterprises in the same region or neighbouring regions with the same type of business operation; they provided a method for calculating the degree of market commonality of logistics enterprises in the same region and neighbouring regions. In addition, George [36] suggested that in the same competitive field, firm *i* will try to avoid competing with rival *j* whose market share is 50% higher. Zhu et al. [37] used this approach to model the network of competitive relationships in the property and casualty insurance industry.

Building material enterprises play a remarkable role as crucial entities within the construction supply chain. Conducting qualitative and quantitative analyses of the market-competition status of these enterprises is a vital prerequisite for optimising the resilience of the construction supply chain. However, compared with other types of enterprises, building material enterprises often face unique challenges due to the varying service radii of different materials, hampering the qualitative and quantitative study of their competitive relationships. To date, few scholars have embarked on research in this area. This paper aims to analyse the market-competition status of building material enterprises qualitatively and quantitatively. Drawing on previous research achievements in enterprise competition relationships and the application status of complex network theory, this paper focuses on building material enterprises, considering factors such as geographic location, service radius, and theoretical market size to explore the mechanisms and calculation methods for defining competitive relationships and intensity. Based on complex network theory and using enterprise transaction data as a foundation, this paper constructs a Boolean (unweighted and symmetric) competitive relationship network model, with enterprises as nodes and competition relationships as edges, as well as a weighted competitive relationship network (WCRN) model, with enterprises as nodes and competition intensity as edge weights. This approach achieves the objective of quantitative and qualitative analyses of the market competition status of building material enterprises. This paper offers new perspectives and methods for the study of competitive relationships amongst enterprises within the construction supply chain. Further, this paper adopts prefabricated component (PC) enterprises as the subject for empirical research. Using web-crawling techniques, this paper collects data on bid wins by building PC enterprises and their actual geographical distribution in the Beijing–Tianjin–Hebei region from 2016 to 2022. This paper constructs the Boolean competitive relationship network (BCRN) and the WCRN of PC enterprises in the Beijing–Tianjin–Hebei region for 2016–2020. This paper facilitates the qualitative and quantitative analyses of the market competition status of PC enterprises in the Beijing–Tianjin–Hebei region, thereby verifying the effectiveness of the model.

The key issues addressed in this paper include (a) investigating the mechanisms and calculation methods for defining the competitive relationships and intensity amongst building material enterprises and (b) quantifying the market competition pressure between building material enterprises, breaking through the limitations of previous purely qualitative research. The innovative aspects of this research are (a) constructing a dynamic

competition model for building material enterprises based on complex network theory and (b) fully considering the characteristics of construction enterprises when studying the construction mechanism of competitive relationship networks, making their service radius an important factor in defining competitive relationships.

2. Modelling

2.1. Competitive Relationships

Firstly, the geographical region where a firm is located decides the amount of resources it can compete for. In this paper, regarding the definition of the competitive relationship between enterprises in the nodes of the construction supply chain, the service radius is a very typical characteristic of the enterprise, and is determined by the size of the enterprise. Moreover, the enterprise's product supply capacity is largely dependent on the service radius, which has a strong spatial distribution characteristic. Therefore, the competitive relationship between node enterprises should firstly be expressed as whether the region where the service radius of the enterprise is located is cross. If the node enterprises have the same demand side or target customers within their respective service radii, then a competitive relationship exists amongst the enterprises.

Secondly, the bidding owner pays great attention to the overall scale strength of the bidding party in the bidding. They review the overall qualifications of the bidders, and different project sizes require that the qualifications of the bidders are not the same. Usually, the bidding enterprises involved in the same project are similar in size. When defining the competitive relationship in this paper solely through George's theory, the leading or monopolistic enterprises in the market have a large difference in market share with other enterprises. This kind of enterprise is shown as an isolated node in the network by defining the competitive relationship in this manner, and it is not conducive to the analysis of the overall competitive relationship in the market. Therefore, in this paper, based on George's theory, the theoretical market share is replaced with the theoretical market (the amount of supply required by all the demanders within the service radius) within the service radius and stipulates that firms do not compete with firms with more than 50% of their theoretical market share.

Figure 1 shows the specific process of defining competitive relationships.

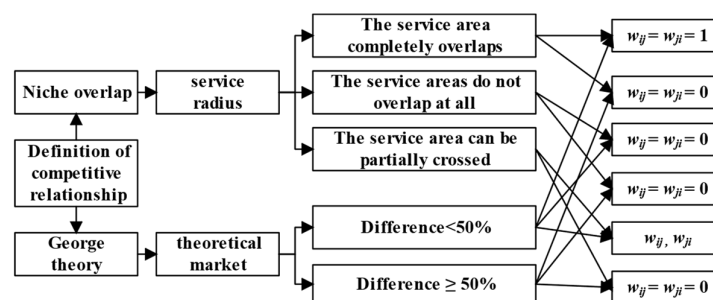


Figure 1. Specific process of defining competitive relationships.

(1) If the areas included in the service radii of building material enterprises i and j do not overlap, their customer goals are completely different, and they have no competitive relationship, that is, $w_{ij} = w_{ji} = 0$, where w_{ij} is the intensity of competition given by enterprise i to enterprise j , that is, the competitive pressure that enterprise j feels from enterprise i ; w_{ji} is the intensity of competition that enterprise j gives to enterprise i , that is, the competitive pressure that enterprise i feels from enterprise j .

(2) If the areas included in the service radius of building material enterprises i and j are completely coincident, their customer goals are exactly the same. Combined with George's theory, when the theoretical market of enterprises i and j are less than 50%, the competition intensity is 1, that is, $w_{ij} = w_{ji} = 1$. When the theoretical markets of enterprises

i and j are $\geq 50\%$, although enterprises i and j have the same target customers, they have no competitive relationship due to the large gap in the theoretical market, that is, $w_{ij} = w_{ji} = 0$.

(3) If the areas included in the service radius of the building material enterprises i and j intersect, then combined with George's theory, when the theoretical market of enterprises i and j are less than 50%, the competition intensities are w_{ij} and w_{ji} , respectively. When the theoretical markets of enterprises i and j are $\geq 50\%$, although they have the same target customers, they have no competitive relationship due to the large gap in the theoretical market, that is, $w_{ij} = w_{ji} = 0$.

2.2. Complex Network Modelling

2.2.1. Boolean Competitive Relationship Network Model

Taking an enterprise in the construction supply chain as a node, two enterprises are connected to form an edge when the ranges covered by their respective service radii intersect and the theoretical market difference is less than 50%. According to the above rules, a BCRN model is constructed. The set of BCRN is expressed as $G = (F, A)$, where F is the set of node firms in the construction supply chain, and A is the adjacency matrix of the competitive relationships between node firms in the construction supply chain.

