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The Knowledge Spillover Effect of Multi-Scale Urban Innovation Networks on Industrial Development: Evidence from the Automobile Manufacturing Industry in China

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Abstract: Multi-scale urban innovation networks are important channels for intra- and inter-city knowledge spillovers and play an important role in urban industrial innovation and growth. However, there is a lack of direct evidence on the impact of multi-scale urban innovation networks on industrial development. Drawing upon the "buzz-and-pipeline" model, this paper analyzes the impact of multi-scale urban innovation networks on industrial development by taking the automobile manufacturing industry in China's five urban agglomerations as an example. Firstly, based on the Form of Correlation between International Patent Classification and Industrial Classification for National Economic Activities (2018) and co-patents, we construct urban innovation networks on three different geographical scales, including intra-city innovation networks, inter-city innovation networks within urban agglomerations, and innovation networks between cities within and beyond urban agglomerations. Then, we employ the ordinary least squares model with fixed effects at the urban agglomeration level to explore the impact of urban multi-scale knowledge linkages on the development of the automobile manufacturing industry and the results showed that urban innovation networks at three different geographical scales have different impacts on industrial development. Specifically, intra-city innovation networks have a facilitating effect on industrial development, while both inter-city innovation networks within urban agglomerations and innovation networks between cities within and beyond urban agglomerations have an inverted U-shaped impact on industrial development. The interactions between urban innovation networks on three different geographical scales have a negative effect on industrial development. Simultaneously, the agglomeration level of urban industry plays a positive moderating role in the impacts of multi-scale urban innovation networks on industrial development.

Keywords: urban innovation networks; knowledge spillovers; buzz-and-pipeline; automobile manufacturing industry; co-patents; urban agglomerations

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1. Introduction

According to the new growth theory, knowledge spillover is a crucial endogenous variable for economic growth [1,2], which has become a consensus among economic geographers. Traditionally, knowledge spillover was deemed a highly localized phenomenon [3,4] with strong distance decay [5]. Face-to-face encounters and interactions based on geographic proximity are conducive to the acquisition of tacit knowledge which is difficult to disseminate through formal channels [6–8]. Co-located innovation actors can access new knowledge and innovations through frequent learning, thereby stimulating economic growth of enterprises and regions.

Nevertheless, this view has been increasingly challenged by many studies [9,10], which have indicated that knowledge can spread over long distances through mechanisms such as foreign direct investment [11,12], labor mobility [13,14], and technological proximity [15].

Findings for selected industries show that innovation comes mainly from the inflow remote knowledge [16,17]. Bathelt et al. [9] pioneered the "buzz-and-pipeline" model, which combines localization and distant knowledge spillovers in one explanatory framework. They argue that both the buzz of local networks and the "pipeline" of global networks are key to the success of business clusters, and that the two models play different roles in driving firm and cluster growth.

Within the "buzz-and-pipeline" framework, some studies have paid attention to the knowledge spillover of multi-scale innovation networks [10,18–20]. However, existing studies have mainly focused on the impact of innovation networks on urban innovation capability, while exploring the impact of multi-scale innovation networks on industrial development has gained relatively few attentions. This is a very important research topic. Since localized and distant knowledge spillovers vary by industry [10,21], urban innovation networks at different geographical scales may have differential impacts on industry development.

This paper addresses this gap in the literature by taking China's automobile manufacturing industry as an example. Firstly, the automobile industry is already an industry driven by open innovation [22], whose innovation and development increasingly relies on the integration of knowledge and technology across regions and domains [23]. Secondly, China is the largest country in the world in terms of automobile production. According to the International Automobile Association, China's automobile production accounted for about 31.8% of the global total in 2022. Therefore, it is representative to explore the impact of multi-scale urban innovation networks on industrial development by taking China's automobile manufacturing industry as an example. Specifically, this paper takes the cities in China's five major urban agglomerations as research objects, and then based on the co-patents constructs urban innovation networks on three different geographical scales, including intra-city innovation networks, inter-city innovation networks within urban agglomerations, and innovation networks between cities within and beyond urban agglomerations. Furthermore, we employ the econometric model to explore the knowledge spillover effect of multi-scale urban innovation networks.

