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Does the Digital Economy Promote Industrial Collaboration and Agglomeration? Evidence from 286 Cities in China

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Abstract: Relying on high penetration and strong diffusion capabilities, the digital economy is becoming a new driving force for industrial integration and development. It is of great significance to promote the coordinated development of manufacturing and producer services. This paper took panel data on 286 prefecture-level cities and above in China from 2011 to 2019 as its research object, and used the two-way fixed effect model, threshold effect model, and the Spatial Durbin Model (SDM) as its econometric testing methods. This analysis explored the impact of the digital economy on the synergetic agglomeration between manufacturing and productive service industries in China. The results of the research showed that the synergetic agglomeration of industries is significantly promoted by the digital economy. This conclusion was still valid after an endogeneity test was carried out. The digital economy's role was found to mainly involve promoting knowledge spillovers and expanding the market size. An in-depth analysis of the digital economy has enabled the collaborative agglomeration of manufacturing and producer services in large, medium-sized, and small cities. The digital economy had the greatest effect on small cities, followed by medium-sized cities and large cities. The synergetic aggregation between the manufacturing and high-end producer services industries is significantly promoted by the digital economy. However, it was not found to have had a significant effect on the synergetic agglomeration between the manufacturing and low-end producer services industries. The impact of the digital economy on industrial collaborative agglomeration is nonlinear. Only when the level of the digital economy exceeds the threshold can the promoting effect of the digital economy on industrial collaborative agglomeration be manifested. In summary, the development of the digital economy was found to have promoted industrial collaboration and agglomeration in the study areas and their neighboring regions in the study period. The research results of this article are of great significance for achieving the goal of the "two-wheel drive" of the manufacturing and producer services industries, as well as high-quality economic development in China.

Keywords: digital economy; industrial collaboration and agglomeration; knowledge spillovers; market size

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1. Introduction

The transformation from the "industrial economy" to the "service economy" has made the collaborative agglomeration of China's manufacturing industry and producer services increasingly apparent (Ke et al., 2014) [1]. As an intermediate input industry, producer services have substantial knowledge and service characteristics. They run through the entire manufacturing industry chain. They also provide strong support for manufacturing process optimization, technological innovation, and the transformation of development modes (Taylor et al., 2014) [2]. The manufacturing industry is highly related to producer services, which can promote the development of the manufacturing industry towards having a high-end industrial value chain (Zheng and He, 2022) [3]. Although China is the largest manufacturing country in the world, its position in the international value chain is still far behind developed countries. The main reason for this phenomenon is that its manufacturing industry has a low level of technology and lacks core competitiveness (Zhou et al., 2022) [4]. China should proceed from the realities of development. Compared with reducing the proportion of the country's manufacturing industry, it is more effective to enhance the benign interactions between industries (Liu and Gu, 2015) [5]. The essential realistic spatial feature of the integration and mutual promotion of manufacturing and producer services is the collaborative agglomeration of manufacturing and producer services (Guo and Yuan, 2022) [6]. The coordinated distribution of the manufacturing and productive service industries in geographical space not only helps to reduce transaction costs and improve the correlation between upstream and downstream industries, but also promotes knowledge sharing and technology diffusion among industries, thereby maximizing the industrial integration of the development of economies of scale. Therefore, it is urgently necessary to accelerate the integrated development between the manufacturing and producer services industries in order to achieve high-quality economic development. That is, there is a need for a "dual-wheel drive" of the collaborative agglomeration of the manufacturing and productive service industries.

Due to advances in information and communication technology (ICT), the world has entered the digital era (Wang et al., 2022) [7]. The digital transformation of various elements and the integrated application of information and communication technologies drives the digital economy (Watanabe et al., 2018) [8]. With the modern information network being the primary carrier, it has become essential to change the global competition pattern (Avom et al., 2020; Wang et al., 2022) [9,10]. In China, the digital economy has been developing fast. Digital technology is also developing rapidly and was widely used in China in 2022 (Zhang et al., 2022) [11]. According to the China Digital Economy Development Report (2023), in 2022, the scale of China's digital economy was CNY 50.2 trillion, and the proportion of the digital economy to GDP was 41.5%, equivalent to the proportion of the secondary industry to the national economy. In 2022, the scale of digital industrialization was CNY 9.2 trillion, and the scale of industrial digitization was CNY 41 trillion. The important position of the digital economy in the national economy is evident. China included the concept of a "digital economy" in the report of the 19th National Congress of the Communist Party of China in 2017. The 2019 Central Economic Work Conference proposed to vigorously develop the digital economy. Since 2021, local governments have intensively introduced action plans to promote the development of the digital economy. The diffusion and penetration of digital technology among industries provide new impetus for integrating and developing related industries. The question remains, however, whether the development of the digital economy promotes the collaborative agglomeration of urban industries. If so, what is the internal mechanism of this phenomenon? On this basis, what are the differences in the collaborative agglomeration of the digital economy between different producer services and manufacturing industries? How does the spatial spillover effect of the digital economy on urban industries synergetic agglomeration? The 14th Five-Year Plan emphasizes that the government should focus on the real economy and accelerate building manufacturing and quality power. Further, local governments should promote high-end, intelligent, green manufacturing and the deep integration of advanced manufacturing and modern service industries. The construction of the digital economy should be accelerated, and digital technology should be integrated into the real economy. At the same time, traditional industries in China have recently been transformed and upgraded. New initiatives, new forms, and new business models have combined to form a new economic growth engine. Therefore, exploring the mechanism and impact of the digital economy on industrial collaborative agglomeration not only enriches the research content of the digital economy in theory, but also has important practical significance for the integration of industries and even the high-quality development of China's economy.

The current research on digital economic effects mainly focuses on the following aspects: (1) Economic development or the quality of economic development. Baxtiyajon and Baxriddin (2020) [12] analyzed the significance of developing the digital economy for the economic development of Uzbekistan. The research of Guo et al. (2023) [13] showed that the digital economy has significantly promoted the high-quality development of China's urban economy, and improving human capital and promoting green technology innovation are the main channels through which the digital economy affects the high-quality development of the economy. (2) Green technology innovation or innovation efficiency. Based on the data from listed companies in China from 2011 to 2019, the digital economy has significantly improved the green innovation capabilities of enterprises (Liu et al., 2022) [14]. Wang and Cen (2022) [15] took data on Chinese provinces as their research object. They tested the impact of the digital economy on innovation efficiency using spatial econometric methods, finding that it has had a significant effect on innovation efficiency and has had a significant spatial spillover effect. (3) Upgrade of industrial structure. Based on the data from 275 Chinese cities from 2011 to 2018, Li et al. (2021) [16] found that the transformation and upgrading of industrial structures are significantly driven by the digital economy. Wu and Shao (2022) [17] showed that the digital economy has promoted industrial structure upgrading, and that the improvement of labor efficiency and promotion of technology spillovers were the important mechanisms behind this. (4) Energy conversion or green total factor energy efficiency. Based on the data from 72 countries, Shahbaz et al. (2022) [18] showed that the digital economy has positively impacted energy transition. Zhao et al. (2022) [19] found that the digital economy and green total factor energy efficiency show nonlinear characteristics. That is to say, only when the digital economy reaches a certain level can it significantly promote green total factor energy efficiency. (5) Environmental pollution or the green economy. Xu et al. (2022) [20] argued that there is a mutually restrictive relationship between the digital economy and environmental pollution. Pollution emissions are reduced by the digital economy, but its development is inhibited by the pollution emissions. Zhang et al. (2022) [11] found that the digital economy has promoted China's low-carbon development. Li et al.'s (2022) [21] research on China's urban level found that the digital economy has improved the efficiency of the green economy. In summary, there are relatively few studies in the existing literature that directly explore the impact of the digital economy on industrial collaborative agglomeration. However, the development of industrial integration is of great significance to improving industrial production efficiency and promoting enterprises' green transformation and upgrading. Industrial integration makes the industrial value chain move towards the middle and high ends, thus promoting high-quality economic development. Regarding the influencing factors of industrial collaborative agglomeration, the study by Guo and Yuan (2022) [6] is more relevant to this article. It explores the impact of internet development on industrial collaborative agglomeration and believes that the internet can improve labor skills and expand export trade to promote industrial collaborative agglomeration, but does not explore the impact of the digital economy on industrial collaborative agglomeration. Scholars have also theoretically elaborated on the impact of the digital economy on industrial integration. They believe that the digital economy, with its high innovation, strong permeability, and diffusion characteristics, helps upstream and downstream industries better communicate and cooperate, promoting their integrated development (Ayres and Williams, 2004; Bencsik, 2020) [22,23], and have not explored theoretically and empirically how the digital economy affects industrial collaborative agglomeration. Based on theoretical analysis, this paper uses data from 286 cities in China as research samples, and uses the two-way fixed effect model, threshold effect model, and SDM model to systematically study the impact of the digital economy on industrial collaborative agglomeration. It provides a useful reference for the green transformation and high-quality development of urban industries in China.