2.2.2. Weighted Competitive Relationship Network Model

BCRN only considers whether a competitive relationship exists between the firms in the construction supply chain and how many competitors the firms face; it does not consider the intensity of competition in the market. Grasping the intensity of business competition amongst firms in the construction supply chain to develop a competitive strategy is even more relevant. In this paper, the intensity of the competitive relationship between firms at the nodes of the construction supply chain is measured by the theoretical market commonality, which is the degree to which firms i and j share the theoretical market. The competitive pressure between firms is quantified based on the concept of theoretical market commonality. Then, a WCRN model is constructed using competitive pressures as side weights. The theoretical market commonality is calculated as shown in Equation (1). The geospatial distance between firms in the construction supply chain is fully considered in determining the theoretical market commonality.

$$m_{ij} = \sum_{seti \cap setj} p_{ij} \quad (1)$$

where m_{ij} is the theoretical market commonality between firms i and j , $seti$ is the area covered by the service radius of enterprise i , $setj$ is the area covered by the service radius of enterprise j and p_{ij} is the demand at any demand point in the region where firms i and j intersect.

$$w_{ij} = m_{ij}/p_i, w_{ji} = m_{ij}/p_j \quad (2)$$

where p_i is the theoretical market for firm i , and p_j is the theoretical market for firm j . Figure 2 shows the detailed model construction.

In Figure 2, r_{ik} is the straight-line distance from enterprise i to all demand points k that it can supply, and r_{jk} is the straight-line distance from enterprise j to all demand points k that it can supply.

(a) i and j are any two enterprises, whose service radii are determined and denoted as R_i and R_j , respectively.

(b) According to R_i and R_j , the service areas of the i and j are determined, and the theoretical markets p_i and p_j within the service radius of i and j are calculated.

(c) The intersection state of the service areas of i and j are determined. If they do not intersect, then no competitive relationship exists between i and j ; otherwise, go to the next step.

(d) The market mutuality m_{ij} of enterprises i and j is calculated according to Equation (1).

(e) w_{ij} and w_{ji} are calculated according to Equation (2).

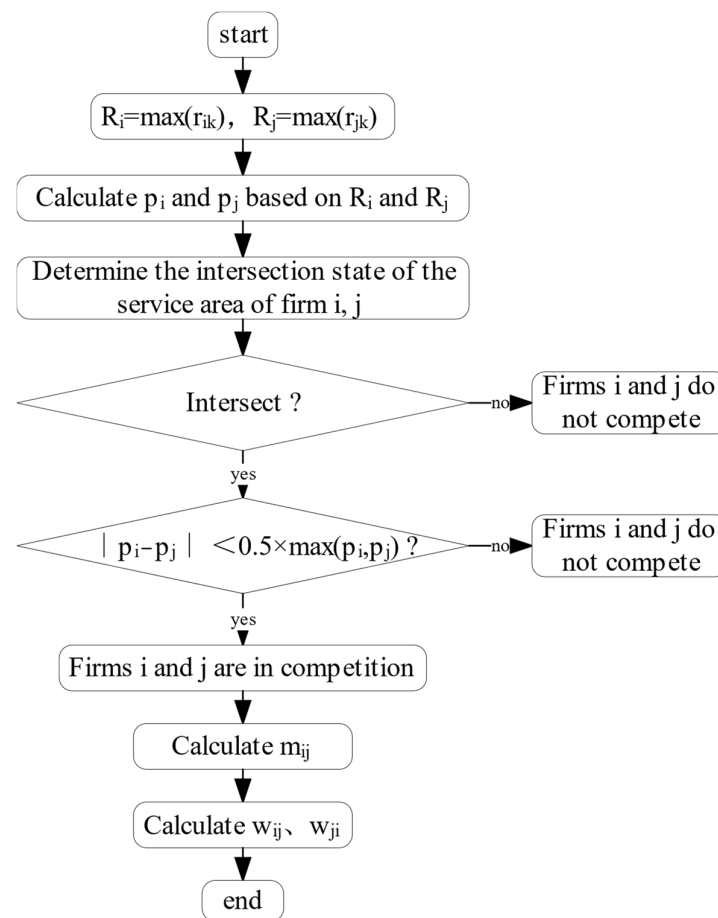


Figure 2. Model construction flowchart.

2.3. Comparison with Existing Research

Table 1 shows the comparison between the constructed model of this paper and the existing research results, and it can be found that the research of this paper opens up a new perspective in the study of the competitive relationship of construction enterprises, and at the same time, it enriches the application field of complex networks in the study of the competitive relationship of enterprises.

Table 1. The node degree of BCRN in 2016–2022.

Existing Research	Research Target	Analysis Methods	Factors in Competitive Analysis	Model
Xie [21]	logistics industry	quantitative	service area	WCRN
Gao [23]	logistics industry	quantitative	Enterprise size, business type	BCRN
Yang [25]	ceramic industry	quantitative	product category	BCRN
Long [28]	timber trade industry	quantitative	product source	BCRN, WCRN
Zhu [37]	Property insurance industry	quantitative	Business type, market share	WCRN
Afraz [38]	construction industry	qualitative	supply chain innovation	/
			Number of Bidding Companies, Number of Winning Projects	/
Wang [39]	construction industry	qualitative	Service radius, theoretical market, service area	BCRN, WCRN
This Paper	construction industry	quantitative		

3. Model Analysis

The main difference between the BCRN and WCRN to be constructed in this paper is that the former builds the network from the number of competitive relationships, whereas

the latter mainly establishes the network from the strength of competitive relationships. Thus, the following indicators are introduced to compare and analyse the topological indicators of the model.

3.1. Node Degree and Degree Distribution

Node degree (ND) is an important statistic for Boolean networks. ND is the number of neighbouring edges of a node, as shown in Equation (3).

$$k_i = \sum_{j \in N} a_{ij} \quad (3)$$

where k_i is the degree of node i , and a_{ij} is the matrix element of the adjacency matrix. When a relationship exists between nodes i and j , $a_{ij} = a_{ji} = 1$ and 0 otherwise.

