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Research on the Measurement and Characteristics of Virtual Agglomeration Based on Social Network Analysis: Evidence from 29 Manufacturing Industries in China

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Abstract: (1) Background: Virtual agglomeration reshapes the organizational form and drives the sustainable development of the manufacturing industry. How to measure the virtual agglomeration level of the manufacturing industry is an important and difficult problem for current research. (2) Methods: In this study, we constructed a social network for the virtual agglomeration of the manufacturing industry, with each industry representing a node in the network. We also measured the virtual agglomeration level of the overall manufacturing industry using the network edge number and network density indicators in the social network analysis method. Each sub-industry virtual agglomeration level was measured using the point centrality index. Furthermore, the virtual agglomeration characteristics of the manufacturing industry were examined through cluster analysis and core–periphery analysis. The data sources include the supply chain statistics and virtual agglomeration text data of manufacturing enterprises. The virtual agglomeration text data were obtained with the help of Python crawler technology. Two types of data were matched, and the virtual agglomeration data of 29 manufacturing industries in China from 2012 to 2022 was obtained. (3) Results: The virtual agglomeration level of the overall manufacturing industry is constantly improving, but there are large differences among different industries. Moreover, the virtual agglomeration of the manufacturing industry has the characteristics of both specialization and diversification. The virtual agglomeration social network of the manufacturing industry is experiencing an evolution process from a "core–periphery" structure to a "core–semi-periphery–periphery" structure. (4) Conclusions: This study provides a theoretical basis and practical reference for improving the virtual agglomeration level of the manufacturing industry.

Keywords: virtual agglomeration of the manufacturing industry; social network analysis; text analytics; cluster analysis; core–periphery analysis

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1. Introduction

In the era of the digital economy, virtual agglomeration phenomena such as online education, Internet medical care, and online shopping are widespread. COVID-19 has accelerated virtual agglomeration [1]. People have realized the importance of virtual agglomeration due to COVID-19. When face-to-face geographic agglomeration is difficult to achieve, virtual agglomeration becomes an important way to support people's normal lives and work. Supply and demand subjects from the same or different geographical spaces gather on Internet platforms, thus realizing the transition of information exchange carriers from a geographical space to a virtual space. In addition to the virtual agglomeration forms that can be seen everywhere in life, digital technology subverts the channels through which manufacturing enterprises communicate and cooperate. Manufacturing enterprises break through geographical boundaries and carry out information exchange and cooperation

with relevant subjects on the industrial Internet platform, accelerating the transformation of manufacturing from geographical agglomeration to virtual agglomeration [2]. In particular, during the worst period of COVID-19, the scarcity of medical supplies forced the manufacturing industry to both share manufacturing resources through virtual agglomeration and improve the efficiency of resource allocation. The virtual agglomeration of the manufacturing industry has become an important means of support to withstand economic uncertainty.

Virtual agglomeration reduces the dependence of enterprises on geographical spaces and accelerates the development of networks without geographical boundaries [3,4]. On the one hand, the virtual agglomeration of manufacturing amplifies the positive externalities of geographic agglomeration, realizes real-time and zero-cost enterprise information exchange among different regions, promotes the integration and sharing of manufacturing resources across various regions and industries, and reduces information asymmetry. According to Metcalfe's law, the virtual agglomeration of manufacturing acquires a large amount of demand information through the industrial Internet platform, thereby accelerating the formation of enterprise economies of scale. The personalized and diversified demand promotes the formation of enterprise-scope economies [5,6]. On the other hand, the industrial Internet platform does not limit the number of agglomeration subjects, thus avoiding negative effects, such as rising agglomeration costs and environmental pollution caused by too many subjects in geographic agglomeration [7,8]. In addition, virtual agglomeration among manufacturing enterprises with geographical distances increases the transportation distance of offline logistics services. However, the deep integration of digital technology in the manufacturing and logistics industries enhances real-time interaction [9]. Logistics supply and demand information is interconnected with supply and demand subjects in geographic space through the industrial Internet platform, which reduces the response time of logistics information, thereby reducing the logistics cost of the virtual agglomeration of enterprises.

Compared with geographic agglomeration, the virtual agglomeration of manufacturing has many advantages. Based on this context, in this study, we propose three research questions. How does the manufacturing industry carry out virtual agglomeration? How can we measure the virtual agglomeration level of the manufacturing industry? What are the virtual agglomeration characteristics of the manufacturing industry? These questions have not been answered in the existing literature. As a new organizational form in the era of the digital economy, only by clarifying the above problems can we more rapidly improve the virtual agglomeration level of the manufacturing industry and achieve the goal of becoming a manufacturing power. In addition, as China is the country with the most complete manufacturing industry in the world, China is chosen as the research object of virtual agglomeration in the manufacturing industry, this helps us to define the current situation of virtual agglomeration in different manufacturing industries and provide differentiated suggestions for improving the level of virtual agglomeration in each industry.

There are three main branches in the literature closely related to this study. The first branch involves defining virtual agglomeration. Virtual agglomeration originates from the concept of cyberspace proposed by Wilson [10]. The interconnection of communication devices in different geographical spaces changes the communication carrier of enterprises from a geographical space to a virtual space. This change provides the conditions for a transformation from geographical agglomeration to virtual agglomeration. In 1997, a network research group composed of seven universities proposed the concept of virtual agglomeration, proposing that the process of enterprises from different industries forming a collective in the virtual space is called virtual agglomeration, with the members of the collective being able to share market opportunities [11]. Sumita et al. [12] define virtual agglomeration using two dimensions: decentralization and technology dependence. They believe that virtual agglomeration refers to the organizational form of subjects scattered in different geographical spaces that rely on similar technologies for information exchange. Zhang et al. [13] define virtual agglomeration from the perspective of the foundation

and function of virtual agglomeration, arguing that virtual agglomeration is based on the domain of integrated digital technology, guided by the optimization of resource allocation, and the logic of enterprise behavior changes from "self-interest" to "altruism based on self-interest", thus empowering each other to construct a value network form with blurred boundaries. Some scholars propose multiple concepts such as virtual industrial clusters, electronic clusters, and virtual work, all of which enrich and extend the definition of virtual agglomeration [14,15]. It can be seen that extensive research has been carried out in the existing literature on the definition of virtual agglomeration.