This article mainly expands on the existing literature in three aspects: First, from the perspective of the digital economy, this paper explores its effect on the synergy agglomeration of manufacturing and producer services. This serves as a beneficial expansion of the existing research on the influencing factors of the industrial collaborative agglomeration of related industries. Secondly, it investigates the mechanism of the digital economy that affects the synergetic agglomeration of industries. It is essential to explore the effect of the digital economy on the synergetic agglomeration of industries. However, only by exploring the mechanism of this can we deepen our understanding of how the digital economy affects industrial collaborative agglomeration and better provide a theoretical basis and empirical evidence for the digital economy's promotion of industrial collaborative agglomeration. Thirdly, it investigates the threshold effect and spatial spillover effect of the digital economy on industrial collaborative agglomeration. Further, the paper analyzes the heterogeneity characteristics of the digital economy that affect the synergetic agglomeration of industries from the perspective of different cities and industries. This is a deeper study on the impact of the digital economy on industrial collaborative agglomeration, which provides more specific empirical evidence for promoting industrial synergetic agglomeration through the development of the digital economy among different regions and industries.

The other sections of this paper are arranged as follows: Section 2 forwards the mechanism and research hypothesis, which provides a solid research basis for the study's empirical research. It discusses how the digital economy promotes the collaborative agglomeration of manufacturing and productive services by promoting knowledge spillovers and expanding the market scale. Section 3 details the research method. This mainly includes the setting of econometric models, the measurement of variables, data description, and descriptive statistical analysis. Section 4 provides the empirical test method and analysis of the result. It mainly includes the full-sample estimation results, robustness test, endogeneity test, and mechanism test. Section 5 provides further discussion. This mainly involves a discussion and analysis of the heterogeneity of different city sizes, an analysis of industry heterogeneity, and an analysis of the spatial spillover effect. Section 6 features the conclusion, policy recommendations, and future research.

2. Mechanism and Research Hypothesis

2.1. The Digital Economy Promotes the Collaborative Agglomeration of Manufacturing and Producer Services by Facilitating Knowledge Spillovers

Industrial collaborative agglomeration refers to industrial agglomeration. According to the theory of external agglomeration, Knowledge spillovers are the key to industrial agglomeration (Marshall, 1890) [24]. Technology spillovers affect the collaborative agglomeration of industries (Ellison et al., 2010) [25]. In this era of network intelligence, and with the support of 5G, big data, and the Internet of things, the digital economy is a new type of economic and social operation (Don, 1996) [26]. Through the value, volume, variety, and velocity of big data, digital technologies can effectively reduce the cost of information searches, thereby breaking the "information island" (Li et al., 2022) [21]. The application of big data, AI, IoT, etc., can accelerate the diffusion of new technologies among industries (Zhang, 2021) [27]. Therefore, in the context of the digital economy, enterprises acquire information and knowledge more conveniently. Enterprises tend to cluster in regions with strong technology spillover effects and rapid technological progress (Martin and Ottaviano, 1999) [28]. This assists enterprises in more conveniently mastering new technologies, gaining advanced management experience in "learning by doing", improving their production efficiency and enhancing their competitiveness, which attracts the further inflow of enterprises, so that the development situation of the spatial agglomeration of enterprises can be formed. Knowledge spillovers are conducive to enterprises' obtaining more external information and technology and internalizing them as their innovation capabilities. Knowledge spillovers directly or indirectly reduce R&D investment, minimize the risk of R&D, and shorten the innovation output cycle in enterprises (Hou et al., 2019) [29]. Further, they can reduce the innovation costs of enterprises and promote the generation of new knowledge. However, the regional agglomeration and production of firms often intensifies competition. The cost of manufacturers pursuing personalized design and R&D

is increasing day by day. With the continuous increase in market demand for the division of labor and service specialization, the intermediate service originally undertaken by the manufacturing industry itself has been transferred to the productive service industry, thus forming a diversified industrial agglomeration of the influential service industry around the manufacturing industry (Abraham and Taylor, 1996; Venables, 1996) [30,31]. In addition, knowledge spillovers can also help enterprises integrate advanced production technology and ideas into their processes of production and manufacturing. They have been found to promote high value-added products and improve the technical level of the manufacturing industry. Knowledge spillovers can significantly improve the productivity and operating conditions of manufacturing enterprises (Yang et al., 2016) [32]. Further, they are predicted to strengthen the link between the industrial correlation effect of manufacturing and producer services (Solheim and Tveterås, 2017) [33]. At the same time, they can also strengthen the exchange and cooperation between the manufacturing industry and the producer services industry, as well as promote the integrated development of the industries. In this way, the collaborative agglomeration between the manufacturing industry and producer services can be realized. Therefore, in this paper, we made the following assumptions:

Hypothesis H1. *The digital economy can reduce the cost of information searches for enterprises, promote the sharing of knowledge and innovative technologies, and promote knowledge spillovers, thereby promoting the collaborative agglomeration of manufacturing and producer services.*

2.2. The Digital Economy Promotes the Collaborative Agglomeration of Manufacturing and Producer Services by Expanding the Market Scale

The widespread use of information technologies such as the Internet and big data has broken through information barriers in the market (Li et al., 2022) [21]. By alleviating information asymmetry and reducing the costs of search and transaction, the digital economy can reduce transaction barriers, break market boundaries, and facilitate the flow of resources in a wider range (Goldfarb and Tucker, 2019) [34], as well as enable extensive connection and close collaboration between parties. Additionally, the development of the digital economy has transformed the one-way output flow characterized by a single product supplier into a two-way exchange flow among several product suppliers. The digital economy will stimulate the demand for product diversification, thereby driving increases in the production and variety of products (Jiao and Sun, 2021) [35] and then further expanding the market scale. The larger the market size and the higher the consumer demand in a given area, the more enterprises tend to gather in that area (Ji et al., 2014) [36]. With the expansion of the market scale, the number of enterprises and production scale will expand, and the production process will become more subdivided (Francois, 1990) [37]. The Smith–Young Theorem also indicates that the expansion of market size can promote the social division of labor. With the deepening of the social division of labor, the industry types will become more refined, promoting the separation of producer services from manufacturing, and the scale and types of producer services will continue to expand.

Further, with the increase in new enterprises in producer services, the spatial agglomeration of producer services will gradually form. According to recent economic geography theory, based on the consideration of transportation costs and geographical convenience, the layout of the manufacturing industry and producer services tends to be unified due to the relationship between input and output (Krugman, 1991) [38]. This is beneficial for manufacturing enterprises to obtain the intermediate goods service with a low price and good quality, undoubtedly promoting the development of the manufacturing industry, and the producer services industry also realizes its own development by providing intermediate goods services, which promotes the coordinated development of the manufacturing industry and the producer services industry.

Therefore, the article proposes H2.

Hypothesis H2. *The digital economy promotes the expansion of the market scale and the coordinated development of manufacturing and producer services, thus promoting the collaborative agglomeration of manufacturing and producer services.*

3. Econometric Model Setting, Variable Measurement, and Data Description

3.1. Econometric Model Setting

This study mainly analyzed the effect of the digital economy (*De*) on the collaborative agglomeration between manufacturing and producer services (*Coagg*). To minimize estimation deviation, the study referred to the research of Han and Xie (2017) [39], Wang et al. (2022) [40], Gao et al. (2021) [41], and Su and Li (2011) [42]. Human capital (*H*), foreign direct investment (fdi), transportation infrastructure ($infra$), financial development (fin), and urbanization (urb) are also essential factors that affect industrial collaborative agglomeration. Therefore, these were taken as the control variables. The econometric model was constructed as follows:

$$\ln Coagg_{it} = \alpha_0 + \alpha_1 \ln De_{it} + \alpha_2 \ln H_{it} + \alpha_3 fdi_{it} + \alpha_4 \ln infra_{it} + \alpha_5 urb_{it} + \alpha_6 fin_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (1)$$

where i and t represent the city and year, respectively; α_0 denotes the intercept term; α_1 to α_6 represent the parameters to be estimated; μ_i and ν_t describe the urban and time fixed effects, respectively; ε represents random disturbance terms.