In addition, degree distribution is one of the important indicators to describe the network structure. This property is often expressed in terms of the distribution function of the ND $P(k)$ or the cumulative degree distribution function $P(>k)$ [40]. $P(k)$ denotes the ratio of the number of nodes with ND k to the number of all nodes in the network. $P(>k)$ is the probability distribution of nodes with degree not less than k , as described in Equation (4).

$$P(>k) = \sum_{i=k}^{\infty} P(i) \quad (4)$$

According to the findings of Amaral et al. [41]: the ND distribution characteristics in many real networks belong to three types, namely, scale-free network, wide-scale network and single-scale network.

3.2. Node Strength

To describe the weighted network, two important concepts are introduced: edge weight and point weight. Edge weight w_{ij} refers to the connection weight of nodes i and j . Point weight represents the node strength (NS), and in an undirected network, the point weight denotes the sum of all edge weights of a node. NS is defined by Equation (5) [42].

$$s_i = \sum_j a_{ij} w_{ij} \quad (5)$$

Point weights in directed networks are accordingly split into out- and in-degree weights. The out-degree weight of a node is the sum of all edge powers from that point, representing the sum of competitive pressures brought by the firms at that node to the other firms, as defined by Equation (6).

$$s_i^{out} = \sum_j a_{ij} w_{ij} \quad (6)$$

The corresponding total weight is defined by Equation (7).

$$s_i = s_i^{out} + s_i^{in} \quad (7)$$

NS difference is the gap between the out-degree weight and the in-degree weight, which decides the competitive position of the node firm in the market, as defined by Equation (8).

$$s_i(\Delta) = s_i^{out} - s_i^{in} \quad (8)$$

If $s_i(\Delta) > 0$, node enterprise i brings competitive pressure to its neighbouring enterprises and has a competitive advantage. If $s_i(\Delta) \leq 0$, node enterprise i is mainly under the pressure of its neighbouring enterprises and does not have a competitive advantage.

3.3. Average Nearest-Neighbour Degree

ND only represents the number of adjacent edges to node i . However, even if some nodes have the same ND in the network structure, their positions in the network are dissimilar due to the different connectivity of adjacent edge nodes. Average nearest-neighbour degree (ANND) refers to the average degree of nodes adjacent to node i , which can measure how connected the neighbours of node i are in the network, as defined by Equation (9).

$$\text{annd}_i = \sum_{j \in v(i)} k_j / |v(i)| \quad (9)$$

where $v(i)$ is the set of all neighbour nodes of node i , and k_j is the degree of neighbour j .

The ANND of the network is the mean of the ANND of all nodes, as defined by Equation (10).

$$\text{ANND} = \sum_{i=1}^n \text{annd}_i / n \quad (10)$$

3.4. Average Nearest-Neighbour Strengths

By calculating the average of nearest-neighbour strengths (ANNS), the closeness of the connection between the neighbours of a node can be measured. Even if two nodes have the same ANND, their ANNS may be substantially different. The ANNS of node i is defined by Equation (11).

$$\text{anns}_i = \sum_{j \in v(i)} s_j / |v(i)| \quad (11)$$

The ANNS of the network is the mean of the ANNS of all nodes, as defined by Equation (12).

$$\text{ANNS} = \sum_{i=1}^n \text{anns}_i / n \quad (12)$$

3.5. Clustering Coefficient

Clustering coefficient (CC) indicates the clustering of network nodes and describes the proportion of neighbours of nodes in the network that are also neighbours of one another. The CC of node i is the ratio of the number of existing connected edges to the maximum possible number of connected edges amongst all its neighbours. The CC of node i is defined by Equation (13).

$$cc_i = 2l_i / k_i(k_i - 1) \quad (13)$$

where k_i is the degree of node i , l_i is the number of connected edges between the neighbours of node i and cc_i is the CC of node i .

The CC of the network is the mean of the CC of all nodes, as defined by Equation (14).

$$\text{CC} = \sum_{i=1}^n cc_i / n \quad (14)$$

3.6. Weighted Clustering Coefficient

If border weighted are considered, the weighted clustering coefficient (WCC) of node i is defined by Equation (15).

$$wcc_i = 2 \sum_{j,k \in n(i)} a_{jk} w_{jk} / k_i(k_i - 1) \quad (15)$$

where w_{ij} is the edge weight of nodes i and j , and s_i is the NS of node i .

The WCC of the network is the mean of the WCC of all nodes, as defined by Equation (16).

$$\text{WCC} = \sum_{i=1}^n wcc_i / n \quad (16)$$

3.7. Small World Quotient

This paper uses the ‘Small World Quotient (SWQ)’ proposed by Davis [43] to detect whether BCRN and WCRN have small-world characteristics. The calculation method is as follows:

$$SWQ = \frac{C}{L} \times \frac{L_{random}}{C_{random}} \quad (17)$$

where C is the average CC of BCRN or WCRN; L is the average path length of BCRN or WCRN; C_{random} and L_{random} are the average CC and average path length of random networks, respectively, which have the same number of nodes and average degree as BCRN and WCRN.

If SWQ is greater than 1, the network has ‘small world’ characteristics.

4. Empirical Research

4.1. Data Sources

PC is a type of building construction in which building components are prefabricated in a factory or manufacturing site and then assembled and installed on site. Traditional building construction methods usually require many manual operations and cumbersome construction processes on site, which is not only time consuming and labour intensive but also prone to quality problems. The emergence of PC has changed this situation. By standardising production in factories, PCs enable the precise control of processes and quality assurance. Therefore, building PCs have been widely used in the construction industry as a modern way of building construction. As early as 2016, the Chinese government started to promote the development of assembled buildings with the Beijing–Tianjin–Hebei region and other urban agglomerations as pilot areas, aiming to bring the proportion of assembled buildings in new construction to 30% in about 10 years. The national 14th Five-Year Plan further proposed vigorously developing prefabricated buildings. Until now, the assembly building market in the Beijing–Tianjin–Hebei region has a certain scale.

The research data for this paper were sourced from the China Construction Market Supervision Public Service Platform [44], which is an official data website established by the Ministry of Housing and Urban-Rural Development of the People’s Republic of China. It encompasses databases of enterprises, personnel, and projects, as well as a database for enterprise integrity within the construction field across the whole country. The project database includes information such as project names, project addresses, and project bidding information. The data collection process is as follows:

(a) Source Data Acquisition: We used “prefabricated components” as the search term, with the time range set from 2016 to 2022 and the geographical scope limited to the Beijing–Tianjin–Hebei region. Through web crawling, we obtained bid-winning information for a total of 8964 projects. Each project’s bid-winning entry includes information such as the project name, project address, tendering owner, bid-winning date, bid-winning enterprise, and bid-winning amount.