The second branch involves measuring the level of virtual agglomeration. Yang et al. [16] argue that regional digital economy indices can measure the level of virtual agglomeration. They constructed a digital economy index system using three dimensions—information development, Internet development, and digital transaction development—which was used to measure the level of regional virtual agglomeration. Tian and Zhang [17] construct an index system of virtual agglomeration using four dimensions: a geographic network, a pure network, talent innovation, and external resources. However, the research perspectives of both studies are grounded in geographical space. Ning et al. [18] use both social network analysis to construct an enterprise R&D cooperation network and the centrality of the cooperative network to characterize the virtual agglomeration level of enterprises. However, the use of R&D cooperation data alone does not indicate virtual characteristics. Ren and Liang [19] consider membership in Alibaba China Integrity as the criterion for determining whether a company achieves virtual agglomeration. They then multiply the virtual variables to measure virtual agglomeration using the supply chain data of the enterprise. In the existing literature on the measurement level of the virtual agglomeration of manufacturing, only Ren and Liang [19] consider virtualization characteristics; however, the indicator for measuring virtual agglomeration is relatively singular.

The third branch involves analyzing the characteristics of the virtual agglomeration of manufacturing. Kawa and Ratajczak-Mrozek [20] point out that virtual agglomeration subjects exhibit digital proximity characteristics. Lin and Kloet [21] highlight that virtual agglomeration platforms are open and inclusive. Wasko et al. [22] propose that virtual agglomeration has cross-spatial characteristics. Enterprises can collaborate on a larger scale, enabling remote, low-cost collaborative production and trading. Soete [23] suggests that virtual agglomeration transforms the traditional mode of production and distribution activities, forming a complex system composed of multiple network modules. These characteristics are mainly based on theoretical analysis, which is an overall explanation of the characteristics of virtual agglomeration. However, they lack discussions on the factual characteristics of the current development of virtual agglomeration. Tian and Zhang [17] analyze the spatial distribution characteristics of virtual agglomeration in various provinces, municipalities, and autonomous regions in China from a regional perspective. They conclude that virtual agglomeration shows the spatial distribution characteristics of "high in the east and low in the west" and "coastal is better than inland". Ren and Liang [19] divide manufacturing enterprises into two categories—high-tech manufacturing enterprises and non-high-tech manufacturing enterprises—based on the perspective of enterprises and conclude that the virtual agglomeration level of non-high-tech manufacturing enterprises is higher than that of high-tech manufacturing enterprises. Tian and Zhang [17] as well as Ren and Liang [19], further analyze the current virtual agglomeration characteristics of regions and firms on the basis of measuring the virtual agglomeration level of regions and firms, which is rich literature that summarizes the characteristics from a theoretical level.

Based on the existing literature, we can see that the research on virtual agglomeration in the context of the digital economy is gradually becoming more enriched. However, there are still shortcomings in the following three aspects. Firstly, the existing literature defines the perspective of virtual agglomeration from a relatively singular and scattered perspective. Some scholars choose the characteristic perspective of virtual agglomeration subjects. Some scholars choose the perspective of change in virtual agglomeration carriers. There are

also scholars who choose the basic and functional perspectives of virtual agglomeration. However, few studies consider the elements and processes of virtual agglomeration and comprehensively define virtual agglomeration. Secondly, the existing literature mostly measures the level of virtual agglomeration from macro-regions and micro enterprises. Few scholars measure the level of the virtual agglomeration of the manufacturing industry from the perspective of the industry. Additionally, the existing literature mostly uses statistical data. Few scholars use multiple forms of data to conduct research. Thirdly, most of the existing literature focuses on summarizing the characteristics of virtual agglomeration from the theoretical level. There is little literature that analyzes the realistic characteristics of the virtual agglomeration of the manufacturing industry. The existing research is insufficient to provide a foundation for this study.

Based on the shortcomings of the existing research, the marginal contributions of this study include the following three aspects: Firstly, in this study, we define the virtual agglomeration of the manufacturing industry from the perspective of the elements and processes of virtual agglomeration. We construct a conceptual model of virtual agglomeration from subject, foundation, carrier, and network, which enriches the current research on the definition of virtual agglomeration from a single perspective. Secondly, the virtual agglomeration level of the manufacturing industry is measured with the help of social network analysis. We use the number of network edges and network density indicators to measure the level of virtual agglomeration in the overall manufacturing industry. We use the point degree centrality index to measure the level of virtual agglomeration of manufacturing sub-industries. This study expands the study of virtual agglomeration measurements from regional and enterprise levels to the manufacturing industry level. Moreover, the data used in this study include text and statistical data, which make up for the measurement bias caused by the use of statistical data alone. Thirdly, cluster analysis and core–periphery analysis methods are used to study the characteristics of the virtual agglomeration of the manufacturing industry.

2. The Construction of a Virtual Agglomeration Social Network in the Manufacturing Industry

Social network analysis is a set of norms and methods used to analyze the overall structure of a relationship formed by different individuals and the distinctions among individuals, and this relationship structure is usually expressed in the form of social networks [24]. In a social network, different individuals are called nodes, and the relationships among individuals are represented by wires. If there is a one-way connection among individuals in the social network, it constitutes a directed network. If the individuals are connected in both directions, an undirected network is formed. In addition, the connections among individuals in the network may have a strong relationship, usually expressed by the weight of the connection. The greater the weight, the stronger the connection. A network that does not have a strong relationship among individuals is a powerless network, and a network with a strong relationship is called a power network. A social network includes four types, according to whether the connection among individuals has direction and weight: directed entitlement network, directed disentitlement network, undirected entitlement network, and undirected disentitlement network.

The virtual agglomeration of the manufacturing industry subverts the definition of geospatial agglomeration based on the new economic geography theory. This study defines the virtual agglomeration of manufacturing as "manufacturing industry and related service industries from the same or different geographical space gather on the industrial Internet platform with the support of digital technology, release supply and demand information and share various manufacturing resources, and accelerate the process of cooperation in R&D, manufacturing and sales". According to the definition of the virtual agglomeration of the manufacturing industry, the virtual agglomeration of the manufacturing industry is composed of virtual agglomeration subjects, foundations, carriers, and networks, as shown in Figure 1. The virtual agglomeration subjects are the manufacturing industry

and related service industries. The basis of virtual agglomeration is a digital technology group composed of digital technologies such as artificial intelligence, blockchain, cloud computing, and big data. The virtual agglomeration carrier is primarily the industrial Internet platform for industry connections [25,26]. As the carrier of the virtual agglomeration of manufacturing, the industrial Internet platform accelerates the platforming and intelligent transformation of enterprise organization and reconstructs the resource allocation mode of traditional geographic agglomeration [27,28]. Virtual agglomeration networks include R&D, manufacturing, and sales networks [29,30]. The industrial Internet platform accelerates the flow of supply and demand information in the R&D, manufacturing, and sales links of the manufacturing industry and realizes the real-time virtual aggregation of different production links [31–33]. From the components and formation process of the virtual agglomeration of the manufacturing industry, it can be understood that the virtual agglomeration process of the manufacturing industry is a social network formation process.