According to the above theoretical mechanism analysis, the digital economy can promote the collaborative agglomeration of manufacturing and producer services by promoting knowledge spillovers and expanding market size. To verify the role of these mechanisms, this study established the following test model by referring to the research of Ye and Zhuang (2022) [43]:

$$\ln M_{it} = \beta_0 + \beta_1 \ln De_{it} + \theta_j Control_{it} + \psi_i + \kappa_t + \eta_{it} \quad (2)$$

where M is an intermediate variable and $Control$ is the control variable; i and t represent the city and year, respectively; β_0 is the intercept terms; β_1 and θ_j are the parameters to be estimated; ψ_i and κ_t represent urban and time fixed effects, respectively; η denotes random disturbance terms.

3.2. Variable Measurement and Data Description

This paper took 286 prefecture-level cities and above in China from 2011 to 2019 as the research sample (Tibet, Hong Kong, Macao, and Taiwan were not included in the sample). The data of the digital economy were derived from the China Urban Statistical Yearbook, Peking University Digital Inclusive Finance Index (2011–2019). The data of industrial collaborative agglomeration, human capital, transportation infrastructure, balance of deposits and loans from financial institutions, and total amount of social retail goods were derived from the China Urban Statistical Yearbook. The data of the foreign direct investment were derived from the China Urban Statistical Yearbook, China Regional Economic Statistical Yearbook, and China Statistical Yearbook. The number of patent authorizations were derived from China Research Data Service Platform (CNDRS). The data of urbanization were derived from the statistical yearbooks of provinces and cities, and the bulletin of urban national economic development and social statistics. Descriptive statistics of the variables are shown in Table 1. The detailed indicators were as follows:

Table 1. Statistical description of variables.

Variable	Mean	Standard Deviation	Min	Max
$Coagg$	2.3933	0.5311	0.7628	4.4998
De	1.2236	0.1206	1.0225	1.8847
$H(person)$	94,088.2400	166,667.7000	1.0000	1,152,995
$fdi(Percentage)$	1.6622	1.8058	0.0000	21.0066
$infra$ (m^2)	13.1918	8.8927	0.5000	108.3700
urb	0.5499	0.1482	0.2126	1.0000
fin	0.9879	0.6135	0.1180	9.6221

(1) Explained variable: the collaborative agglomeration degree of the manufacturing industry and producer services($Coagg$). According to the research of Zheng and He (2022) [3], the measurement formula of the industrial collaborative agglomeration level is as follows:

$$Coagg_{it} = (1 - \frac{|Magg_{it} - Sagg_{it}|}{Magg_{it} + Sagg_{it}}) + (Magg_{it} + Sagg_{it}) \tag{3}$$

where $Magg$ and $Sagg$ represent manufacturing industry agglomeration and producer service industry agglomeration, respectively; i and t represent the city and year, respectively.

According to the research of Zhao et al. (2021) [44], the agglomeration degree of the manufacturing industry and producer services is measured by the location entropy index. The formula is:

$$Magg_{ij}(Sagg_{ij}) = (\frac{q_{ij}}{q_j})/(\frac{q_i}{q}) \tag{4}$$

where $Magg_{ij}$ and $Sagg_{ij}$ are the location entropy indexes of the manufacturing industry and producer service industry, respectively, in the city i; q_{ij} is the number of employees in j sectors in the city i; q_i is the number of employees in all industries in the city i; q_j is the number of employees in industry j nationwide; q is the number of employees in all sectors nationwide. j represents manufacturing or producer services. The selection of producer services was based on the practice of Xie et al. (2019) [45]. The seven industries of transportation, warehousing and postal services, information transmission computer services and the software industry, the wholesale and retail industry, the financial industry, the leasing and commercial service industry, the scientific research and technical service industry, and the environmental governance and public facilities management industry were combined to represent producer services.

(2) Core explanatory variable: the digital economy (De). Referring to the research of Li and Wang (2022) [46], this study measured the urban digital economy according to internet development and digital finance. These include the Internet penetration rate, mobile phone penetration rate, Internet-related employees, Internet-related industry output, and digital finance development. See Huang et al. (2022) [47] for details. Referring to the practice of Yu and Chen (2019) [48], the comprehensive level of digital economy is measured by the entropy method. The specific calculation steps are as follows:

① Standardize raw data:

$$\overline{x_{ij}} = \frac{x_{ij} - \min\{x_{ij}\}}{\max\{x_{ij}\} - \min\{x_{ij}\}} \quad (i = 1, 2, \ldots\ldots, m; j = 1, 2, \ldots\ldots, n)$$

where x_{ij} represents the value of the digital economy indicator j for city i.

② Due to the occurrence of 0 in the standardized indicator value, which is not conducive to subsequent calculations, it is necessary to perform a coordinate translation on the standardized data. The formula is: $P'_{ij} = 1 + \overline{x_{ij}}$

③ Calculate the proportion of the jth digital economy indicator in city i; the formula is:

$$P_{ij} = P'_{ij} / \sum_{i=1}^{m} P'_{ij}$$

④ Calculate the entropy and coefficient of variation of the jth digital economy indicator; the formula is:

$$e_j = -\frac{1}{1nm}\sum_{i=1}^{m} P_{ij}\ln P_{ij} \qquad g_j = 1 - e_j$$

⑤ Calculate the weight of the jth digital economy indicator in the comprehensive evaluation:

$$W_j = g_j / \sum_{j=1}^{n} g_j$$

⑥ Calculate the Comprehensive Index of the Digital Economy:

$$De_i = \sum_{j=1}^{n} W_j P'_{ij}$$

(3) Control variables. Human capital (H) was expressed by the number of college students. The higher the level of human capital, the higher the knowledge and skills of workers. The good integration and development of the manufacturing industry and producer services cannot be separated from the support of a highly skilled labor force. Transportation infrastructure ($infra$) was expressed by the urban per capita road area. Good transportation infrastructure is conducive to reducing transport and transaction costs and speeding up the flow of factors, thus promoting industrial collaboration and agglomeration. Foreign direct investment (fdi) was expressed by the proportion of utilized FDI in GDP. As the representatives of advanced technology, the technology spillovers brought by foreign direct investment are conducive to promoting industrial collaboration and agglomeration. Urbanization (urb) referred to the proportion of the urban population in the total population. On the one hand, the process of urbanization will lead to population agglomeration; on the other hand, urbanization also promotes the construction of urban infrastructure. Both are of great significance to promoting the development of industrial collaboration and agglomeration. The credit balance of financial institutions as a share of GDP represented economic development (fin). The developed financial development level has reduced the external financing costs of enterprises. Reducing financing costs has promoted industrial agglomeration (Zhang and Wang, 2009) [49].

(4) Mediation variables. M is knowledge spillovers and market size. For the measurement of knowledge spillover, refer to the research of Han and Li (2019) [50]. The measurement formula is as follows:

$$Ks_j = \sum_{v \neq j, v=1}^{m} \left(\frac{U_v}{d_{jv}^{\delta}}\right) + \frac{U_j}{d_{jj}^{\delta}} \tag{5}$$

where U refers to the number of patents granted in a given city. The number of patents granted represents a region's effective knowledge and technology output. The more patents granted, the higher the effectual knowledge output of the area (Zhang, 2014) [51]. Both j and v represent cities. d_{jj} refers to the distance of the city itself. Referring to the research of Head and Mayer (2004) [52], $d_{jj} = (2/3)R_{jj}$, where R_{jj} refers to the radius of a given city, $R_{jj} = \pi^{-1/2}A^{1/2}$, and A is the built-up area of the municipal jurisdiction of the city. δ is the distance attenuation parameter, which was set to 1. d_{jv} refers to the distance between cities. The distance between cities was calculated by using the longitude and latitude of the cities. The specific formula for this is: $d_{ij} = r * \arccos(\cos(\gamma_i - \gamma_j)\cos\theta_i\cos\theta_j + \sin\theta_i\sin\theta_j)$, where γ is the radius distance of the Earth's large arc (6378 km). γ_i and γ_j are the longitudes of the two cities, and θ_i and θ_j are the latitudes of the two cities.

The market size (Ms) measurement was expressed by the total amount of retail and social commodities, which was converted into the constant price in 2003 using the consumer price index.