(b) Acquisition of Latitude and Longitude Coordinates: We utilized the Python programming language to call the Google Maps API, obtaining the latitude and longitude coordinates for each project address and bid-winning enterprise.

(c) Data Input: We divided all the bid-winning information from 2016 to 2022 into seven parts by year and input them into the model constructed in Section 2. The data input into the model include project address, project latitude and longitude coordinates, name of the bid-winning enterprise, latitude and longitude coordinates of the bid-winning enterprise, and the bid-winning amount of the project.

4.2. BCRN and WCRN of PC Enterprise

The computational results of the model in this paper are output in the form of matrices, yielding a total of 14 matrices: the Boolean competitive relationship matrix and the weighted competitive relationship matrix for each year from 2016 to 2022. The matrices for the same year have the same order, and the order of the matrices represents the number of enterprises.

Table 2 lists the order of matrices for each year, indicating that within the network of competitive relationships among PC component enterprises in the Beijing–Tianjin–Hebei region, there were 12 enterprises in 2016, 37 enterprises in 2017, 54 enterprises in 2018, 397 enterprises in 2019, 568 enterprises in 2020, 323 enterprises in 2021, and 168 enterprises in 2022.

Table 2. Order of the matrix in 2016–2022.

Year	2016	2017	2018	2019	2020	2021	2022
order of the matrix	12	37	54	397	568	323	168

Figure 3 shows a part of the Boolean competitive relationship matrix for the year 2020, where letters a–g represent different enterprises. An element of 1 in the matrix indicates the existence of a competitive relationship, while an element of 0 indicates the absence of such a relationship. Figure 4 presents a part of the weighted competitive relationship matrix for 2020. The elements in the matrix indicate the intensity of competition; for example, $w_{be} = 0.6$ indicates the competitive pressure enterprise b places on enterprise e, while $w_{eb} = 0.3$ indicates the competitive pressure enterprise e places on enterprise b.

	a	b	c	d	e	f	g
a	0	0	1	0	0	0	1
b	0	0	0	0	1	0	0
c	1	0	0	1	0	1	1
d	0	0	1	0	0	0	0
e	0	1	0	0	0	0	1
f	0	0	1	0	0	0	0
g	1	0	1	0	1	0	0

Figure 3. Partial Boolean Competitive Relationship Matrix of 2020.

	a	b	c	d	e	f	g
a	0	0	0.4	0	0	0	0.8
b	0	0	0	0	0.6	0	0
c	0.2	0	0	0.3	0	0.6	0.5
d	0	0	0.1	0	0	0	0
e	0	0.3	0	0	0	0	0.8
f	0	0	0.7	0	0	0	0
g	0.7	0	0.2	0	0.5	0	0

Figure 4. Partial Weighted Competitive Relationship Matrix of 2020.

4.2.1. BCRN of PC Enterprise

We use the Boolean competitive relationship matrix for each year as the source data and combine it with the Gephi 0.10.1 software to draw the BCRN graph. Figure 5 shows the BCRN graph for each year from 2016–2022, the nodes in the graph indicate different

enterprises, the grey connecting lines indicate the competitive relationships existing between enterprises, the more competitive relationships enterprises have, the larger their node degree is node, and the colour is closer to red.

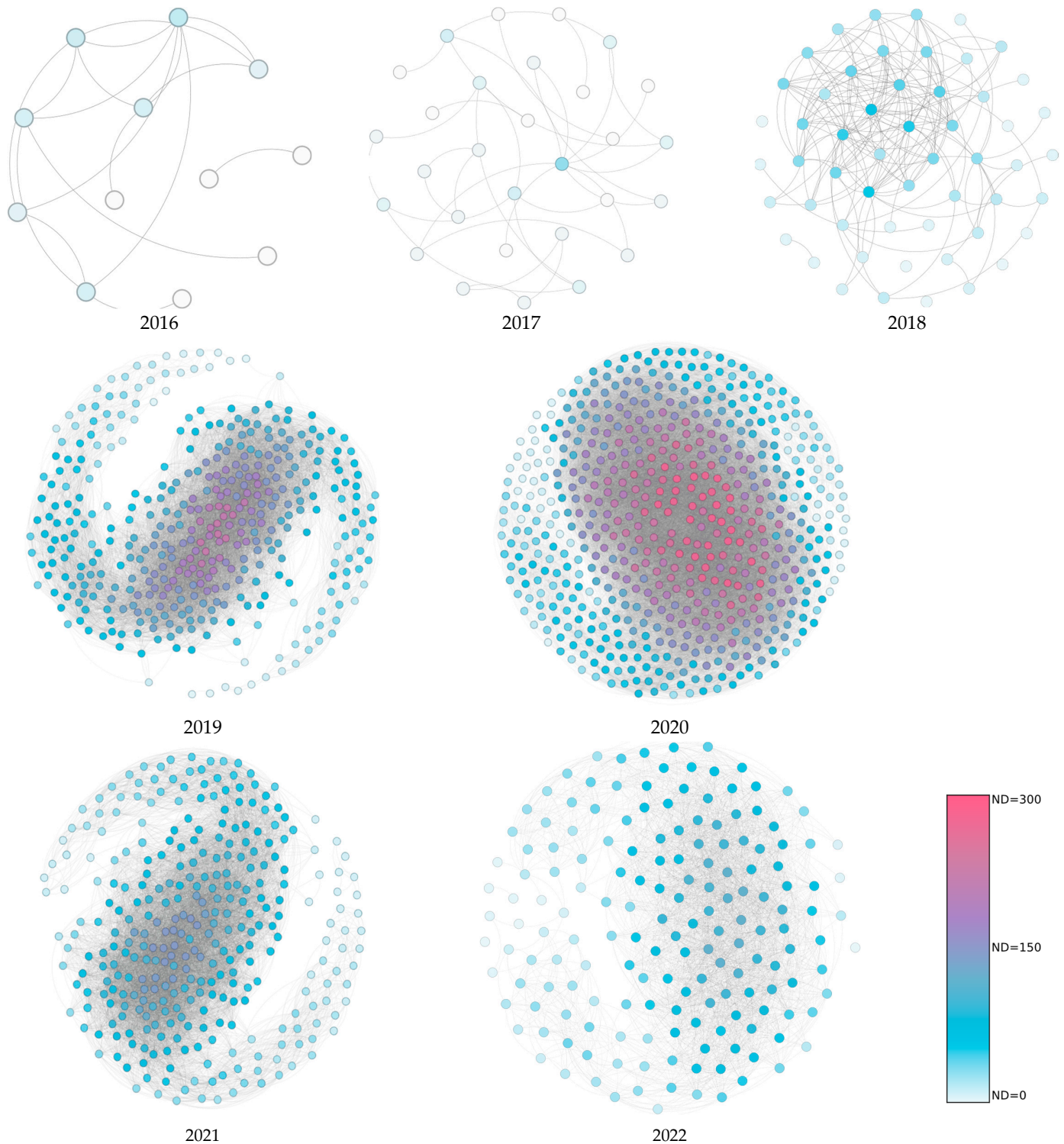


Figure 5. BCRN in 2016–2022.