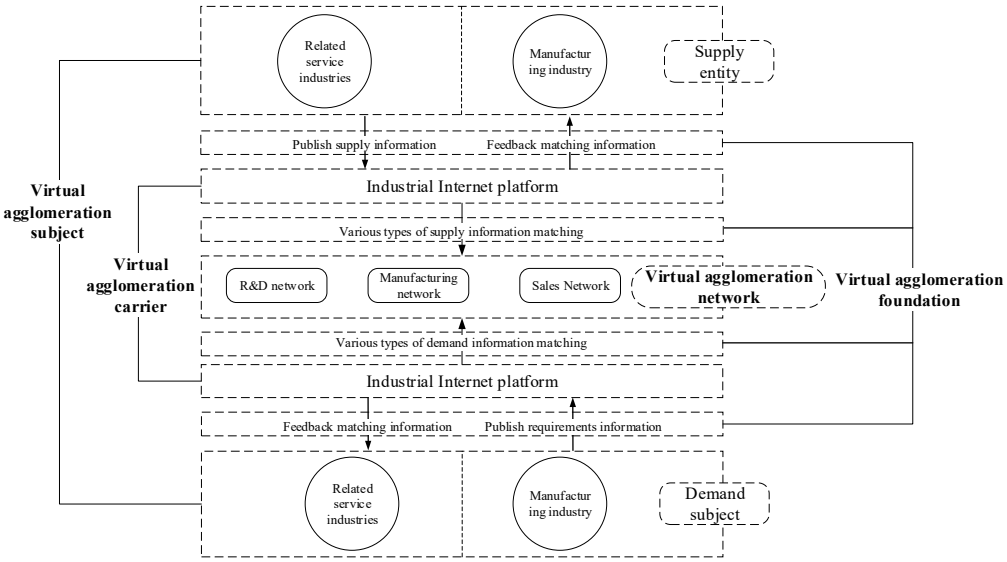


Figure 1. A conceptual model of the virtual agglomeration of the manufacturing industry.

Drawing upon social network analysis methods to construct a social network of the virtual agglomeration of the manufacturing industry, we study the virtual agglomeration of the manufacturing industry from the perspective of industry, with each industry representing a node in the network and virtual agglomeration among industries representing a connection in the network. Because virtual agglomeration connection from the perspective of the manufacturing industry is difficult to measure directly, we first use the supply chain data and virtual agglomeration text data of manufacturing enterprises to obtain the virtual agglomeration connections of manufacturing enterprises, and then categorize the enterprise data into the different manufacturing industries as well as construct a social network of the virtual agglomeration of the manufacturing industry. First, we identify the connections among companies based on the supply chain data. Then, according to the definition of the virtual agglomeration of the manufacturing industry, the keywords of the virtual agglomeration of the manufacturing industry are identified using three dimensions: virtual agglomeration foundations, virtual agglomeration carriers, and virtual agglomeration networks. Under the premise that the two enterprises have a supply chain cooperative relationship, if the virtual agglomeration keyword appears in the annual reports of the two enterprises, it is considered that the two enterprises have generated a virtual agglomeration connection. Finally, the enterprise data are aggregated into the different manufacturing industries. The virtual agglomeration of different manufacturing industries is a two-way street. In addition, when aggregating virtual clusters of different manufacturing firms into industries, multiple identical virtual clusters of industries may

emerge. Therefore, the social network of the virtual agglomeration of the manufacturing industry is an undirected entitlement network.

3. Research Methods and Data Sources

3.1. Methods for Measuring the Virtual Agglomeration Levels of the Manufacturing Industry

The carrier of the virtual agglomeration of the manufacturing industry changes from a geographical space to a virtual platform. This changes the definition of geographic agglomeration. Methods for measuring geographic agglomeration no longer work with virtual agglomeration. The virtual agglomeration of the manufacturing industry presents obvious network characteristics. Different manufacturing industries generate close virtual agglomeration links in the network. Social network analysis can help us to identify the virtual agglomeration level of the overall manufacturing industry as well as different industries. Simultaneously, the network analysis method can also analyze virtual agglomeration characteristics using multiple dimensions. Therefore, the social network analysis method is introduced into the level measurement and characteristic analysis of the virtual agglomeration of the manufacturing industry. This study improves upon the existing research methods for virtual agglomeration.

Social network analysis is used to measure the level of the virtual agglomeration of the manufacturing industry. The social network analysis method can measure the overall level of social networks and the individual level in the network. The measurement indicators of the overall level mainly include the network size, edge number, and density. The network size refers to the number of nodes that make up the social network. The number of network edges refers to the number of connections among nodes in the network. The network density refers to the actual number of connections among nodes compared to the theoretical maximum number of connections. Measures at the individual level include point centrality, proximity centrality, and mediation centrality. Among them, point centrality refers to the connection ability of nodes, which is measured by the number of nodes directly connected, without considering other nodes. Proximity centrality and mediation centrality emphasize the ability to connect across individuals. Since the number of manufacturing industries engaged in virtual agglomeration did not significantly change from 2012 to 2022, the number of network edges and network density are used to measure the overall virtual agglomeration level of the manufacturing industry. In addition, not all manufacturing industries will have industrial virtual agglomeration connections; thus, proximity centrality and intermediary centrality are not suitable for measuring the virtual agglomeration level of each manufacturing industry. Point centrality is used to measure the level of virtual agglomeration for each manufacturing industry.

The number of network edges is measured using the number of connections generated among manufacturing industries, as shown in Equation (1):

$$L = \sum_{i=1}^{n} x_i \tag{1}$$

In Equation (1), L represents the number of connections in the virtual agglomeration social network of the manufacturing industry, n represents the number of industries in the network, and x_i indicates the number of connections generated by industry i to other industries.

The network density is measured using the actual number of connections among nodes compared to the theoretical maximum number of connections. We consider that the virtual agglomeration of the manufacturing industry network constructed in this study is an undirected entitlement network, and the calculation is shown in Equation (2):

$$d = L/n(n-1) \tag{2}$$

In Equation (2), d represents the network's density, and the other variables have the same meaning as the variables in Equation (1). They will not be elaborated further.