The rest of the paper is organized as follows: In the next section we review the existing literature. We then describe the data and methods used and further present the results, which include the characterization of multi-scale urban innovation networks in the automobile manufacturing industry of China's five urban agglomerations and the estimated results of their impact on industrial development. Finally, this paper offers conclusions and outlines the policy implications of the findings and potential directions for future research.

2. Literature Review

2.1. The Geography of Knowledge Spillovers

Since the work of Jaffe [24], the research perspective of knowledge spillovers has gradually shifted from the firm level to the geographical unit. Traditionally, new knowledge is argued to be incompletely encoded, and access to its tacit component which is difficult to disseminate through formal communication relies heavily on face-to-face interaction [6–8]. Thus, early knowledge spillovers are considered highly localized [3,4]. The relevant scholars have pointed out that talents, firms, universities, and research institutions located in the same geographic location interact through face-to-face exchanges, which are conducive to promoting innovation output and economic growth within a region. Many studies have verified the geographic attenuation effect of knowledge spillovers for different regions through a variety of methods [7,25,26].

However, empirical evidence suggests that geographical proximity is not a necessary condition for knowledge spillovers [12,16,17]. For example, Gertler and Levitte [16] focuses on the biotechnology industry and find that high-value innovations are mainly derived from knowledge spillovers at a distance. Thus, distant knowledge spillovers received widespread attention [9,10]. The researchers argue that without external knowledge inflow, the exchange, sharing, and reorganization of local knowledge may lead to diminishing the value of knowledge, ultimately resulting in technology lock-in and reduced local innovation capacity [4,27]. Distant knowledge inflow would bring more heterogeneous and complementary knowledge sources, which is helpful to break local technological lock-in and facilitate the formation of breakthrough innovations [9,17,28].

Some research has explored the impact of industry heterogeneity based on a harmonized research framework combining localized and distant knowledge spillovers [10,19]. Malerba et al. [19] focus on six large industrialized countries and discover that national and international, intersectoral and intersectoral R&D spillovers vary across chemicals, electronics, and machinery industries. The study about metropolitan counties in the US by Kekezi et al. [10] also suggests that localized and distant knowledge spillovers vary by sector.

2.2. Research on Urban Innovation Networks

Urban innovation networks have received more attention under the rapid development of urban network research. Matthiessen et al. [29,30] earlier investigated the characteristics and influence factors of global urban innovation networks by co-authored papers. Subsequently, lots of scholars have conducted research on urban innovation networks in different regional and socioeconomic contexts, such as North America [31], Europe [32], and East Asia [33–35].

The research scales of urban innovation networks are increasingly diversified, gradually shifting from the global scale [29,30] to the regional [32], urban agglomeration [35], and intra-city scales [36]. Moreover, a group of scholars has paid attention to the multi-scale attributes of innovation networks [18,20,33,34]. For instance, taking China's Yangtze River Delta region as an example, Li and Phelps [33,34] constructed the framework of multi-scale urban innovation networks on global, national, and megapolitan scales, and comprehensively analyzed the differentiated characteristics and mechanisms of the innovation network of the Yangtze River Delta region at different scales. Furthermore, they also constructed a finer-scale urban innovation network by taking intra-city special economic zones as the research object [36].

Recently, studies on the performance of urban innovation networks have become increasingly popular. These studies have mainly focused on the relationship between urban innovation networks and innovation performance [18,20,31,37], while fewer studies have focused on the relationship between urban innovation networks and industrial development. For example, based on the "buzz-and-pipeline" framework, Cao et al. [18] explored the impact of intra- and inter-regional innovation networks on urban innovation capacity through Chinese cities, and Ren et al. [20] have analyzed intra- and inter-city innovation networks. Operti and Kumar [37] focused on the U.S. Metropolitan Statistical Areas (MSAs) and explored the relationship between regional innovation and multi-scale urban innovation networks.