4.2.2. WCRN of PC Enterprise

Similarly, we use the weighted competitive relationship matrix of each year as the source data and combine it with the Gephi software to draw the WCRN graph, and Figure 6

shows the WCRN graph for each year from 2016 to 2022. The nodes in the graph represent different firms, and the colour of the line connecting the nodes indicates the intensity of competition between firms, and the greater the intensity of competition between firms, the closer the colour of the line is to red.

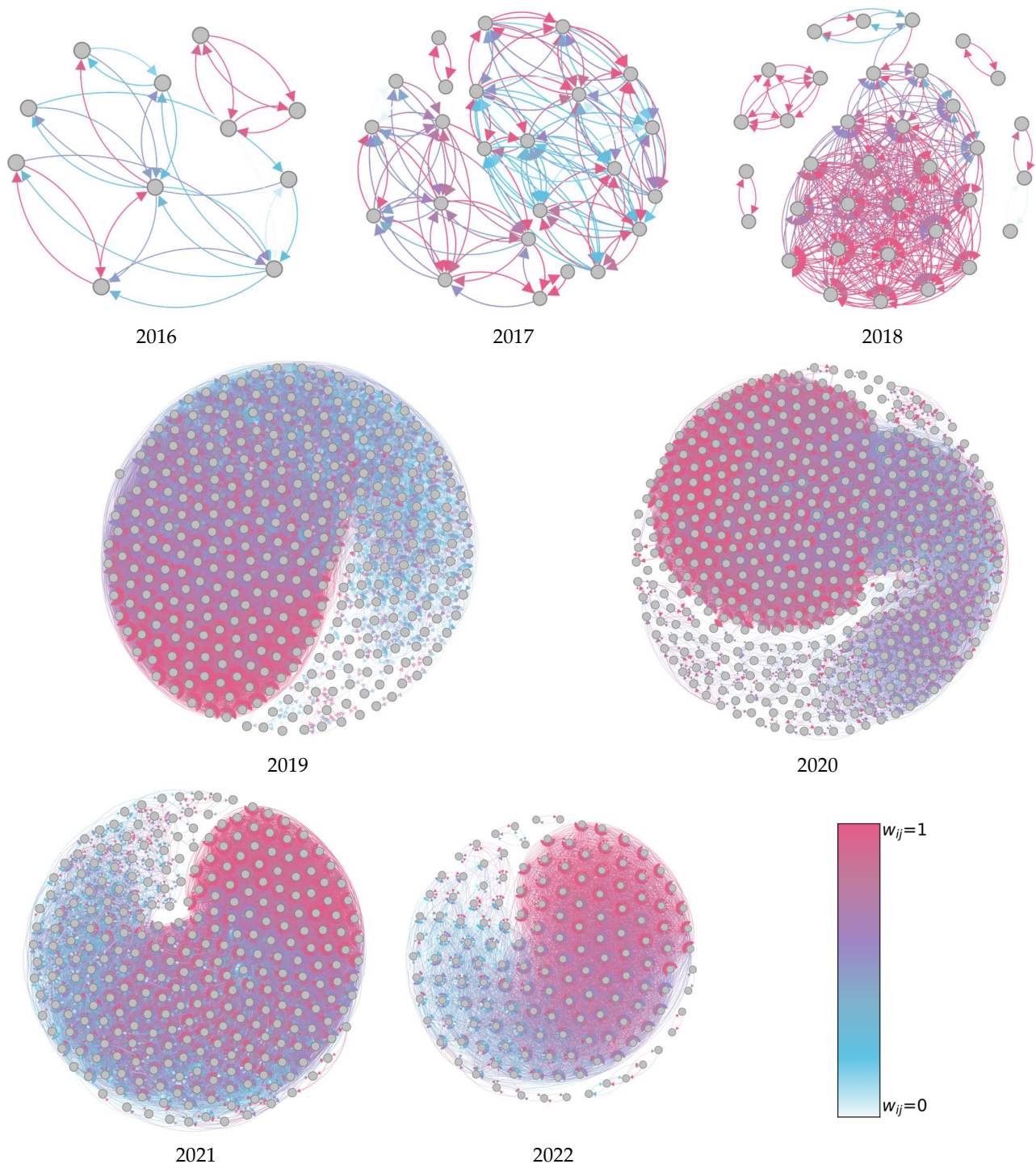


Figure 6. WCRN in 2016–2022.

4.3. Characteristics

4.3.1. Connectivity

1. Degree

In the BCRN model of construction-PC firms, the ND represents how many competitors each construction-PC firm has in the study area. Table 1 presents the average degree, maximum value and standard deviation of nodes in the BCRN of PC construction enterprises in the Beijing–Tianjin–Hebei region from 2016 to 2022. The maximum average of ND in BCRN is 142 in 2020, the minimum is 1.8 in 2016 and the average is 402.2. The remaining parameters such as mean, maximum, and standard deviation of ND for each year are shown in Table 3. The average ND of the Boolean competitive network model of construction-PC company *i* in the study area during 2016–2022 continued to increase until 2020 and then began to decrease; the degree of dispersion of the distribution of the ND in each year is consistent with the trend of the average ND of the network.

Table 3. Node degree of BCRN in 2016–2022.

Year	Average	Maximum	Standard Deviation
2016	1.8	5	1.6
2017	3.7	10	3.3
2018	6.5	20	7.5
2019	105.5	202	73.6
2020	142	294	110.1
2021	73.2	134	46.3
2022	42.6	84	28.4

The distribution of node cumulative degree is the same in each year, taking the cumulative degree distribution of the enterprise competition network in 2020 as an example (Figure 7). As the ND *k* increases, the cumulative degree distribution in 2020 exhibits a rapidly decaying tail, which belongs to a single-scale network.