Point centrality is an indicator that directly depicts the importance of each manufacturing industry in the virtual agglomeration social network, and the calculation formula of the point centrality index of individuals in the undirected entitlement social network is shown in Equation (3):

$$L_i = \sum_{j=1}^{k} x_{ij} \tag{3}$$

where L_i is the point centrality level of different industries, x_{ij} represents the weight of the connection between industry i and industry j, and k represents the number of industries that have generated virtual agglomeration connections with industry i.

3.2. Analysis Method for Virtual Agglomeration Characteristics of the Manufacturing Industry

Cluster analysis refers to an analysis method that classifies nodes that are more closely related. In this study, we use community analysis to classify the closely linked industries in the virtual agglomeration of the manufacturing industry network into one category [34]. Industries within the same community are more closely linked, and industries among different communities are relatively distant. Community analysis is performed using the "Fast Unfolding" algorithm, which first obtains a modularity value when performing community analysis. The modularity value is a measure of whether the division of the community is reasonable. Modularity values range from 0 to 1, with larger values indicating stronger ties among manufacturing industries within different communities. In real network analysis, the modularity value generally ranges from 0.3 to 0.7 [35]. The modularity is calculated as shown in Equation (4):

$$Q = \frac{1}{2m} \sum_{i,j} \left[A_{ij} - \frac{k_i k_j}{2m} \right] \delta(c_i, c_j) \tag{4}$$

In Equation (4), Q is the modularity value of the the virtual agglomeration of the manufacturing industry social network. m represents the number of edges in the social network. A_{ij} is a variable that measures whether industries i and j are directly connected. If industries i and j are directly connected, the value of A_{ij} is 1. If industries i and j are not directly connected, the value of A_{ij} is 0. The k_i and k_j are the numbers of connections generated between industries i and j. c_i and c_j represent community indices for industries i and j, respectively. $\delta(c_i, c_j)$ indicates whether industries i and j are in a community. If industries i and j are in the same community, then $c_i = c_j$ and $\delta(c_i, c_j) = 1$. If industries i and j are not in the same community, then $c_i \neq c_j$ and $\delta(c_i, c_j) = 0$.

Core–periphery analysis refers to a special structural form composed of multiple nodes with tightly connected centers and sparsely scattered peripheries, which accelerates the flow of information and has strong stability. By calculating the core degree of different industries in the virtual agglomeration of the manufacturing industry social network, the position of different industries in the network and the structural characteristics of the overall network can be judged. Typically, the core–periphery model includes three types of subjects: core, semi-periphery, and periphery. The core subject is in a dominant position in the network and has a close connection with other nodes, the semi-periphery subject plays a connecting role between the core and the periphery subject, and the importance of the periphery subject in the network is generally low. Subjects with a core degree greater than 0.1 are core subjects, subjects with a core degree from 0.1 to 0.05 are semi-periphery subjects, and subjects with a core degree less than 0.05 are periphery subjects [36].

3.3. Data Sources

The raw data in this study include virtual agglomeration text data and supply chain statistics for manufacturing companies. According to the definition of the virtual agglomeration of the manufacturing industry, the keywords of virtual agglomeration are determined using three dimensions—virtual agglomeration foundations, virtual agglomeration carriers, and virtual agglomeration networks—as shown in Table 1. Virtual agglomeration text data are obtained by crawling through the annual reports of listed companies in manufacturing

using Python crawler tools. The China CSMAR Financial and Economic Database provides supply chain data for manufacturing enterprises. Finally, the virtual agglomeration data from the manufacturing enterprises are aggregated into different manufacturing industries. Since there are no cooperation data for the tobacco products industry and the metal products, machinery, and equipment repair industries in the supply chain data, data for these industries are not included in the final 29 manufacturing industries. The sample period selected for this study is 2012–2022.

Table 1. Virtual agglomeration keywords of the manufacturing industry.

Virtual Clustering Features		Keywords
Virtual agglomeration foundations	Digital technology group	5G; Big data; Data mining; Data network; Data center; Artificial intelligence; Blockchain; Internet of Things; Mobile Internet; Industrial Internet; Machine learning; Industrial intelligence technology; Cloud computing; Cloud ecology
Virtual agglomeration carriers	Industrial Internet platform	The names of the 50 industrial Internet platforms that appear in the "List of Cross-industry and Cross-field Industrial Internet Platforms in 2023" released by the Ministry of Industry and Information Technology of China
Virtual agglomeration networks	R&D network	Online R&D collaboration; Online design collaboration; Virtual R&D network; Cooperative R&D network; Cooperative R&D platform; Cooperative innovation network; Cooperative innovation platform; Virtual innovation network; Digital technology exchange; Digital knowledge exchange; Distributed R&D; Interactive R&D; Interactive innovation
	Manufacturing network	Online collaborative manufacturing; Network collaborative manufacturing; Remote collaboration; Virtual factory; Distributed manufacturing; Intelligent collaborative manufacturing; Manufacturing resource digitalization; Digital manufacturing resources; Manufacturing resource sharing
	Sales network	Internet marketing; Internet sales; Intelligent marketing; E-commerce; B2B; Digital marketing; Online to offline; Online and offline; Logistics tracking; Intelligent warehousing; Intelligent logistics; Digital supply chain

4. Results and Discussion

4.1. Analysis of Measurement Results of the Overall Virtual Agglomeration Level of the Manufacturing Industry

In this study, we calculated the number of edges and the network density of the virtual agglomeration of the manufacturing industry social network from 2012 to 2022. The existing literature mostly focuses on the changes in the quantitative dimensions and uses statistical data, such as the number of websites and e-commerce transaction volumes, to investigate the level of virtual agglomeration [37–39]. The network edge index used in this study reflects the change in the overall virtual agglomeration of the manufacturing industry level for the quantity dimension. The network density reflects the change in the overall virtual agglomeration of the manufacturing industry level for the quality dimension. The changes in the two indicators are shown in Figure 2. The increasing number of network edges for the virtual agglomeration of manufacturing indicates that more manufacturing industries cluster virtually. Network density is slowly rising, indicating that virtual agglomeration among manufacturing industries needs to be improved. A possible reason for this is that manufacturing information has not been fully shared on the industrial Internet platform.