4. Empirical Test and Result Analysis

4.1. The Spatial Distribution Characteristics of Digital Economy and Industrial Collaborative Agglomeration

To analyze the spatial relationship between digital economy and industrial collaborative agglomeration, the Arcgis10.4 software was used for visual display, and the results are shown in Figures 1 and 2. From Figures 1 and 2, it can be seen that in 2011 and 2019, the cities with the highest level of digital economy development were Beijing, Tianjin, Shanghai, Shenzhen, Guangzhou, Zhongshan, Nanjing, Hangzhou, Zhuhai, Ningbo, Xiamen, Suzhou, Dalian, Harbin, Chengdu, etc., forming a digital economy development pattern centered around the Beijing Tianjin Hebei Urban cluster, Yangtze River Delta urban cluster, Northeast urban cluster, Chengdu Chongqing urban cluster, and Guangdong Hong Kong Macao urban cluster, especially in the Yangtze River Delta urban cluster. Regions with high levels of industrial synergy and agglomeration are also core cities in urban clusters such as the Beijing Tianjin Hebei cluster, Yangtze River Delta cluster, Northeast China urban cluster, Chengdu Chongqing urban cluster, and Guangdong Hong Kong Macao cluster. This means that regions with good digital economy development also have higher levels of industrial collaborative agglomeration. To explore the impact of the digital economy on industrial collaborative agglomeration, we will use econometric models to verify.

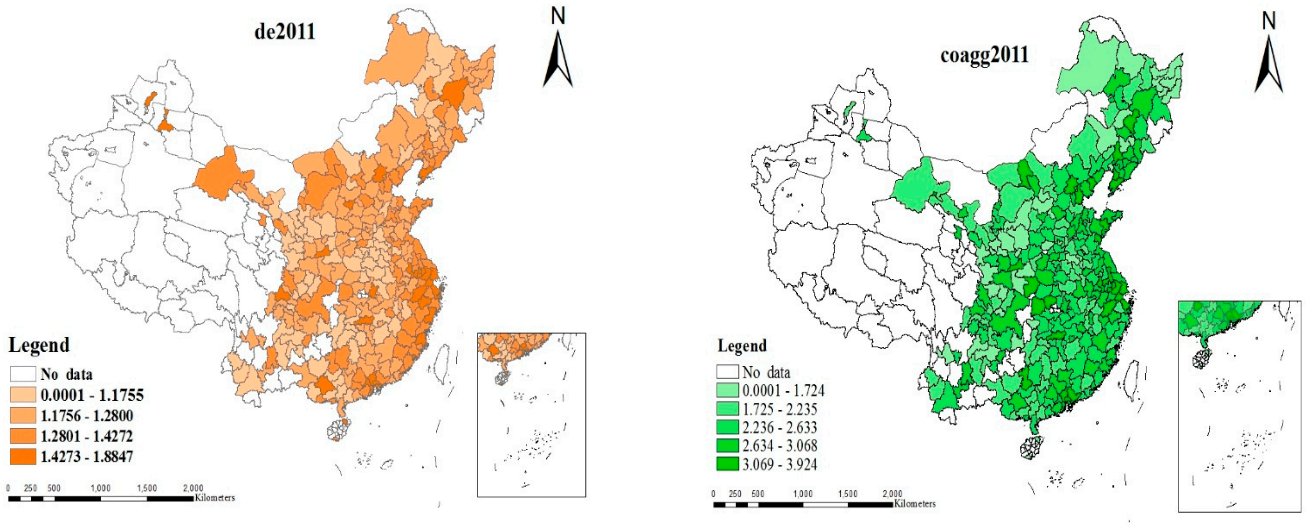

Figure 1. The spatial distribution of digital economy and industrial synergetic agglomeration in 2011.

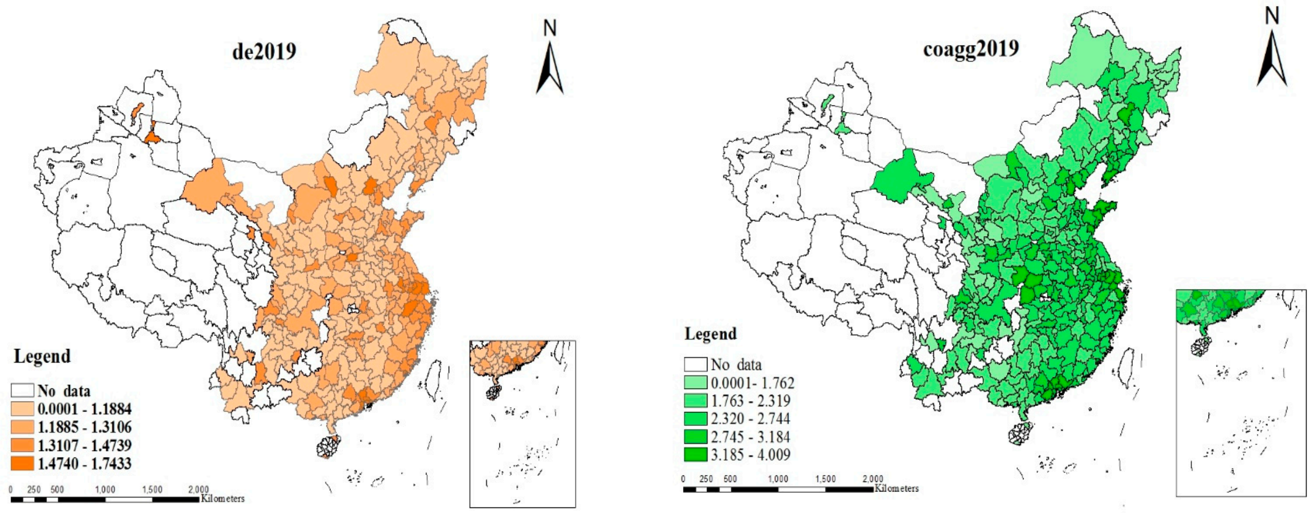

Figure 2. The spatial distribution of digital economy and industrial synergetic agglomeration in 2019.

4.2. Estimation Results of Full Sample

To overcome the influence of unobservable factors that do not change with time, this paper used a two-way fixed effect model to mitigate the endogeneity issues to improve the estimated results' reliability. For the convenience of comparison, the article only lists the results of fixed urban influences. Table 2 shows the estimated results of the analysis of the digital economy's effect on industrial agglomeration. The estimation results shown in column (1) in Table 2 did not take the control variables and time effects into account, while column (2) shows the estimation results that did not take the control variables into account but did control for the time and urban effects. After introducing the control variables, the results of not controlling for the time effect were calculated, which are shown in column (3), while column (4) contains the result of controlling for the time and urban effects. According to the data sheets, the estimated coefficients of the digital economy were positive at around 1%, meaning that the digital economy was found to have promoted the synergistic agglomeration of the manufacturing and producer service industries. The digital economy takes the modern information network as its main carrier, and digital knowledge and information as its main production factors (Lin et al., 2017) [53]. It is characterized by permeability, integration, and synergy (Jiao and Sun, 2021) [35]. Further, it expands the industrial chain division of labor boundaries, accelerates the integration and development of various industries, and further promotes the synergistic aggregation of these industries. In this study, among the control variables, the estimated coefficient of human capital ($\ln H$) was negative but not statistically significant, which indicates that human capital did not have a significant effect on the collaborative agglomeration of manufacturing and producer services. This is inconsistent with the research conclusion of Gao et al. (2021) [41]. The reason for this phenomenon is that the quality of education in China has not been improved by the increase in the number of educated people. Many people still work in low-technology fields (Zhao and Ye, 2018) [54]. This restricts the ability of the synergistic aggregation of human capital to promote manufacturing and producer services. As shown in columns (3) and (4), the estimated coefficient of transportation infrastructure ($\ln infra$) was significantly positive, indicating that transportation infrastructure had a positive effect on the manufacturing industry and productive service industry. This is consistent with the expected results. Perfect transportation infrastructure in a given area reduces transportation and trade costs, and attracts related companies to the area. This also strengthens the connection between upstream and downstream enterprises, thus promoting industrial collaboration and agglomeration.

The estimated coefficient of foreign direct investment (fdi) did not pass the significance test, which means that it did not have a significant impact on industrial agglomeration. This is consistent with the research results of Wang et al. (2022) [40]. Although foreign capital represents advanced technology, actively attracting foreign capital to promote economic growth leads to "bottom competition". This affects the quality of the foreign investment attracted, thus restricting the technology spillovers of foreign direct investment. The urbanization (urb) estimation coefficient was significantly positive at 5% after controlling for the urban and time effects. This is consistent with the research conclusion of Su and Li (2011) [42]. This shows that urbanization significantly promoted the industrial collaborative agglomeration, and it brought about the urban concentration of a large number of people. Urbanization provides enterprises with an abundant labor force and is conducive to improving urban infrastructure, thus promoting industrial collaboration and agglomeration. The financial development (fin) estimation coefficient was found to be negative and insignificant when both the urban and time effects were controlled. There was no obvious effect of financial development on the collaborative agglomeration of manufacturing and producer services. This is inconsistent with the research conclusion of Gao et al. (2021) [41]. Under information asymmetry, traditional financial institutions are generally reluctant to lend, and many enterprises face severe external financing constraints (Sun et al., 2019) [55]. Further, the external financing cost of enterprises is high, which affects the development of enterprises, and is unfavorable to the coordinated development of industries.