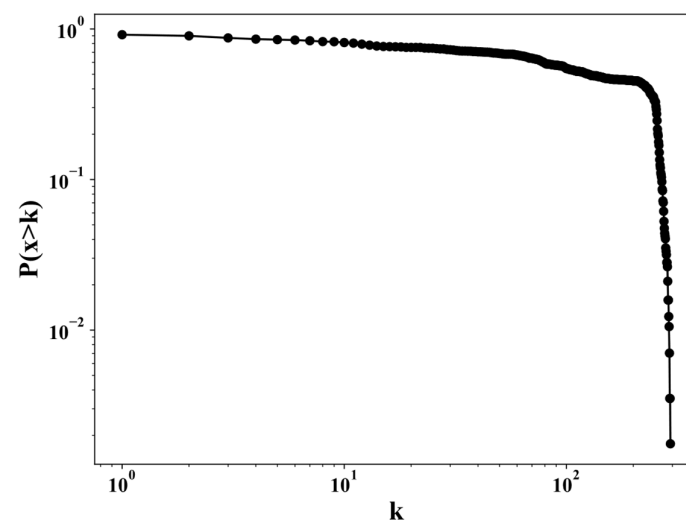


Figure 7. Cumulative degree distribution in 2020.

2. Node strength

The WCRN is constructed based on the theoretical market commonality, and the NS portrays the competitive intensity of construction-PC firms. Table 4 shows the average, maximum and standard deviation of NS in the WCRN of PC construction enterprises in the Beijing–Tianjin–Hebei region from 2016 to 2022. The maximum NS in 2016 to 2022 is 479.62 in 2020, and the minimum is 6.01 in 2016. The average value of each year increased

from 2016 to 2020, reached the maximum value every year, then began to decrease. The increase and decrease trend is consistent with the ND.

Table 4. Node strength of WCRN in 2016–2022.

Year	Average	Maximum	Standard Deviation
2016	2.27	6.01	1.96
2017	4.57	12.23	4.00
2018	11.1	33.44	13.17
2019	145.36	327.76	115.23
2020	226.97	479.62	200.96
2021	100.48	205.94	70.97
2022	62.20	140.14	49.02

Similarly, the cumulative distribution of nodal entry and exit intensities is generally consistent across years. Taking 2020 as an example (Figures 8 and 9), the cumulative in-degree distribution and the cumulative out-degree distribution exhibit rapidly decaying tails, consistent with single-scalar properties.

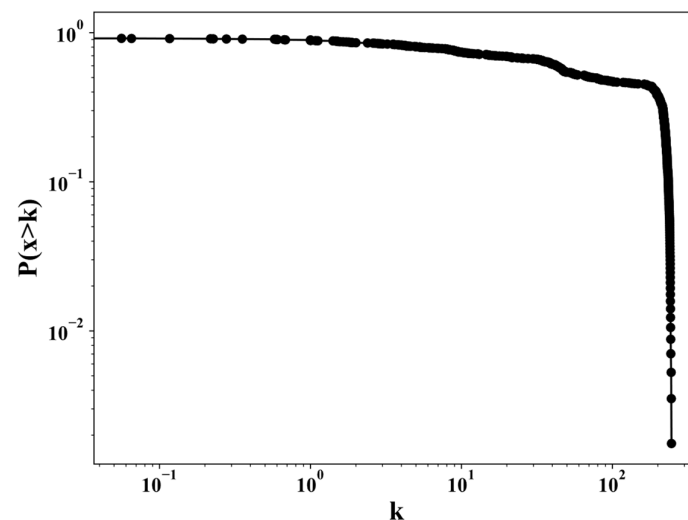


Figure 8. Cumulative out-degree distribution in 2020.

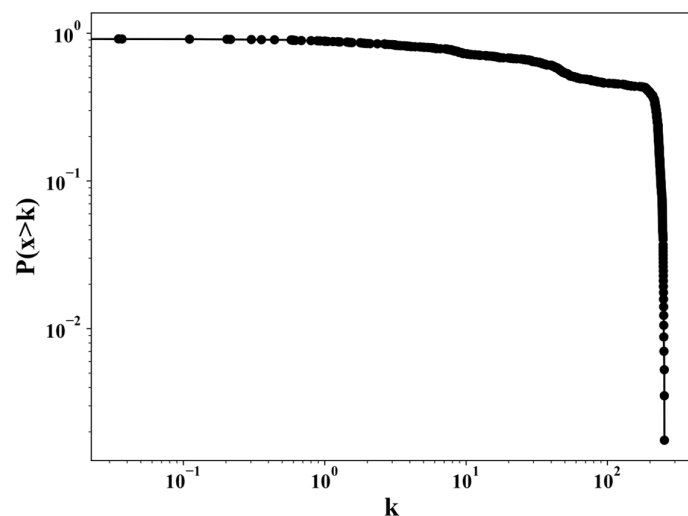


Figure 9. Cumulative in-degree distribution in 2020.

Figure 10 shows the scatter diagram of the difference in corporate strength in each year. The maximum value of competitive pressure that companies export to the outside world,

namely, 65.51, was observed in 2020, and companies were affected by the outside world. The maximum value of competitive pressure is 57, but the overall distribution shows that the distribution of competitive pressure in each year is balanced.

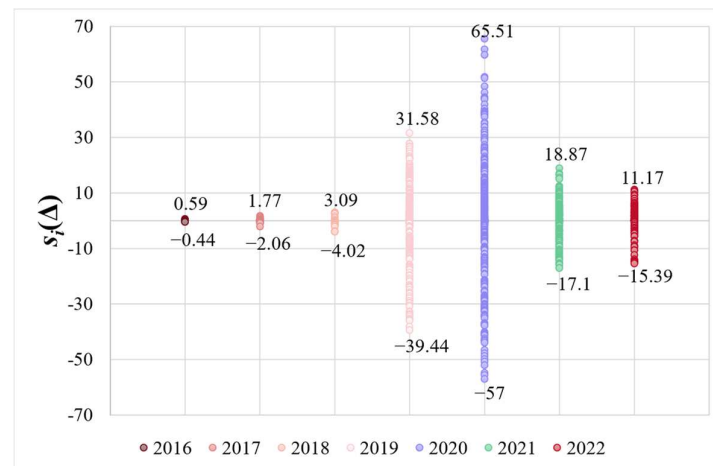


Figure 10. Scatter diagram of enterprise degree difference in 2016–2022.

4.3.2. Assortativity

Assortativity refers to the competition amongst enterprises with large NDs. On the contrary, disassortativity refers to enterprises with large NDs competing only with enterprises with small NDs. To study whether the competition network of construction-PC enterprises has assortativity, firstly, the average degree of neighbours of nodes is studied from the perspective of Boolean competition network, and the correlation between this index and ND is analysed.