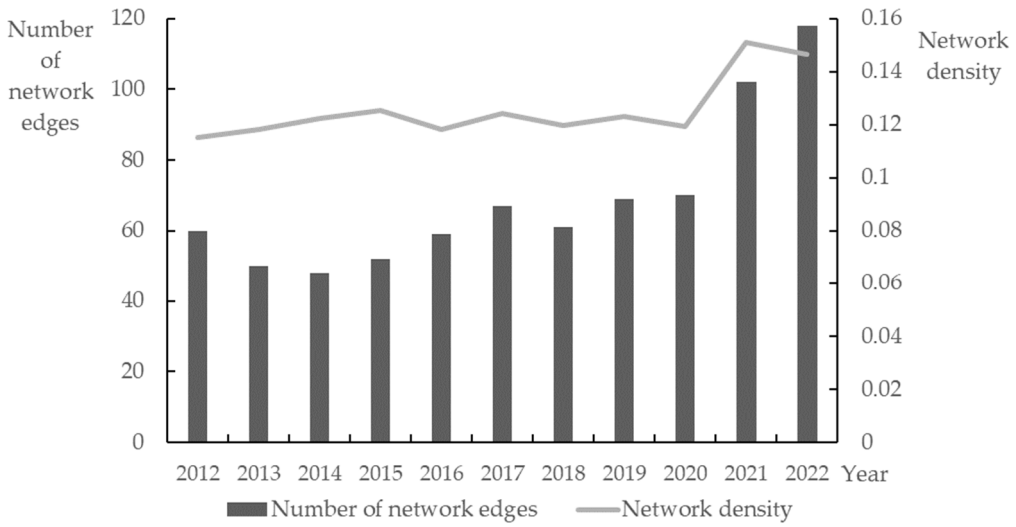


Figure 2. Number of network edges and network density of the virtual agglomeration of the manufacturing industry social networks in 2012–2022.

In this study, we further explored the change in the number of network edges from 2012 to 2022. The change in the number of network edges from 2012 to 2022 can be divided into three stages. The first stage was implemented in 2012–2015, the embryonic period of the virtual agglomeration of manufacturing. During this period, most of the research on Internet platforms focused on Internet enterprises, while manufacturing focused on the internal information construction of enterprises. In January 2012, China's State Council issued the Industrial Transformation and Upgrading Plan (2011–2015), proposing to vigorously develop R&D and design software to provide strong support for digital, networked, and intelligent manufacturing. By the end of 2015, 99.7% of manufacturing enterprises carried out production and operation activities through the Internet, laying the foundation for manufacturing enterprises to shift from internal information construction to the digital upgrading of organizational forms between enterprises, and promoting the development of the virtual agglomeration of manufacturing into the second stage.

The second stage was implemented in 2016–2020, which was the beginning of the virtual agglomeration of manufacturing. In December 2016, China's Ministry of Industry and Information Technology issued the "Intelligent Manufacturing Development Plan (2016–2020)", proposing to promote the development of new formats and models such as Internet-based crowd-creation and crowdsourcing, which means that the virtual agglomeration of manufacturing became an important direction for the development of the manufacturing industry. Since 2018, the number of industrial enterprises in China has increased year by year, and by the end of 2020, the proportion of industrial enterprises migrating to the cloud was 47%, and the cloud rate for industrial equipment was 13%. Based on the advantages of automation systems and industrial software, manufacturing enterprises have begun constructing industrial Internet platforms and gradually realized the expansion from internal information construction to digital exchanges among enterprises.

The third stage is the development period of the virtual agglomeration of manufacturing, spanning from 2021 to the present. By the end of 2022, the industrial Internet had been integrated into 45 national economic categories, and there were more than 240 influential industrial Internet platforms.

In this study, we found that the changes in the overall virtual agglomeration of manufacturing are more consistent with the direction of digital transformation set by the Chinese government. The government has introduced policies to encourage and guide the virtual agglomeration of the manufacturing industry. This finding has also been confirmed in the process of the virtual agglomeration of manufacturing in other countries [40,41].

The social networks of the virtual agglomeration of the manufacturing industry in 2012 and 2022 are shown in Figure 3. The social network graph in 2022 is more complex than in 2012, indicating that nodes are more closely connected. This result also shows that the virtual agglomeration level of overall manufacturing is constantly improving.

Figure 3. Social network diagram of the virtual agglomeration of the manufacturing industry.

4.2. Analysis of the Measurement Results of Each Level of the Virtual Agglomeration of the Manufacturing Industry

In this study, we calculated the point centrality of each manufacturing industry from 2012 to 2022, as shown in Table 2. The last column of Table 2 shows the evolution of the virtual agglomeration level of each industry. In this table, " ↑ " represents the rising level of virtual agglomeration, "-" indicates that the level of virtual agglomeration is basically stable, and " / " indicates that there is no significant virtual agglomeration feature in the manufacturing industry. In Table 2, from 2012 to 2022, the level of virtual agglomeration in 17 industries, including electrical machinery and equipment manufacturing, continuously improved. The level of virtual agglomeration in seven industries, including the textiles, garments, and apparel industry, remained basically unchanged. Five industries, including the comprehensive utilization of waste resources, showed almost no virtual agglomeration connections with other industries. Comparing the virtual agglomeration level of the overall manufacturing industry with subdivided industries, we find that an improvement in the overall manufacturing level is achieved through some industries. Individual industries need to accelerate the transformation of virtual agglomeration. It can be concluded that virtual agglomeration in China's manufacturing industry is still in an asynchronous and unbalanced stage.

Table 2. The point centrality of manufacturing from 2012 to 2022.