Table 2. Estimation results of full sample.

Explanatory Variables	(1)	(2)	(3)	(4)
$\ln De$	0.1753 ***	0.2411 ***	0.1729 ***	0.2275 ***
	(2.90)	(3.48)	(2.86)	(3.28)
$\ln H$			−0.0027	−0.0019
			(−0.79)	(−0.54)
$\ln infra$			0.0130 *	0.0169 **
			(1.88)	(2.41)
fdi			0.0003	−0.0002
			(0.20)	(−0.12)
urb			−0.0053	0.1452 **
			(−0.12)	(2.37)
fin			−0.0090 *	−0.0037
			(−1.72)	(−0.67)
$cons$	0.8106 ***	0.7986 ***	0.8195 ***	0.7140 ***
	(67.40)	(48.77)	(20.12)	(14.43)
R^2	0.0037	0.0213	0.0066	0.0268
Urban FE	Yes	Yes	Yes	Yes
Time FE	No	Yes	No	Yes
Number of samples	2574	2574	2574	2574

Note: The t-statistic values are in brackets in the table; *, **, and *** are significant at 10%, 5%, and 1% levels, respectively. The following table is the same.

4.3. Robustness Test

To ensure the accuracy of the above research conclusions, a robustness test was conducted. This involved replacing the core explanatory variables and removing the sampling data from various cities, as well as using an endogeneity test.

(1) Robustness Test of Substituted Variables and Rejecting Sampling Data from Certain Cities

The robustness of the regression results' finding that the digital economy promotes the collaborative agglomeration of manufacturing and producer services was tested by both replacing the variables measured by the level of the digital economy and by removing the sampling data from several cities. Referring to the practice of Liang et al. (2021) [56], the "Internet+" digital economy index in the China Internet + Index Report (2016–2020) released by the Tencent Research Institute was taken as the proxy variable of the development level of the digital economy, and this was re-estimated using the double fixed-effect model. Since the report in 2020 did not list the "Internet plus index" of the cities in detail, the "Internet plus" index of the cities in 2019 was estimated by multiplying the previous year's data by the average growth rate from 2015 to 2018. In addition, because of their special economic position, higher administrative level and more resources, the municipalities directly under the Central Government are more favorable for the development of various fields, which would have had a certain impact on the research results. Therefore, the data from Beijing, Shanghai, Tianjin, and Chongqing were excluded from the regression analysis. The robustness test results of the above two domains are described in Table 3. Columns (1) and (2) in Table 3 show the estimation results of replacing the core explanatory variables and removing the sampling data from Beijing and other municipalities directly under the Central Government, respectively. Table 3 shows that the digital economy ($\ln De$) had a significant positive effect on the collaborative agglomeration of manufacturing and producer services, regardless of whether it was a replacement indicator or an adjusted sample data set was used. Compared with the regression analysis results in Table 2, these results show the stability of the regression analysis, with no essential changes being observed.

Table 3. Robustness test results: substituted variables and rejecting sampling data from certain cities.

Explanatory Variables	**(1)**	**(2)**
$\ln De$	0.0467 *** (4.76)	0.2350 *** (3.33)
$\ln H$	−0.0018 (−0.16)	−0.0020 (−0.56)
$\ln infra$	0.0016 (0.18)	0.0169 ** (2.40)
fdi	−0.0021 (−1.21)	−0.0001 (−0.04)
urb	0.4391 *** (2.79)	0. 1390 ** (2.24)
fin	0.0083 (1.28)	−0.0039 (−0.70)
$cons$	0.6065 *** (4.31)	0.7124 *** (14.32)
R^2	0.0693	0.0269
Urban FE	Yes	Yes
Time FE	Yes	Ye
Number of samples	1430	2538

Note:The t statistic values are in brackets in the table; ** and *** indicate significance at the 5% and 1% levels, respectively.

(2) Endogeneity test

Although the article controlled for the factors affecting the collaborative agglomeration of urban manufacturing and producer services, there were some other potential influences on industrial collaborative agglomeration. During the modeling process, it is difficult to incorporate various influencing factors into the model, which may cause endogeneity problems. To address this issue and ensure the accuracy of the above estimation results, the article referred to the research of Li and Wang (2022) [46]. This took the number of post offices per million residents in Hangzhou in 1984 and the spherical distances between Hangzhou and various cities as instrumental variables of the digital economy. Because these instrumental variables involved cross-sectional data, the panel instrumental variable was calculated by multiplying the instrumental variable by the annual dummy variable. In addition, this study applied the two-stage least square method (2SLS) to the first-order lag and the second-order lag items of the development level of the digital economy, and conducted an endogeneity test for the above two instrumental variables. The measurement and estimation results of the above instrumental variables are shown in Table 4. Column (1) of Table 4 shows the estimation results using the number of post offices per million people in 1984, the intersection of the spherical distance from Hangzhou to each city, and the annual dummy variable as the tool variables. As shown in Column (2) in Table 4, the development level of the digital economy lagged behind the estimation results of the first and second stage instrumental variables. Table 4 shows that the statistical value of KP rk LM was significant at 1%, indicating that the model had enough instrumental variable identification; further, the KP rk Wald F statistic was greater than the critical value of the Stock–Yogo weak identification test at the 10% level, so weak instrumental variables were able to be excluded. This also shows that the tool variables were reasonable and effective. After controlling for the potential endogeneity problem, the estimation coefficients of the digital economy were found to be significantly positive. This shows that the digital economy was found to be able to promote the coordinated development of manufacturing and producer services. This conclusion was still valid, which supports the conclusion obtained by the earlier econometric regression analysis.

Table 4. Robustness test results: regression of instrumental variables.

Explanatory Variables	(1)	(2)
$\ln De$	1.3732 *** (9.12)	1.1615 *** (4.46)
$\ln H$	0.0266 *** (6.64)	−0.0208 *** (−2.96)
$\ln infra$	0.0314 *** (4.02)	0.0081 (1.05)
fdi	0.0151 *** (5.64)	−0.0039 *** (−3.26)
urb	−0.0551 (−0.77)	−0.0006 (−0.01)
fin	−0.0788 *** (−8.07)	0.0004 (0.05)
$cons$	0.3028 *** (6.63)	0.8083 *** (5.82)
R^2	0.3588	0.9310
Kleibergen–Paap rk LM	385.5860 [0.0000]	55.1810 [0.0000]
Kleibergen–Paap rk Wald F	26.9710 {11.37}	27.4100 {19.93}

Note: In parentheses are Z statistics and concomitant probabilities, and in brackets are Stock–Yogo test thresholds; *** indicate significance at the 1% level.

4.4. Mechanism Test

Previous empirical research results have shown that the digital economy can significantly promote the collaborative agglomeration of manufacturing and producer services. Theoretically, the digital economy can promote knowledge spillovers and expand the market size, thus promoting the synergistic agglomeration of various industries. However, the specific mechanism has yet to be tested. Table 5 reports the results of the mechanism inspection based on model (2). Column (1) and column (2) in Table 6 show the estimated results of the knowledge spillovers and market size as explained variables, respectively. The results in column (1) show that the estimated coefficient of the digital economy ($\ln De$) was significantly positive at the 5% level. This illustrates the role of the development of the digital economy in promoting knowledge spillovers and proves hypothesis 1; that is, the development of the digital economy → knowledge spillovers → the collaborative agglomeration of manufacturing and producer services. Through the development of the digital economy, enterprises have gained more convenient access to information and knowledge, and new technologies are spreading faster and faster among industries. At the same time, the development of the digital economy can also introduce advanced production technology and management ideas into the production and manufacturing processes, thereby greatly improving the production efficiency of the manufacturing industry. It has also strengthened the correlation effect between manufacturing and producer services, thus increasing the interconnection between the two industries.