Table 5 presents the ANND of the BCRN of PC construction enterprises in the Beijing–Tianjin–Hebei region from 2016 to 2022. Table 6 shows the correlation coefficients between the ANND and ND for the BCRN in each year. ANND rose from 2.1 in 2016 to 147 in 2020 and then dropped to 44.5 in 2022. Except for the ND–ANND correlation coefficient in 2016, namely, 0.77, which is lower than 0.9, the correlation coefficients of ND–ANND for the rest of the years are greater than 0.9, and the ND and the average degree of neighbouring points correlation coefficients are large and stable.

Table 5. ANND in 2016–2022.

Year	2016	2017	2018	2019	2020	2021	2022
ANND	2.1	3.9	6.8	110.4	147	76.6	44.5

Table 6. ND–ANND correlation coefficient in 2016–2022.

Year	2016	2017	2018	2019	2020	2021	2022
ND–ANND	0.77	0.94	0.96	0.96	0.98	0.96	0.96

Figure 11 also shows that ND and ANND are linearly distributed, indicating that the competition amongst building PC enterprises in the network model occurs amongst enterprises with similar NDs. The network belongs to assortative network and has strong stability.

Table 7 presents the ANNS of the WCRN of PC enterprises in the Beijing–Tianjin–Hebei region from 2016 to 2022. Table 8 shows the correlation coefficients between the ANNS and the NS for the WCRN in each year. Analysis in terms of a weighted network of competitive relationships leads to the same conclusions as the Boolean competitive network. The change in ANNS of construction-PC companies is similar to that of ANND,

which increased from 2016 to 2020 and then began to decrease. The correlation coefficients of NS-ANNS are in the range of 0.82–0.97 during the study period. From the perspective of the WCRN, the results of the competitive relationship network assortativity test of the construction-PC firms are also very satisfactory, and the network has strong assortativity, which can also be illustrated by combining with the NS-ANNS scatter distribution of 2019–2022 in Figure 12.

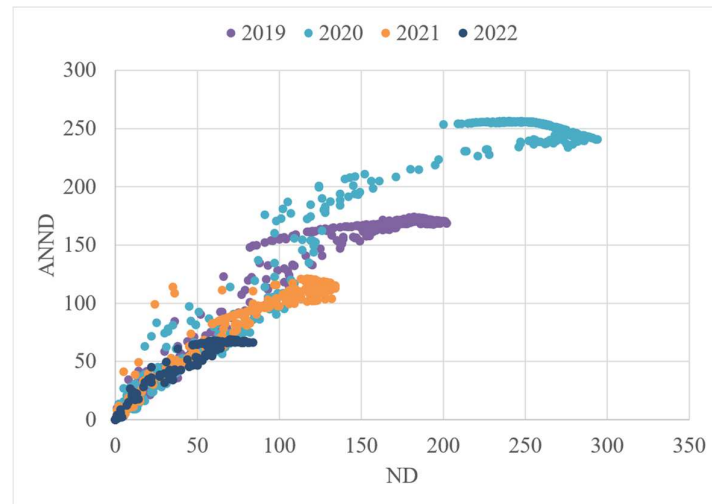


Figure 11. ND-ANND scatter distribution map in 2019–2022.

Table 7. ANNS in 2016–2022.

Year	2016	2017	2018	2019	2020	2021	2022
ANNS	2.6	4.8	11.6	151.8	234.9	104.8	64.9

Table 8. NS-ANNS correlation coefficient in 2016–2022.

Year	2016	2017	2018	2019	2020	2021	2022
NS-ANNS	0.82	0.91	0.96	0.96	0.98	0.94	0.96

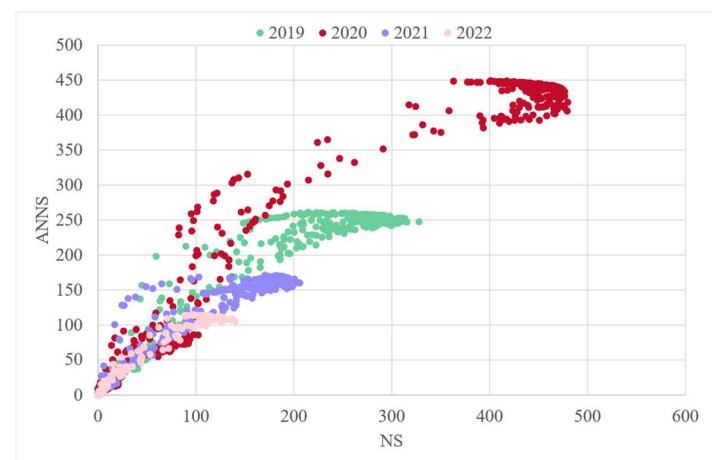


Figure 12. NS-ANNS scatter distribution map in 2019–2022.

4.3.3. Clustering

The CC of node i is the ratio of the number of existing connected edges to the maximum possible number of connected edges amongst all its neighbours in the network. which

represents the completeness of the network. Analysing the relationship between the CC and the ND reveals the general situation of the competitive relationship between the enterprise group with strong clustering and the enterprise with large ND. Table 9 lists the CC of the BCRN and the WCC of the WCRN of PC enterprises in the Beijing–Tianjin–Hebei region from 2016 to 2022. The network CC is small in 2016 to 2018, all less than 0.5, indicating the network does not have a strong clustering during this period, and the CC is between 0.65 and 0.71 from 2019 to 2022, indicating the network during this period has a certain degree of agglomeration. In addition, the weighted CC of each year is larger than the Boolean CC, indicating the weighted network has higher clustering.

Table 9. CC of BCRN and WCC of WCRN in 2016–2022.

Year	2016	2017	2018	2019	2020	2021	2022
CC	0.41	0.46	0.46	0.66	0.71	0.65	0.64
WCC	0.6	0.57	0.77	0.86	0.96	0.9	0.92

Table 10 shows the correlation coefficients of the CC–ND in BCRN and WCC–NS in WCRN for PC enterprises in the Beijing–Tianjin–Hebei region from 2016 to 2022. During 2016–2022, the correlation coefficients between Boolean network CC and ND, weighted network CC and NS are all positive, the minimum value is 0.40 and the maximum value reaches 0.85. This outcome shows that most construction-PC enterprises have large ND (strength) values, and their clustering is large. For enterprises with large ND (strength) values, the competition between adjacent enterprises is also strong.

Table 10. Correlation coefficients of CC–ND in BCRN and WCC–NS in WCRN from 2016 to 2022.