Serial Number	Industry Name	The Point Centrality in the Manufacturing Industry											
		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Trend
1	Electrical machinery and equipment manufacturing	11	10	11	3	5	17	13	16	10	21	31	↑
2	Textiles, garments, and apparel industry	4	6	5	3	6	3	3	2	3	3	1	-
3	textiles	3	3	4	1	3	3	5	2	4	5	3	-
4	Non-metallic mineral products industry	10	10	4	1	2	6	3	4	2	7	8	-
5	Comprehensive utilization of waste resources	0	0	0	0	0	0	0	0	0	0	1	/
6	Ferrous metal smelting and rolling processing industry	3	8	6	8	5	12	5	17	9	16	8	↑
7	Chemical fiber manufacturing	1	1	3	1	1	2	0	0	1	3	1	↑
8	Chemical raw materials and chemical products manufacturing	11	11	7	14	7	19	16	9	12	25	25	↑
9	Computer, communications, and other electronic equipment manufacturing	18	21	9	10	16	17	15	13	9	25	39	↑
10	Furniture manufacturing	0	0	0	0	0	0	0	0	0	0	1	/
11	Metal products industry	4	2	5	9	5	7	7	7	7	10	13	↑
12	Liquor, beverage, and refined tea manufacturing	0	0	0	1	0	0	0	2	2	1	2	↑
13	Wood processing and wood, bamboo, rattan, palm, and grass products industry	0	0	0	0	0	1	0	0	0	1	0	/
14	Agricultural and sideline food processing industry	1	0	0	0	0	0	0	0	4	6	6	↑
15	Leather, fur, feathers, and their products and footwear industry	0	0	0	0	1	1	1	1	1	0	0	/
16	Other manufacturing industries	4	4	6	3	9	8	6	6	4	5	3	-
17	Automotive manufacturing	8	10	8	5	13	15	19	14	15	20	21	↑
18	Petroleum processing, coking, and nuclear fuel processing industries	5	2	1	0	2	2	0	4	2	6	2	-
19	Food manufacturing	3	3	3	7	3	2	1	2	2	2	2	-
20	Railway, shipbuilding, aerospace, and other transportation equipment manufacturing	6	8	1	3	3	3	3	4	5	13	10	↑
21	General equipment manufacturing	10	4	4	5	6	8	7	10	12	21	28	↑
22	Culture, education, industry and art, sports, and entertainment goods manufacturing	1	1	1	1	1	0	0	0	0	2	0	/
23	Rubber and plastic products industry	7	8	2	7	4	5	4	7	3	11	11	↑
24	Pharmaceutical manufacturing	11	3	7	10	11	11	19	14	20	38	40	↑
25	Instrumentation manufacturing	0	0	2	0	2	2	7	3	5	16	22	↑
26	Printing and recording media reproduction industry	1	1	0	0	0	0	0	0	0	0	3	↑
27	Non-ferrous metal smelting and rolling processing industry	1	2	5	3	6	11	10	8	7	10	11	↑
28	Paper and paper products industry	4	2	4	3	6	5	2	2	2	0	2	-
29	Special equipment manufacturing	14	16	3	15	12	12	13	12	19	41	39	↑

Note: The " ↑ " represents the increase of the level of virtual agglomeration, "-" represents the level of virtual agglomeration remains unchanged, and " / " represents the level of virtual agglomeration is almost 0.

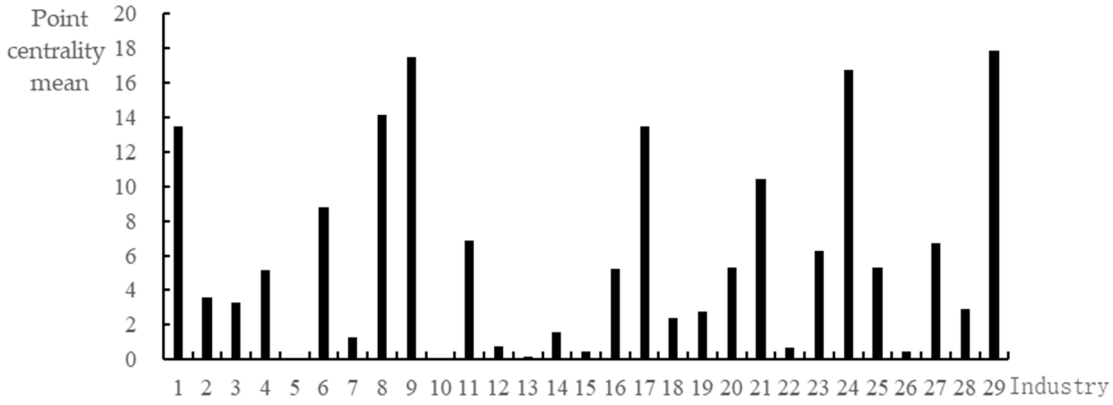
We can see that the virtual agglomeration level of different industries varies greatly, based on the measurement results. There are many reasons for this discrepancy. They may not only come from the support and demand of external governments and consumers for virtual agglomeration in specific industries [42], but also from the strategic layout and practice of virtual agglomeration talent training, technical equipment purchase, and technological innovation within each industry [43].

The point centrality mean of 29 manufacturing industries is calculated for 2012 to 2022, as shown in Figure 4. The average level of virtual agglomeration in the special equipment manufacturing industry is the largest. On the one hand, the special equipment manufacturing industry has advanced technical requirements [44]. In the context of the digital economy, this technology is more manifested as digital technology. The demand for advanced digital technology accelerates the virtual agglomeration of industries. On the other hand, the special equipment manufacturing industry provides equipment support for production activities in various industries. Computer, communications, and other electronic equipment manufacturing ranks second. This is because the manufacturing of computers, communications, and other electronic devices is a high-tech industry that is at the forefront of digital technology innovation. The computer industry has a more advanced digital technology base. At the same time, the manufacturing of computers, communications, and other electronic equipment is a basic industry. Virtual agglomeration in every manufacturing industry requires hardware and software technology support from the manufacturing of computers, communications, and other electronic devices. The pharmaceutical manufacturing industry ranks third. Biotechnology innovation in the field of pharmaceutical manufacturing is inseparable from the support of a new generation of information technology. As a result, the new generation of information technology has accelerated the virtual agglomeration of pharmaceutical manufacturing [45]. Furthermore, the pharmaceutical manufacturing industry not only needs to be connected with the chemical raw materials and chemical products manufacturing industry upstream of the industrial chain but also needs to be connected with various equipment manufacturing industries.

Chemical raw materials and chemical products manufacturing, automobile manufacturing, and electrical machinery and equipment manufacturing industries rank fourth, fifth, and sixth, respectively. These three industries also occupy a relatively important position in the virtual agglomeration of manufacturing social network. This is mainly because the chemicals, automobiles, and motor products produced by the three industries are used in many industries and fields, thus affecting the production activities of many industries.

In addition, leather, fur, feathers, and related product and footwear manufacturing; wood processing, as well as the manufacturing of wood, bamboo, rattan, and grass products; and furniture manufacturing hardly engage in virtual agglomeration activities. As a result, the level of the virtual agglomeration of manufacturing for these three industries is almost zero. This may be because the production activities of enterprises in these industries are still in the stage of machinery manufacturing, and the level of platform and network development is low [46].

Comparing the average value of virtual agglomeration in different industries in the manufacturing industry, we find that the level of virtual agglomeration in medium and high-tech industries is higher than that in low-tech industries. This finding shows that China's mid-to-high-tech industries have stronger digital awareness and a faster pace of transformation than low-tech manufacturing industries. This result is also confirmed in a study by Ren and Liang [19].