In this study, from the estimation results shown in column (2), the digital economy was found to have greatly promoted the expansion of the market size. This confirms hypothesis 2: the development of the digital economy → the expansion of the market size → the synergetic agglomeration between manufacturing and producer services. The application of digital technology has enabled a breakthrough in the application of e-commerce in the market, reducing the costs of searching, trading, and matching. At the same time, the trade barriers within the same industry have also been reduced, which has been conducive to the extensive connection and cooperation of various market entities, thereby expanding the scale of their markets. Through the continuous expansion of the market scale, the production process has been further subdivided, and due to the increasing dependence on manufacturing and producer services, the synergy between the two industries has also increased.

Table 5. Test of the effect of the mechanism of digital economy on industrial collaborative agglomeration.

Explanatory Variables	(1)	(2)
$\ln De$	0.5445 **	0.3421 **
	(1.97)	(2.41)
$\ln H$	0.0184	0.0042
	(1.33)	(0.60)
$\ln infra$	0.0474 *	0.0310 **
	(1.70)	(2.18)
fdi	0.0183 ***	0.0078 **
	(2.93)	(2.45)
urb	0.5647 **	0.2782 **
	(2.32)	(2.23)
fin	0.0186	−0.0516 ***
	(0.85)	(−4.61)
$cons$	4.6898 ***	14.5265 ***
	(23.78)	(143.76)
R^2	0.6539	0.6824
Urban FE	Yes	Yes
Time FE	Yes	Yes
Number of samples	2574	2574

Note: The values in brackets in the table are *t* statistic values; *, **, and *** are significant at 10%, 5%, and 1% levels, respectively

Table 6. Test results for urban size heterogeneity.

Explanatory Variables	Large Cities	Medium-Sized Cities	Small Cities
$\ln De$	0.1663 **	0.2464 *	0.3632 *
	(1.97)	(1.73)	(1.75)
$\ln H$	0.0068 *	−0.0224 ***	0.0066
	(1.78)	(−3.26)	(0.33)
$\ln infra$	0.0166 *	0.0198	0.0040
	(1.80)	(1.58)	(0.20)
fdi	−0.0010	0.0045	−0.0034
	(−0.58)	(1.14)	(−0.79)
urb	0.0729	0.3326 ***	0.1086
	(0.99)	(2.77)	(0.53)
fin	−0.0348 ***	−0.0155	0.0128
	(−2.74)	(−1.40)	(1.45)
$cons$	0.7808 ***	0.7409 ***	0.4758 **
	(12.79)	(8.16)	(2.29)
R^2	0.0405	0.0651	0.0726
Urban FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Number of samples	1458	783	333

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The *t*-statistic values are in parentheses.

5. Discussion

5.1. Analysis Based on Different City Sizes

Due to differences in factors among major cities, such as internet infrastructure investment, transportation, science and technology, and industrial development levels, the effect of the digital economy on the collaborative agglomeration of manufacturing and producer services may be heterogeneous. Referring to the Notice on Adjusting the Classification Standards of City Size issued by the State Council, this paper divided cities into three categories: large cities (with a population of more than 1 million), medium-sized cities (with a population of 500,000 to 1 million), and small cities (with a population of 500,000 or less) based on their population at the end of the year. Table 6 shows estimates of heterogeneity for the different city sizes. The estimation results show that the estimation coefficient of the digital economy (ln *De*) was significantly positive, indicating that it had a considerable role in promoting the synergistic aggregation of manufacturing and producer services at the three city levels. Regarding the impact of the digital economy on industrial collaborative agglomeration, the city sizes were ranked as follows: small cities > medium-sized cities > large cities. This was the case because, on the one hand, small cities benefit from the high externality and intelligence of the digital economy. On the other hand, compared with large cities, the degree of industrial development in small and medium-sized cities is relatively low in China, and the synergistic agglomeration of manufacturing and producer services has more room for development in such cities; this makes the digital economy more effective in promoting industrial collaborative agglomeration in these types of cities.

5.2. Analysis Based on Industry Heterogeneity

Due to the differences in the sub-sectors of producer services, the digital economy has been found to have produced heterogeneity in the synergistic agglomeration of different producer service and manufacturing industries. Starting from the work of Guo and Yuan (2022) [6], this paper classified productive services into high-end and low-end industries. The financial, information transmission, computer services and software, and scientific research and technology services industries were classed as high-end productive services; the transportation, warehousing and postal services, wholesale and retail, leasing and business services, and environmental governance and public facilities management industries were classed as low-end effective services. Industrial collaborative agglomeration can also be divided into manufacturing and high-end producer services and manufacturing and low-end producer services. Table 7 reports the estimation results regarding the industry heterogeneity. Table 7 shows that the development of the digital economy was found to have significantly promoted the synergetic agglomeration between the manufacturing and high-end producer services, but had no significant impact on the synergetic agglomeration between the manufacturing and low-end producer services. The possible reason for this is that the knowledge spillovers brought by the digital economy can improve the productivity of the manufacturing and promote the development of manufacturing products in the direction of high added value. Compared with low-end producer services, high-end producer services are more knowledge- or technology-intensive. As manufacturing technology improves, manufacturing enterprises will have more frequent contact with high-end producer services, which is conducive to the effective integration of high-end producer services into the manufacturing value chain. Therefore, this will significantly promote the synergetic agglomeration between the manufacturing and high-end producer services.

5.3. Analysis of Threshold Effect

Due to significant differences in the resource endowments and digital infrastructure among different regions, digital infrastructure and digital information platforms are not yet complete when the development level of the digital economy is low. The breadth and depth of digital economy application are severely constrained, its knowledge spillover and cost reduction effect on transactions are limited, and its promotion effect on industrial collaborative agglomeration is limited. At a high level of development in the digital economy, digital facilities and information network platforms gradually improve, industrial systems gradually enjoy digital dividends, and the threshold for digital technology gradually decreases. The role of the digital economy in industrial integration and development is fully unleashed, and its driving effect on industrial collaborative agglomeration is more significant. Therefore, the promoting effect of the digital economy on industrial collaborative agglomeration is not a simple linear feature, and there may be a threshold effect; that is, the impact of the digital economy on industrial collaborative agglomeration has a non-linear characteristic of increasing "marginal effect". To verify the influence of this nonlinearity, drawing on the research of Wang (2015) [57], the panel threshold model is set as follows:

$$\ln Coagg_{it} = \phi_0 + \phi_1 \ln De_{it} \times I(\ln De_{it} \le \gamma) + \phi_2 \ln De_{it} \times (\ln De_{it} > \gamma) + \phi_3 \ln H_{it} + \phi_4 fdi_{it} + \phi_5 \ln infra_{it} + \phi_6 urb_{it} + \phi_7 fin_{it} + \sigma_{it} \quad (6)$$

Among them, $I(\cdot)$ denotes the indicator function, ϕ_0 denotes the intercept term, ϕ_1 to ϕ_7 represent the parameters to be estimated, and γ denotes the specific threshold value of the digital economy level to be estimated. i and t represent the city and year, respectively. σ_{it} represents random disturbance terms.

Table 7. Test results for industry heterogeneity.

Explanatory Variable	Collaborative Agglomeration of Manufacturing and High-End Producer Services	Collaborative Agglomeration of Manufacturing and Low-End Producer Services
$\ln De$	0.3932 ***	0.0923
	(5.03)	(1.16)
$\ln H$	−0.0034	0.0010
	(−0.87)	(0.25)
$\ln infra$	0.0084	0.0256 ***
	(1.07)	(3.21)
fdi	0.0003	−0.0008
	(0.17)	(−0.42)
urb	0.1068	0.1149
	(1.55)	(1.64)
fin	−0.0048	−0.0025
	(−0.78)	(−0.40)
$cons$	0.7492 ***	0.6945 ***
	(13.45)	(12.28)
R^2	0.0589	0.0311
Urban FE	Control	Control
Time FE	Control	Control
Number of samples	2574	2574

Note: *** indicate significance at the 1% level; The *t*-statistic values are in parentheses.

When conducting a panel threshold analysis, it is first necessary to test the significance of the threshold effect; that is, whether there is a threshold effect. This article draws on Hansen's (1999) [58] research method to test the existence of a threshold effect, and the test results are shown in Table 8. The test result of using the development level of the digital economy as a threshold variable is that only a single threshold passes the significance test, and the p values corresponding to the double and three thresholds do not pass the significance test. This indicates that the impact of the digital economy on the resilience of agricultural development has a single threshold feature. Therefore, this article selects a single threshold model for analysis.

Table 8. Diagnostic test results of threshold features.

Threshold Variable	Threshold Number	F Value	p Value	Critical Value			BS Frequency
				10%	5%	1%	
Digital Economy	Single threshold	13.82 *	0.0660	12.8365	14.7492	17.6997	500
	Double threshold	2.38	0.9880	11.8188	15.2947	20.3944	500
	Triple threshold	3.00	0.9120	9.8321	12.3326	16.5420	500

Note: * indicate significance at the 10% level.