Year	2016	2017	2018	2019	2020	2021	2022
CC–ND	0.40	0.84	0.76	0.68	0.68	0.60	0.64
WCC–NS	0.59	0.81	0.80	0.81	0.85	0.63	0.76

4.3.4. Small World

The SWQ of each year is calculated from Equation (17), as shown in Table 11.

Table 11. SWQ of BCRN and WCRN in 2016–2022.

Year	2016	2017	2018	2019	2020	2021	2022
BCRN	0.54	0.31	0.46	1.52	1.37	1.18	1.10
WCRN	0.37	0.25	0.28	1.16	1.01	0.86	0.77

The results show that whether for BCRN or WCRN, the SWQ in 2016–2018 is less than 1, which does not have the small-world characteristic, and the SWQ in 2019–2020 is greater than 1, indicating that the competitive relationship network during the period has the small-world characteristic. In 2021–2022, the SWQ of BCRN is greater than 1, but the SWQ of WCRN is less than 1, indicating that when only the number of competitions is considered but not the intensity of competition, the competitive relationship network during the period has small-world characteristics.

5. Economics Explanation

Changes in the topological indicators of the BCRN network can illustrate the evolving characteristics of the competitive relationships of construction-PC firms. From 2016 to 2022, the average ND and its standard deviation of the construction-PC firms in the BCRN became larger from 2016 and then decreased from 2020, suggesting more competitors and greater competition amongst the construction-PC firms, which intensified and peaked

in 2020 mainly due to the national policy push. The indicator started to decrease after 2020 because of COVID-19 at the end of 2019, which led to a downturn in the market for construction-PC in the study area and even in the country. Moreover, many companies faced closure because they had not had any order for a long time, and this is why the overall volumes of network modelling for 2021 and 2022 were much smaller than that for 2020. The single-scale characteristic of the cumulative ND distribution shows that when only the number of competitions is considered, the competition pressure heterogeneity level faced by firms in the competition network is high.

WCRN's NS analysis shows that the construction-PC market in the study area has always maintained a high level of competition even under the influence of COVID-19 when many companies closed and exited the market. However, with COVID-19, a downturn in the overall construction industry market was noted. For the existing companies, the competition did not decrease much. This outcome can also be seen from the scatter plot of enterprise intensity difference. Although the overall volume became smaller after the epidemic, the maximum-pressure output value and the maximum-pressure input value of each node company has a small difference, and the intensity of competition in the market is still high. Similarly, the cumulative distribution of node access intensity conforms to the single-scale feature, indicating that considering the intensity of competition, the level of heterogeneity of competitive pressure faced by firms in a competitive network is high.

The study of network assortativity reveals the competition network of building PC enterprises in the study area has a strong assortment. Amongst enterprises, competition is only formed when the ND (NS) is not much different, and situations where an enterprise with a large ND (NS) competes with an enterprise with a small ND (NS) are rare. This situation is mainly determined by the characteristics of the bidding on industrial projects. The scales of bidding enterprises for the same project are similar, and their ND (NS) in the network are also similar so that the competition network of construction-PC enterprises has a strong assortativity.

The results of aggregation analysis show that nodes with large ND (NS) values have a stronger ability to form reverse groups, which means their opponents have a higher probability of being competitors mainly because an enterprise with a large ND (NS) has a larger service radius and enterprise scale. Once they compete with other enterprises, enterprises have similar service areas and enterprise scales. Conversely, when some enterprises have similar enterprise scales and have large service radii, the key factor determining whether they can form competition is the location of the enterprises. Elements such as enterprise address, service radius, and enterprise size are key factors influencing the structure of the competitive relationship network of architectural PC firms.

The analysis results of the small-world characteristics of the network show that with the development of the construction-PC enterprise market, the competitive relationship network of construction-PC firms will begin to have small-world characteristics after 2019, and the market competition will be very fierce. However, in 2021 and 2022, when only the number of competitive relationships is considered, the competitive relationship network has the small-world characteristics, and the entire market is very competitive. but considering the intensity of competition, the network does not have the small-world characteristics, and the actual competition in the entire market is no longer fierce. However, as the industry slowly recovers, its competition intensity should gradually become stronger, so that the network has the small-world characteristics. The overall development trend shows that the competitive relationship network in the construction-PC enterprise market is developing towards a small-world network.

6. Conclusions

This paper, taking the building-materials enterprise as the research object, considers the geographical location, service radius, theoretical market size, and other factors of the enterprise to explore the mechanisms and calculation methods for defining competitive relationships and intensity. Based on complex network theory and using enterprise trans-

action data as a foundation, this paper constructs a BCRN model and WCRN model. The empirical study was conducted with the winning records of PC component enterprises in Beijing–Tianjin–Hebei region from 2016 to 2022 as the source data, and the results of empirical analyses are as follows:

(a) The competitive relationship network of architectural PC enterprises in the Beijing–Tianjin–Hebei region is characterised by the development of a network towards small-world characteristics, but due to the large effect of COVID-19 on the market, it has not yet recovered to the level of competition in the market before the epidemic.

(b) The competition network of construction-PC enterprises in the Beijing–Tianjin–Hebei region has a strong homogeneous nature. No situation exists where enterprises with large NDs (strength) continue to compete with companies with small NDs (intensity). The entire competitive market has strong stability.

(c) The cumulative degree (strength) distribution function curves of the competitive relationship network of construction-PC enterprises all show a rapidly decaying tail, indicating the heterogeneity level of competitive pressure faced by enterprises in the network is high, but no enterprise possesses a particularly highly competitive pressure.

The results of empirical research fully verify the feasibility and effectiveness of the model constructed in this paper. The research in this paper opens up a new perspective for the study of the competitive relationship of construction enterprises, and enriches the application field of complex networks in the study of the competitive relationship of enterprises. In addition, this paper realises the qualitative and quantitative analysis of the competitive relationship of the market of building-materials enterprises, which provides methodological guidance for the promotion of the sustainable market development of the main body of the supply side of the construction supply chain, and this paper has high theoretical significance and practical significance. There are some limitations in this paper, firstly, the empirical analyses in this paper are carried out in a specific region, and the results may be affected by geographical factors, and secondly, the smaller amount of data reduces the accuracy of the enterprise radius in the model calculation. Despite these limitations of this paper, this study still provides valuable insights into the quantitative study of the current state of competition in the market of construction enterprises, and lays the foundation for subsequent research on the identification of key nodes and network optimisation of the competitive relationship network of construction enterprises.

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