1. Electrical machinery and equipment manufacturing 2. Textile, garment, and apparel industry 3. Textile industry 4. Non-metallic mineral products industry 5. Comprehensive utilization of waste resources 6. Ferrous metal smelting and rolling processing industry 7. Chemical fiber manufacturing 8. Chemical raw materials and chemical products manufacturing 9. Computer, communication, and other electronic equipment manufacturing 10. Furniture manufacturing 11. Metal products industry 12. Liquor, beverage, and refined tea industry 13. Wood processing and wood, bamboo, rattan, palm, and grass products industry 14. Agricultural and sideline food processing industry 15. Leather, Fur, feathers, and their products and footwear industry 16. Other manufacturing 17. Automotive manufacturing 18. Petroleum processing, coking, and nuclear fuel processing industry 19. Food manufacturing 20. Railway, shipbuilding, aerospace, and other transportation equipment manufacturing 21. General equipment manufacturing 22. Culture, education, industry and art, sports, and entertainment goods manufacturing 23. Rubber and plastic products industry 24. Pharmaceutical manufacturing 25. Instrumentation manufacturing 26. Printing and recording media reproduction industry 27. Non-ferrous metal smelting and rolling processing industry 28. Paper and paper products industry 29. Special equipment manufacturing

Figure 4. The point centrality means of 29 manufacturing industries from 2012 to 2022.

4.3. The Characteristic Analysis of Virtual Agglomeration in the Manufacturing Industry

4.3.1. Cluster Analysis Results

In order to compare the differences in community division in different years, we used the community analysis method to study the social networks of the virtual agglomeration of the manufacturing industry in 2012, 2017, and 2022. The modular values of the different years are 0.402, 0.34, and 0.307, respectively, indicating that the results of community division are reasonable. The social networks are divided into five communities in 2012 and 2017 and they are divided into six networks in 2022. The number of communities divided by year varied, but the overall results are basically consistent. Therefore, we analyzed the results of community division in 2022, as shown in Figure 5. The different colors in Figure 5 represent different communities. Labeled circles represent different sub-sectors of the manufacturing industry. The lines among the circles represent the virtual agglomeration connections that arise among industries. The circles without labels represent the service sector, which has a virtual agglomeration connection with the manufacturing industry. Since the service sector is outside the scope of this study, the service industry is not labeled.

We can see from Figure 5 that there are three types of virtual agglomeration relationships among industries, which are differentiated according to the community analysis method. The first type is the specialized virtual agglomeration of different links in the same industrial chain. The second type is diversified virtual agglomeration among industries with similar knowledge bases. The third type is diversified virtual agglomeration among industries with large knowledge differences. The virtual agglomeration relationships in different communities vary significantly. Purple and light green communities exhibit two diverse types of virtual agglomeration. The blue and orange communities include both specialized and diversified virtual gatherings. The dark green and pink communities are mainly specialized virtual agglomeration. It is found that the classification criteria of specialization and diversification under the form of geographic agglomeration are not applicable to virtual agglomeration. The virtual agglomeration of the manufacturing in-

dustry crosses the boundaries of industries and changes to a hybrid agglomeration form. Most of the existing literature derives this characteristic from a theoretical level [47]. In this study, a conclusion is drawn from a practical level using textual and statistical data. The findings of this study enhance the persuasiveness of virtual agglomeration as a change in economic form.

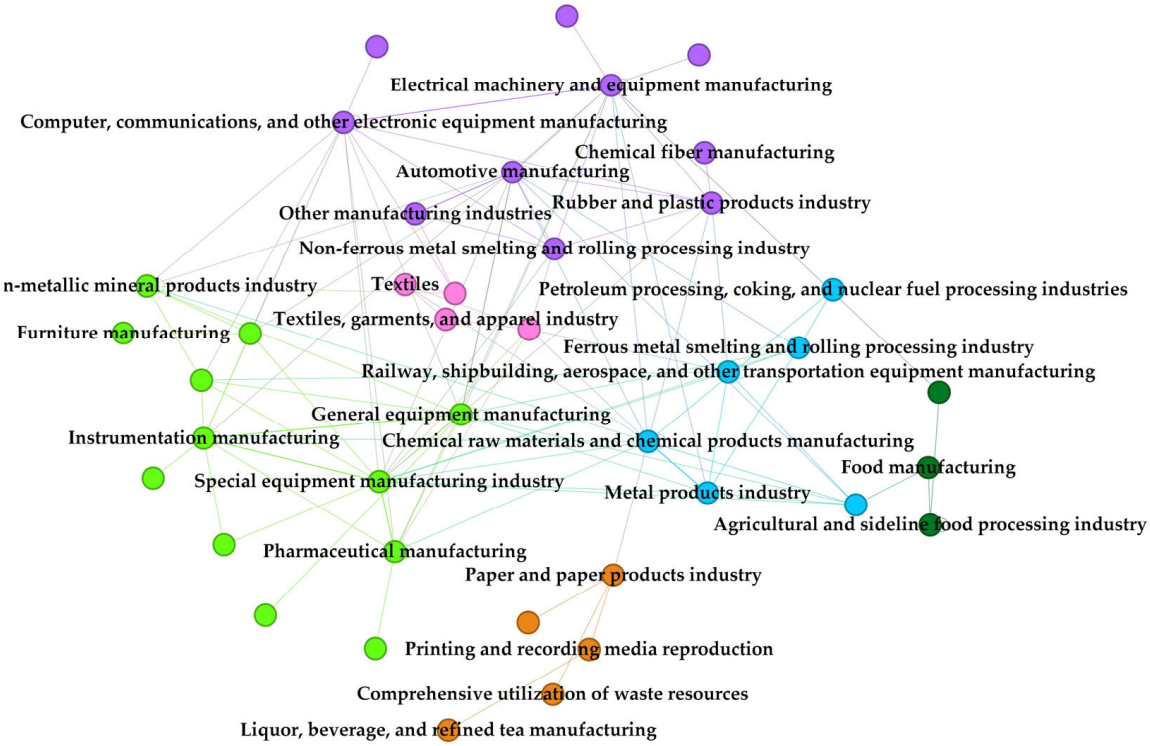


Figure 5. The community division of the virtual agglomeration of the manufacturing industry networks in 2022.

Diversified virtual agglomeration is primarily manifested among communities and mainly occurs between purple and light-green communities, as well as purple and blue communities. For example, the manufacturing of computers, communications, and other electronic equipment in the purple community and general equipment manufacturing and special equipment manufacturing in the light green community. Automobile manufacturing in the purple community and ferrous metal smelting and rolling processing industry, chemical raw materials and chemical products manufacturing industry in the blue community. By comparing the differences in the types of virtual agglomeration within and among communities, it is found that specialized virtual agglomeration mostly occurs within the same community. This finding also indicates that the results of the community analysis method division are reasonable.