Table 9 reports the threshold regression results based on the development level of the digital economy. From Table 9, when the development level of the digital economy was below 1.0869, the estimated coefficient of the impact of the digital economy on industrial collaborative agglomeration was 0.2213, but did not pass the significance test. This indicates that when the level of the digital economy was below the threshold value, the digital economy did not have a significant impact on industrial collaborative agglomeration. The reason for this is that when the digital economy is in a lower development stage, the digital infrastructure and digital platforms are not yet complete, and the application of technologies such as the Internet and big data is not deep enough, affecting the spillover and dissemination of new knowledge, as well as the widespread connection and close co-operation of various market entities. Therefore, the promotion effect of the low-level digital economy on industrial collaborative agglomeration has not yet been shown. When the digital economy reaches a higher stage of development, digital facilities and information network platforms gradually improve. The application of big data, artificial intelligence, and cloud computing accelerates the dissemination of new technologies, which is conducive to the sharing of innovative technologies and knowledge among enterprises, breaks the information gap in the market, reduces transaction barriers, and fully demonstrates spillover effects and economies of scale, Thus, the promoting effect of the digital economy on industrial collaborative agglomeration can be demonstrated.

Table 9. Threshold Effect Regression Results.

Variable	Coefficient Estimation	T statistical Value
$\ln De \times I(\ln De \leq 0.0833)$	0.2213	1.39
$\ln De \times I(\ln De > 0.0833)$	0.6378 ***	3.54
$\ln H$	−0.0027	−0.79
$\ln infra$	0.0134 *	1.95
fdi	0.0004	0.23
urb	−0.0063	−0.15
fin	−0.0085	−1.63
$cons$	0.8208 ***	19.86

Note: *, *** indicate significance at the 10%, 1% levels, respectively.

5.4. Analysis of Spatial Spillover Effect

The degree of collaborative agglomeration among local industries will impact neighboring regions, and the industrial agglomeration in neighboring regions will also affect the regional industrial agglomeration through the feedback effect. It has been noted that the collaborative agglomeration of manufacturing and producer services is characterized by a certain spatial autocorrelation (Guo and Yuan, 2022) [6]. Due to spatial dependence, factors affecting industrial collaborative agglomeration can have an impact on surrounding areas through the spatial correlation effect of inter-regional industrial collaborative agglomeration. Therefore, in addition to the digital economy, other influencing factors may also have spatial interaction effects with industrial collaborative agglomeration in surrounding areas. Therefore, in Equation (1), the spatial interaction terms of industrial collaborative agglomeration, digital economy, and control variables are introduced, and further expanded into a spatial econometric model:

$$\begin{aligned}\ln Coagg_{it} = {} & \lambda_0 + \rho \sum_{i \neq j}^{N} w_{ij} \ln Coagg_{jt} + \lambda_1 \ln De_{it} + \lambda_2 \ln H_{it} + \lambda_3 \ln infra_{it} + \lambda_4 fdi_{it} \\ & + \lambda_5 urb_{it} + \lambda_6 fin_{it} + \chi_1 \sum_{i \neq j}^{N} w_{ij} \ln De_{jt} + \chi_2 \sum_{i \neq j}^{N} w_{ij} \ln H_{jt} + \chi_3 \sum_{i \neq j}^{N} w_{ij} \ln infra_{jt} \\ & + \chi_4 \sum_{i \neq j}^{N} w_{ij} fdi_{jt} + \chi_5 \sum_{i \neq j}^{N} w_{ij} urb_{jt} + \chi_6 \sum_{i \neq j}^{N} w_{ij} fin_{jt} + \omega_i + \tau_t + \xi_{it}\end{aligned} \tag{7}$$

where ρ is the spatial autoregressive coefficient, which reflects the spatial autocorrelation of industrial collaborative agglomeration between different regions. Both i and j represent cities, and t represents years. λ_1 to λ_6 are the parameters of the variables to be estimated, and χ_1 to χ_6 are the parameters of the spatial interaction terms of the variables to be estimated. w_{ij} represents the spatial weight matrix. ω_i,τ_t and ξ_{it} represent the space effect, time effect, and random disturbance term, respectively. Further, based on the research of Zhang et al. (2021) [59], this study constructed three kinds of matrices: a geographic distance matrix (w_{ij}^1), economic distance matrix (w_{ij}^2), and financial and geographic nested matrix (w_{ij}^3). The geographic distance matrix (w_{ij}^1) was established by the reciprocal of the geographic distance between cities, $w_{ij}^1 = 1/d_{ij}(i \neq j)$, where d_{ij} is the distance between cities; at that time, $i = j$, $w_{ij}^1 = 0$. The economic distance matrix $w_{ij}^2 = 1/\left|\overline{Q}_i - \overline{Q}_j\right|$. $\overline{Q}_i$ and $\overline{Q}_j$ are the average GDP per capita of the cities i and $j(i \neq j)$ in 2011–2019, respectively. The economic and geographic distance nested matrix $w_{ij}^3 = \vartheta w_{ij}^1 + (1-\vartheta) w_{ij}^2$, ϑ, took 0.5. Formula (7) is a spatial interaction term that contains both the dependent variable and the explanatory variables, which is called the spatial Durbin model.

Drawing on Elhorst's (2014) [60] method, the spatial econometric model is selected using the "specific to general" and "general to specific" approaches. The test results for model selection are shown in Table 10. The results of LM Spatial lag Test, Robust LM Spatial lag Test, LM Spatial error Test, and Robust LM Spatial error Test all passed the significance test. Except for the Robust LM Spatial lag Test in sFE that did not pass the significance test, overall, the null hypothesis of no spatial lag and no spatial error was rejected, indicating that both the spatial lag model and the spatial error model are applicable. The LR Spatial Test and LR Time Test both passed the significance test at the 1% level, indicating the presence of spatial or temporal fixed effects. The results of the Hausman Test rejected the random effects model. The results of the Wald Spatial Lag Test and Wald Spatial Error Test indicate that the original assumption of converting spatial Durbin models into spatial lag (SAR) and spatial error models (SEM) was rejected. Therefore, a spatiotemporal dual fixed spatial Durbin model was chosen for estimation.

Table 10. Results of econometric tests of model selection.

	OLS	sFE	tFE	stFE
LM Spatial lag Test	235.8984 ***	242.0128 ***	213.1848 ***	108.2316 ***
LM Spatial error Test	226.1413 ***	249.3725 ***	142.9683 ***	10.5262 ***
Robust LM Spatial lag Test	40.7280 ***	0.0524	72.9389 ***	101.9818 ***
Robust LM Spatial error Test	30.9708 ***	7.4120 ***	2.7224 **	4.2764 **
LR-Spatial Test	4912.7049 ***			
LR-Time Test	52.8733 ***			
Hausman Test	57.4587 ***			
Wald Spatial Lag Test	24.2584 ***			
Wald Spatial Error Test	25.6447 ***			

Note: In the table, OLS, sFE, tFE, and stFE represent non-fixed effects, spatial fixed effects, temporal fixed effects, and spatiotemporal bidirectional fixed effects, respectively; ** and *** indicate significance at the 5% and 1% levels, respectively.

When the spatial Durbin model is used for estimation, the estimated parameters of explanatory variables cannot reflect their marginal effects. Therefore, in this study, the method of LeSage and Pace (2009) [61] was used for reference, and the variation in the partial differential of variables was used for interpretation. Direct effects were used to explain the impact of the variables in a region on the region's industrial collaborative agglomeration. Indirect effects describe the impact of variables in an area on industrial collaborative agglomeration in other regions. Table 8 reports the estimation results for the direct and indirect effects of the SDM model. Among the three spatial weight matrices, the spatial autoregressive coefficients ρ were significantly positive at 1%, indicating that the collaborative agglomeration of manufacturing and producer services had a positive spatial interaction. Table 11 shows that under the three different spatial weight matrices, the collaborative agglomeration of the manufacturing and producer services industries had a significant positive effect. This shows that with the development of the digital economy, industrial agglomeration in the region developed rapidly. The indirect effect only failed the significance test under the economic distance weight, while the other two weight matrices were significantly positive at the 5% level. In summary, the digital economy was found to play a significant role in promoting the industrial agglomeration of the surrounding areas of the study regions. Due to the in-depth and comprehensive coverage of the digital economy, the cross-regional flow of production factors was accelerated, breaking the constraints of space and time. At the same time, the breadth and depth of inter-regional economic activities was enhanced and, to a certain extent, the division of labor between regions was promoted, thus forming spatial spillover effects. Therefore, the digital economy can promote industrial collaboration and agglomeration in the study regions and their surrounding areas.