2.3. Relationships between Multi-Scale Urban Innovation Networks and Industrial Development

Multi-scale urban innovation networks are strategic platforms for knowledge exchange, sharing and reorganization, and play a crucial role in the process of regional knowledge spillovers, which is important for industrial development. However, the characteristics of knowledge flows usually vary according to different geographical scales of innovation networks, which may have heterogeneous impacts on industrial innovation and development. The "buzz-and-pipeline" model proposed by Bathelt et al. [9] provides a good analytical framework for the relationship between urban innovation networks at different geographical scales and industrial development. According to the "buzz-and-pipeline" model and existing studies [18,20], in this paper, intra-city innovation networks are deemed analogous to "local buzz", while innovation networks between cities within and beyond urban agglomerations are deemed analogous to "global pipelines", and inter-city innovation networks within urban agglomerations are deemed to have dual characteristics of buzz and pipelines.

Cities are considered to be innovation machines that not only serve as containers for innovation agents, but also provide an environment for the exchange of knowledge and ideas [38]. Innovation actors within cities are prone to form intensive local interactions or "buzz" due to being in the same location and sharing the same social institutions, values, and cultural atmosphere [39]. "Buzz" facilitates the generation of new knowledge and ideas, which is important for enhancing industrial competitiveness and promoting industrial growth [9]. However, excessive "buzz" may lead to "information overload" on the one hand, causing innovation actors to suffer from a lack of direction and difficulty in decision making [18]. On the other hand, the value of local knowledge will continue to diminish, resulting in technological lock-in and decline [9], which finally would reduce the competitiveness of local industries.

Pipelines are seen as important ways to reduce the dangers of technology lock-in thanks to over-intensive local interactions [9,27]. On the one hand, through "pipelines", intra-city innovation actors have access to new knowledge, technologies, and ideas that are locally unavailable, which are conducive to radical innovation [17], thus enhancing industrial competitiveness. On the other hand, in addition to new knowledge technologies and ideas, "pipelines" can also bring new information on market demand [40], external investment, and specialized labor [41], which may be more important for industrial development. However, excessive "pipelines" can be equally harmful to the development of urban industries. Specifically, when a city's external linkages are significantly higher than its internal linkages, the city may lose their status as innovation agents and its development may be controlled by external cities [18,42]. Therefore, this paper hypothesizes that:

H1. *Multi-scale urban innovation networks have an inverted U-shaped impact on industrial development*.

Generally, "buzz" and "pipelines" are deemed to work together, but there is no consensus among scholars on the effects of synergy [9,37,43,44]. Bathelt et al. [9] and Bathelt [43] point out that there are complementary effects between the "buzz" and the "pipeline" and both them can bring unique competitive advantages to regions, clusters, and firms, which are supported by some empirical studies [16,18,45]. However, some research has recently found that "buzz" and "pipelines" are substitutes for each other [37,44], because over-connectivity imposes high operation and maintenance costs on actors, leading to "information overload" and "mobilization failure" [37,44]. In addition, another study has shown that the effects of "buzz" and "pipelines" interactions vary by the type of innovation [20]. Based on the existing studies, we suggest that "buzz" and "pipelines" interactions may have both positive and negative effects on industrial development, which may be related to the type of industry, the characteristics of the region, and other factors. In this paper, the automobile manufacturing industry characterized by high inputs, high costs, complex supply chains, and excessive linkages will further increase the cost to companies, which may be harmful to industrial development. Hence, this paper hypothesizes that:

H2. *The interaction of multi-scale urban innovation networks has a negative impact on industrial development*.

The impact of multi-scale urban innovation networks on industrial development may be influenced by the agglomeration level of urban industry. A higher agglomeration level of urban industry would produce stronger localized externalities which play a positive role in the development of firms and regional economic growth [46,47]. Based on existing theories and studies, there are at least two ways in which the agglomeration level of urban industry affects the role of multi-scale urban innovation networks in industrial development. Firstly, cities with a higher agglomeration level of industry, indicating that the city has gathered a larger number of factors such as talent, knowledge, and technology in the industrial field, has the ability to identify, absorb, and reorganize knowledge and information quickly input through multi-scale urban innovation networks, which can enhance the competitiveness of the city's industries, thus promoting industrial development. Secondly, a higher agglomeration level of an industry can lead to stronger economies of scale in the industrial field, which can reduce the maintenance and operation costs of multi-scale urban innovation networks and improve industrial efficiency. Thus, this paper hypothesizes that:

H3. *The level of urban industrial agglomeration plays a positive moderating role in the process of the influence of multi-scale urban innovation networks on industrial development*.