4.3.2. Core–Periphery Analysis Results

Based on the data from 2012, 2017, and 2022, we analyzed the core–periphery characteristics of the virtual agglomeration of the manufacturing industry. On the one hand, we examined the core industries in the virtual agglomeration network. On the other hand, we obtained the evolution characteristics of the manufacturing industry's virtual agglomeration social network from 2012 to 2022. The results are shown in Table 3. Computer, communications, and other electronic equipment manufacturing; electrical machinery and equipment manufacturing; special equipment manufacturing; general equipment manufacturing; and chemical raw materials and chemical products manufacturing were all in a core position from 2012 to 2022, indicating that the medium and high-tech manufacturing industries are more closely connected with other industries. The previous measurement

results on the centrality of industry points also confirm that the virtual agglomeration connection of the five industries in the virtual agglomeration social network is more frequent. The results of the evolution of the core–periphery structure show that the virtual agglomeration of manufacturing social network experiences evolution from "core–periphery" to "core–semi-periphery–periphery". This finding illustrates the dynamic change in virtual agglomeration in different industries. This dynamic change leads to mutual learning and common progress among industries. However, few scholars have given attention to the dynamic evolution process of virtual agglomeration.

Table 3. The core periphery analysis results.

Category	2012	2017	2022
Core industries	Computer, communications, and other electronic equipment manufacturing; electrical machinery and equipment manufacturing; special equipment manufacturing; general equipment manufacturing; chemical raw materials and chemical products manufacturing; non-metallic mineral products industry; food manufacturing	Computer, communications, and other electronic equipment manufacturing; electrical machinery and equipment manufacturing; special equipment manufacturing; general equipment manufacturing; Chemical raw materials and chemical products manufacturing; non-metallic mineral products industry; automotive manufacturing; other manufacturing; petroleum processing, coking, and nuclear fuel processing industry; instrumentation manufacturing; textile industry, textile, garment, and clothing industry; chemical fiber manufacturing; rubber and plastic products industry	Computer, communications, and other electronic equipment manufacturing; electrical machinery and equipment manufacturing; special equipment Manufacturing; general equipment manufacturing; Chemical raw materials and chemical products manufacturing; metal products industry; automotive manufacturing; instrumentation manufacturing; pharmaceutical manufacturing; textiles, garments, and apparel industry
Number of core industries	7	14	10
Number of semi-periphery industries	0	0	5
Number of periphery industries	16	9	11
Core–periphery structure type	"core–periphery " structure	"core–periphery " structure	"core–semi-periphery–periphery" structure

5. Conclusions

With 'the development of digital technology, virtual agglomeration has become a new organizational form for information exchange in manufacturing. Some scholars have conducted research on virtual agglomeration from a regional perspective. For example, Yang et al. [16] and Ning et al. [18] measure the level of virtual agglomeration in different regions. Moreover, Wasko et al. [22] propose that virtual agglomeration has cross-spatial characteristics. Measuring virtual agglomeration from the perspective of regions may not fully capture the cross-spatial characteristics of virtual agglomeration. How to measure the level of virtual agglomeration across geographical space in the manufacturing industry is still a focal point and challenge in the current research. In addition, virtual agglomeration is a new type of organizational form. Traditional theories of geographic agglomeration make it difficult to fully explain the virtual agglomeration effect. Therefore, we combined the theory of geographic agglomeration and the theory of network economy to study the virtual agglomeration of the manufacturing industry.

A definition for the virtual agglomeration of the manufacturing industry was proposed and a conceptual model was constructed. Secondly, we used the social network analysis method to measure the virtual agglomeration level of the overall manufacturing industry and its sub-industries. Furthermore, the factual characteristics of virtual agglomeration in China's manufacturing industry were analyzed. Two primary conclusions were drawn. The measurement results show that the virtual agglomeration level of the overall manufacturing industry is constantly improving, but there are large differences among different industries.

The feature analysis shows that the virtual agglomeration of the manufacturing industry simultaneously presents the characteristics of specialization and diversification. The virtual agglomeration network of the manufacturing industry has undergone evolution from a "core–edge" structure to a "core–semi-edge–edge" structure. In order to accelerate the development of virtual agglomeration in the manufacturing industry, it is necessary to start with two aspects: improving the level of development and strengthening the connection between industries.

On the one hand, it is necessary to reduce the differences in virtual agglomeration among different industries. The special equipment manufacturing industry, as well as the computer, communications, and other electronic equipment manufacturing industries, with a high level of virtual agglomeration, should play a leading demonstration role; and pay attention to improving the virtual agglomeration level in the overall production link. They should also focus on enhancing online collaborative R&D, collaborative manufacturing, and digital supply chain management capabilities. Furniture manufacturing, as well as leather, fur, feathers, and related product and footwear manufacturing industries with low levels of virtual agglomeration, should also establish a stronger sense of virtual agglomeration. The basic requirements for virtual agglomeration technology in the sales process are low. Low-tech manufacturing can prioritize online interaction with consumers and improve the level of virtual agglomeration in the sales process [48].

On the other hand, it is necessary to enhance the virtual agglomeration links among industries. Manufacturing should give full play to the advantages of the new organizational form of platform-led and community-based operation in the process of virtual agglomeration. From the two dimensions of the vertical industrial chain and different horizontal industries, the driving role of high-tech manufacturing in low-tech manufacturing should be enhanced. For the virtual agglomeration of different horizontal industries, high-tech industries can modify information exchange methods with low-tech industries, as well as promote the acceleration of virtual agglomeration in low-tech manufacturing industries. It can also provide intelligent and networked products to the low-tech manufacturing industry, thus allowing the low-tech manufacturing industry to more rapidly adapt to the new organizational form of virtual agglomeration.

From the perspective of industry, we used social network analysis to measure the virtual agglomeration of manufacturing for the overall level and the level within each industry. Our measurement method helps to overcome the shortcomings of previous geospatial measurement techniques and enriches the existing research on measuring virtual agglomeration. Although this study innovates the method of measuring the virtual agglomeration of the manufacturing industry, the research perspective only focuses on virtual agglomeration from the perspective of the manufacturing industry. This paper lacks further discussion on the virtual agglomeration of enterprises in the industry. In the future, we can conduct a field investigation to obtain first-hand data on the virtual agglomeration of manufacturing enterprises and explore virtual agglomeration from the perspective of other enterprises.

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