Table 11. Direct and indirect effects of the digital economy on the synergistic agglomeration of urban industrial regions.

Effect Type	Explanatory Variable	Geographic Distance Matrix	Economic Distance Matrix	Nested Matrix
Direct effect	$\ln De$	0.1513 **	0.2377 ***	0.2116 ***
		(2.20)	(3.51)	(2.95)
	$\ln H$	−0.0002	−0.0019	−0.0013
		(−0.05)	(−0.61)	(−0.41)
	$\ln infra$	0.0129 *	0.0162 **	0.0150 **
		(1.96)	(2.54)	(2.35)
	fdi	−0.0018	−0.0001	−0.0008
		(−1.21)	(−0.07)	(−0.58)
	urb	0.1227 **	0.1378 **	0.1545 ***
		(2.08)	(2.48)	(2.72)
	fin	0.0017	−0.0034	−0.0002
		(0.35)	(−0.67)	(−0.05)
Indirect effect	$\ln De$	6.5779 **	−0.0760	1.9224 **
		(1.99)	(−0.40)	(2.53)
	$\ln H$	0.3329	0.0124	0.0763 **
		(1.52)	(1.32)	(2.44)
	$\ln infra$	−0.8224 *	0.0105	−0.0559
		(−1.66)	(0.59)	(−1.02)
	fdi	0.1785 *	−0.0019	0.0202
		(1.81)	(−0.47)	(1.32)
	urb	−0.4747	−0.3965 ***	−0.9215 *
		(−0.23)	(−2.60)	(−1.81)
	fin	0.1144	−0.0673 ***	−0.0696
		(0.47)	(−3.66)	(−1.03)
$w * \ln Coagg$		0.7524 ***	0.0853 **	0.3786 ***
		(10.52)	(2.27)	(4.77)
Spatial FE		Yes	Yes	Yes
Time FE		Yes	Yes	Yes

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Z-statistic values are shown in parentheses.

6. Conclusions, Policy Recommendations, and Future Research

6.1. Conclusions

This paper used panel data on 286 prefecture-level cities and above in China from 2011 to 2019, and employed a two-way fixed effect model, threshold effect model, and SDM to conduct an empirical study on the effect of the digital economy on the synergistic agglomeration between the manufacturing and productive services. The specific conclusions are as follows:

First, according to the overall sampling and estimation results, the digital economy was found to play a significant role in promoting the industrial synergistic agglomeration effect of the manufacturing and producer services industries in the study regions and their surrounding areas. Only when the development level of the digital economy reaches a certain level can its promoting effect on industrial synergy and agglomeration become apparent.

Second, from the mechanism analysis, it can be seen that the digital economy can promote the synergistic aggregation of industries by promoting knowledge spillovers and expanding the market size. In addition, this analysis also examined the mechanism of the digital economy that affects the synergy and agglomeration of manufacturing and productive services. The analysis not only deepens our understanding of how the digital economy affects industrial synergy, but also provides a theoretical basis and empirical evidence for the digital economy's promotion of industrial synergy.

Third, the heterogeneity test examined the role that the spatial spillover effect of the digital economy plays in industrial synergy and agglomeration. It was found that the digital economy played a role in promoting the industrial collaborative agglomeration of large, medium-sized, and small cities, and the effect is small cities > medium-sized cities > large cities. Further, the digital economy was found to promote the synergetic agglomeration between the manufacturing and high value-added producer services. However, no significant effect was found on the synergistic aggregation of the manufacturing industry and low-end producer services. This paper explored the heterogeneity of the impact of the digital economy on industrial synergy from the perspectives of different city sizes and different industries. In summary, this study provides in-depth research on the impact of the digital economy on industrial synergy and agglomeration. This article not only provides empirical evidence on how the digital economy affects industrial collaborative agglomeration, but also provides a scientific basis for government departments to formulate and implement relevant policies.

6.2. Policy Recommendations

Based on the above conclusions, this paper proposes the following policy recommendations:

First, the government should vigorously develop the digital economy and promote the collaborative agglomeration of manufacturing and producer services. A good digital infrastructure provides a basis for developing the digital economy. Therefore, it is necessary to increase investment in the construction of new types of infrastructure, such as the Internet, big data, and artificial intelligence, actively guide social capital to invest in key industries, such as the Internet and big data, promote the leapfrog development of digital economy infrastructure, and accelerate digital transformation and upgrading. Further, the use of digital technology should be strengthened, and the penetration of the digital economy should be promoted. Utilizing digital technology to enhance the integration of industrial informatization and industrialization, relying on digital technology to accelerate the dissemination of scientific and technological knowledge to promote talent exchange between regions, and further breaking through the regional bottleneck of industrial collaborative agglomeration. Through the penetration of new generation technologies and the development of Internet big data, we will strengthen the application of information technology industries, establish standardized industrial interaction platforms, enhance information mobility, promote regional industrial transfer, guide rational industrial layout, and form a collaborative agglomeration model between manufacturing and productive service industries. Further, through accelerating the transformation and development of the manufacturing, and by expanding the division of labor in the industrial chain, the industry's externality in space can be maximized, so as to achieve the cross-regional division of labor and promote the integrated development of the manufacturing and producer services industry. On this basis, the manufacturing industry and the producer services industry can promote each other and the coordinated development of the two.

Second, the synergistic effect of the digital economy on manufacturing and producer services, which is based on knowledge spillovers and market expansion, should be maximized. While encouraging enterprises to actively develop and innovate, the government should also support the research and development of enterprises, thereby promoting the generation of new technologies and knowledge, and also should promote the Increase in production knowledge and create conditions for knowledge spillovers. All localities should also vigorously break down institutional barriers, actively promote regional market integration, enhance cross-regional enterprise staff exchanges and learning, and thus accelerate knowledge spillovers. In addition, through relying on the new development pattern of "double circulation", we should give full play to the advantages of China's super-large market and promote the interactive development of the international and domestic markets. Simultaneously, we should improve the market mechanism, realize the rational distribution of resources, create a market atmosphere of benign competition and promote the expansion of the market scale.

Third, big cities should make full use of their more advantageous digital economy foundations and continue expanding the digital industry's breadth in order to promote the integrated development of enterprises. At the same time, we should actively exert the effect of the network radiation of big cities on surrounding cities, promote the diffusion of the digital industry and technology to small and medium-sized cities, and promote the pattern of the coordinated development of the digital economy inside and outside a given region. In addition, while small and medium-sized cities are actively developing the digital economy, the government should speed up digital infrastructure construction in these regions by increasing policy support. At the same time, it is necessary to vigorously promote the transfer of digital resources from advantageous regions to underdeveloped areas, increase the attractiveness of small and medium-sized cities to talent and high-tech enterprises, and maximize these cities' status in the digital economy regarding industrial collaboration.

Fourth, the digital economy has played a significant role in promoting the synergistic aggregation between manufacturing and high-end producer services, and regions with great advantages in their economic foundations and industrial structure should continue to vigorously develop in this regard. In this era of the digital economy, the high-end producer services industry can make use of its knowledge and technology advantages and use its associated role to enhance its association with the manufacturing industry. Further, digital technology should be used to accelerate the dissemination of new technologies, the production technology levels of the study regions and their surrounding areas should be improved, and industrial transformation and development should be promoted in order to in turn promote the better-coordinated development between the manufacturing and producer services industries.

6.3. Future Research

Due to the availability and uniformity of data, the indicators of digital economy measurement in this paper are not comprehensive enough. For example, the urban level of electronic information industry fixed assets investment, software product scale, information service income scale, the number of electronic information industry manufacturing enterprises, and the indicators reflecting the development environment of the digital economy are not included in the evaluation system, which to some extent affects the reflection of the true level of the digital economy. In addition, although the collaborative agglomeration of manufacturing and productive services can to some extent reflect the development of industrial integration, it cannot more accurately reflect the integration and development of manufacturing and productive services. Industrial integration is reflected through various aspects such as industrial service-oriented, industrial industrialization, industrial informatization, and industrial efficiency. Furthermore, the research object of this article is prefecture level cities and above, which is not yet micro level compared to county-level cities. Therefore, this study has certain limitations in both depth and breadth. How to comprehensively measure the level of urban digital economy, the integration and development of manufacturing and productive services industries, and take the county-level as the research object are the focus of future research.

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