3. Materials and Methods

3.1. Study Area

This paper takes five urban agglomerations in China as research regions (Figure 1). The five urban agglomerations, which consist of 107 cities at the prefecture level and above, include the Beijing-Tianjin-Hebei region (BTH), the Yangtze River Delta region (YRD), the Guangdong-Hong Kong-Macao Greater Bay Area (GBA), the Chengdu-Chongqing region (CHC), and the Middle Reaches of the Yangtze River region (MRY). The five urban agglomerations are representative as they are the most innovative regions in China and have the highest development level of the automobile manufacturing industry in China. According to the fourth economic census yearbook of China and relevant provinces, the number of legal entities in the automobile manufacturing industry in the five major urban agglomerations in 2018 was 59,600, and the business revenue of the automobile manufacturing industry above the scale was CNY 574,148.9 million, which accounted for 68.0% and 72.8% of the national share, respectively. Meanwhile, the rapid development of China's high-speed rail stimulates frequent interactions of urban innovation actors within and across the city and urban agglomeration, which has led to increasingly dense innovation linkages between cities.

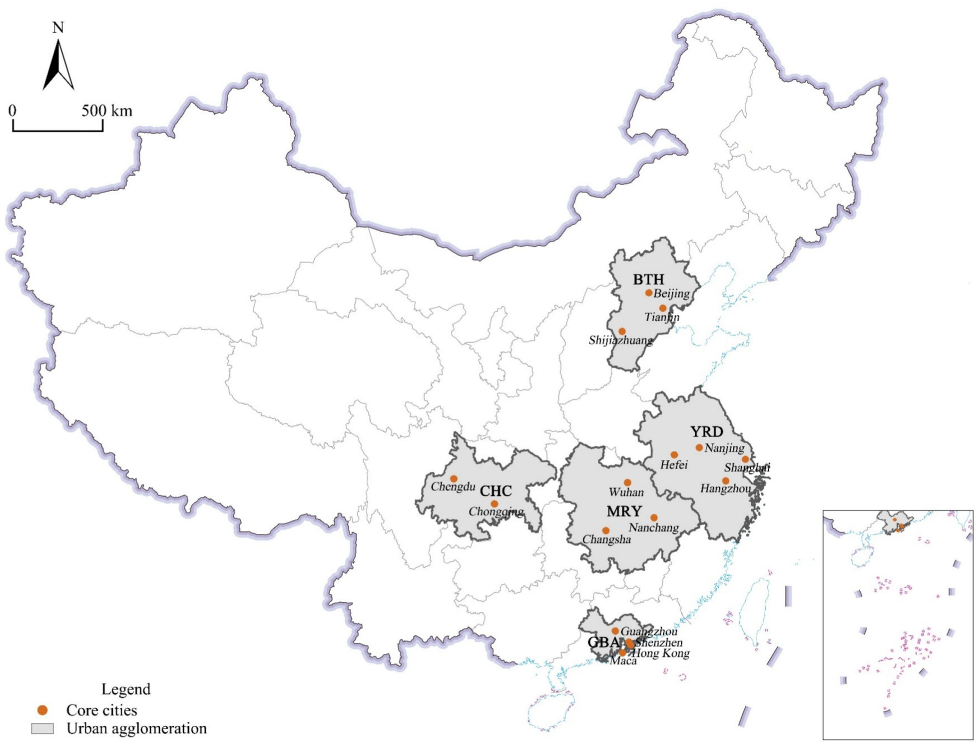

Figure 1. Study area.

3.2. Materials

Innovation output is an important indicator of the level of innovation. Among the many types of data on innovation outputs, patent data are most widely used in recent studies [20,34] and have been confirmed to have significant spatial correlation with innovation activities [6,48]. This paper thus constructs multi-scale urban innovation networks of the automobile manufacturing industry through co-patent data.

Due to the volatility and randomness of single year co-patent data, this paper aggregates the time span to the period 2016–2018, and the steps for data collection and processing are as follows. Firstly, based on the Form of Correlation between International Patent Classification and Industrial Classification for National Economic Activities (2018) (hereinafter referred to as the 2018 Form of Correlation), the four-digit code patents of the automobile manufacturing industry (Table 1) were obtained from the China National Intellectual Property Administration (CNIPA). Secondly, we extracted information such as patent classification code, application year, applicant, inventor, and address through text analysis of the invention patent bulletin. Thirdly, we screened co-patents of the automobile manufacturing industry according to the applicant. Finally, we geocoded the acquired co-patents using Python and obtained the electronic atlas of automobile manufacturing invention patents using ArcGIS 10.8.

Table 1. The statistics of corresponding four-digit patent types of automobile manufacturing industry.

Industry Codes and Types	The Four-Digit Code Patent Types
36 Automobile manufacturing industry	B60K, B62D, F02B, F02D, F02M, A01D, A61G, A62C, B60F, B60P, B60V, B64D, B65F, F41H, B60L, B60M, B61D, F16F, B60B, B60D, B60G, B60J, B60N, B60R, B60S, B60T, B60W, H01R

3.3. Methods

3.3.1. Constructing Multi-Scale Urban Innovation Networks

In this paper, we construct urban innovation networks on three different geographical scales, including intra-city innovation networks, inter-city innovation networks within urban agglomerations, and innovation networks between cities within and beyond urban agglomerations. Intra-city innovation networks are constituted by the innovation linkages within cities measured by the number of co-patents with cities. Inter-city innovation networks within urban agglomerations are formed by the innovation linkages among cities within urban agglomerations. Innovation networks between cities within and beyond urban agglomerations are constituted by the innovation linkages among cities within the urban agglomerations and the cities beyond the urban agglomerations in China. It is worth emphasizing that the four-digit code patent types of the automobile manufacturing industry may also appear in other industries from the 2018 Form of Correlation. For example, the four-digit code patent type B60K appears in the instrument and meter manufacturing industry in addition to the automobile manufacturing industry. Therefore, there is a significant bias that the number of co-patents in the urban automobile manufacturing industry directly measures according to the number of co-patents of the automobile manufacturing industry involving all four-digit code patent types [20,49]. In order to reduce this effect, this paper constructs multi-scale urban innovation networks of the urban automobile manufacturing industry by structurally parsing the 2018 Form of Correlation in the following steps.

Firstly, we constructed a patent-industry relationship matrix for all two-digit industry types corresponding to four-digit patent types in light of the 2018 Form of Correlation, and calculated the proportion of the number of occurrences of each four-digit patent in the automobile manufacturing industry to the total number of occurrences of that four-digit patent in the relationship matrix.

Secondly, the number of co-patents of each four-digit code patent type in automobile manufacturing in each urban agglomeration on three different geographical scales is counted based on the electronic atlas of automobile manufacturing invention patents. What should be noted is that this paper applies a method of full counting to aggregate the times of connectivity between two cities drawing on the existing studies [33].

Finally, the innovation linkages on three different geographical scales are calculated based on the number of co-patents of each four-digit code patent type in the urban automobile manufacturing industry and the proportion of the frequency of each four-digit code patent type included in the automobile manufacturing industry to the total frequency of the four-digit code patent type in the 2018 Form of Correlation, and the formula is:

$$CITY_{ti} = \sum_{l=1}^{N} a_l CITY_{lti} \tag{1}$$

$$MEG_{ti} = \sum_{j=1}^{M} \sum_{l=1}^{N} a_l MEG_{ltij}\ (i \neq j) \tag{2}$$

$$COU_{ti} = \sum_{g=1}^{S} \sum_{l=1}^{N} a_l COU_{ltig}\ (i \neq g) \tag{3}$$

$CITY_{ti}$ is the innovation linkages of intra-city innovation networks for city i in the urban agglomeration t. a_l indicates the proportion of the frequency of the four-digit code patent l in the automobile manufacturing industry to the total frequency of l in the relationship matrix. $CITY_{lti}$ denotes the number of co-patents of four-digit code patent l within city i of the urban agglomeration t, and N is the total number of four-digit code patent types included in the automobile manufacturing industry. MEG_{ti} denotes the innovation linkages of inter-city innovation networks within urban agglomerations for city i in the urban agglomeration t. MEG_{ltij} indicates the number co-patents of four-digit code patent l between city i and city j within urban agglomeration t, and M is the number of cities that have co-patents with city i in urban agglomeration t. COU_{ti} is the innovation linkages of innovation networks between cities within and beyond urban agglomerations for city i in the urban agglomeration t. COU_{ltig} is the number of co-patents of four-digit code patent l between city i in the urban agglomeration t and city g beyond the urban agglomeration t in China. S is the number of cities that have co-patents with city i in the urban agglomeration t beyond the urban agglomeration t in China.

3.3.2. Model

In order to measure the knowledge spillover effect of multi-scale urban innovation networks on the development of industry, this paper introduces the following multiple linear regression model:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots + \beta_p X_{pi} + \delta_i + \varepsilon_i \tag{4}$$

Y_i and X_{pi} are the explanatory and explanatory variable, separately. p is the number of explanatory variables, β_0 is the constant term, β_p is the regression coefficient, δ_i is the fixed effect of urban agglomeration, and ε_i is the random perturbation term. Specifically, in this paper, we take the operating income of the automobile manufacturing industry above the urban scale in 2018 as the explanatory variable, and the innovation linkages on three different geographical scales as the core explanatory variables. Additionally, we also include the control variables affecting the development of urban automobile manufacturing in the regression model.

First, we considered the impact of the level of urban automobile manufacturing agglomeration (*EPAMI*), which mainly promotes regional industrial development by localization externalities [47]. In this paper, it is approximated by the proportion of the average annual number of employees of automobile manufacturing enterprises above the urban scale to the average annual number of employees of manufacturing enterprises above the urban scale.

Second, we employ the GDP per capita (*PGDP*) as the proxy of urban economics which determines the intensity of capital investment in urban innovation, and thus plays a crucial role in the improvement of urban innovation capability [18,20]. In addition, the urban economic level also expresses the market size of the city, which is one of the most important drivers for urban industrial development.

Third, knowledge, technology, and talent are important factors that drive the development of urban industries [50]. The government's investment in science, technology, and education can not only alleviates the financing pressure of enterprises and reduces the cost of acquiring knowledge and technology, but also provides enterprises with sufficient, high-quality labor. In this paper, we choose the proportion of the city government's S&T and education expenditures to the government's financial expenditures (*SE*) to represent the degree of the city's S&T and education investment.

Fourth, given the industry attributes of the automobile manufacturing industry, we control the effect of the city's industrialization level, which is a comprehensive reflection of the city's industrial production factor level, innovation capacity, and market competitiveness. Generally, the better the city's industrial development foundation, the more conducive it is to the development of the city's manufacturing industry. We use the proportion of added value of the secondary industry to GDP (*SGDP*) as a proxy indicator for the level of urban industrialization.

Finally, higher foreign investment can not only provide external funds for the development of city industries [20] and promote the expansion of industrial scale, but also facilitate the acquisition of external knowledge spillover effect and enhance the technological innovation capacity of urban industries, thus promoting industrial development [51]. To control the influence of foreign investment, we adopt the actual amount of foreign investment utilized in the year share in GDP (*FDI*) as a control variable.

To minimize the effect of heteroskedasticity, this paper takes logarithms for all the above variables. In particular, the strength of urban innovation linkages at the three different geographical scales is taken to be logarithmic by adding 1.

Except for co-patent data, the other data are mainly from the fourth economic census yearbook of China and the province where each city is located and the China Urban Statistical Yearbook in 2018, with a few cities with missing data supplemented by the statistical yearbook of the city. Table 2 summarizes the data sources of selected variables.

Table 2. The data sources of variables.

Variables	Label	Data Source
Urban industrial development level	*DEV*	Economic census yearbooks for China and related provinces including Hebei, Jiangsu, Zhejiang, Anhui, Guangdong, Hubei, Hunan, Jiangxi, and Sichuan in 2018
Innovation linkages of intra-city innovation network	*CITY*	The CNIPA database
Innovation linkages of inter-city innovation networks within urban agglomerations	*MEG*	
Innovation linkages of innovation networks between cities within and beyond urban agglomerations	*COU*	
Urban industrial agglomeration level	*EPAMI*	Economic census yearbooks for China and related provinces including Hebei, Jiangsu, Zhejiang, Anhui, Guangdong, Hubei, Hunan, Jiangxi, and Sichuan in 2018
Urban economic development level	*PGDP*	China Urban Statistical Yearbook in 2018
S&T and education investment	*SE*	
Urban industrialization level	*SGDP*	
Foreign investment	*FDI*	

4. Results

4.1. Characteristics of Multi-Scale Urban Innovation Networks in the Automobile Manufacturing Industry of Five Urban Agglomerations

Tables 3 and 4 list the top 20 cities and city pairs in terms of the innovation linkages on three different geographical scales, and Figures 2 and 3 show inter-city innovation networks within urban agglomerations and innovation networks between cities within and beyond urban agglomerations in the automobile manufacturing industry of five urban agglomerations, respectively.

Table 3. Top 20 cities of the five urban agglomerations in terms of innovation linkages at different scales.

Geographical Scales	City	Innovation Linkages	Urban Agglomerations
Intra-city innovation networks	Beijing	203.46	BTH
	Shanghai	125.00	YRD
	Hangzhou	66.63	YRD
	Shenzhen	54.93	GBA
	Chongqing	44.20	CHC
	Changzhou	28.33	YRD
	Guangzhou	22.95	GBA
	Zhuhai	21.65	GBA
	Nanjing	19.52	YRD
	Suzhou	17.75	YRD
	Tianjin	11.89	BTH
	Changsha	11.76	MRY
	Wuhan	9.75	MRY
	Foshan	8.50	GBA
	Huizhou	8.46	GBA
	Ningbo	7.77	YRD
	Dongguan	7.75	GBA
	Yancheng	7.69	YRD
	Hefei	7.49	YRD
	Zhenjiang	6.73	YRD
Inter-city innovation networks within urban agglomerations	Hangzhou	231.58	YRD
	Ningbo	138.52	YRD
	Taizhou	69.93	YRD
	Shenzhen	64.64	GBA
	Beijing	49.57	BTH
	Huizhou	48.05	GBA
	Shanghai	22.10	YRD
	Shijiazhuang	21.61	BTH
	Guangzhou	18.83	GBA
	Tianjin	14.86	BTH
	Nanjing	13.47	YRD
	Jinhua	12.33	YRD
	Dongguan	12.07	GBA
	Suzhou	10.11	YRD
	Hong Kong	8.65	GBA
	Xingtai	6.74	BTH
	Hefei	6.61	YRD
	Langfang	5.69	BTH
	Yancheng	5.54	YRD
	Baoding	5.43	BTH

Table 3. *Cont.*

Geographical Scales	City	Innovation Linkages	Urban Agglomerations
Innovation networks between cities within and beyond urban agglomerations	Beijing	212.49	BTH
	Shenzhen	98.35	GBA
	Suzhou	86.44	YRD
	Hangzhou	53.91	YRD
	Changzhou	43.23	YRD
	Wuhan	34.56	MRY
	Nanchong	29.91	CHC
	Shanghai	28.69	YRD
	Nanjing	26.75	YRD
	Hefei	24.08	YRD
	Guangzhou	23.86	GBA
	Chengdu	23.55	CHC
	Chongqing	21.32	CHC
	Tianjin	20.91	BTH
	Huizhou	16.06	GBA
	Nanchang	15.10	MRY
	Changsha	14.08	MRY
	Wuxi	11.17	YRD
	Langfang	10.00	BTH
	Zhuzhou	9.33	MRY

Table 4. Top 20 city pairs of the five urban agglomerations in terms of innovation linkages at different scales.

Geographical Scales	City Pairs	Innovation Linkages	Urban Agglomerations
Inter-city innovation networks within urban agglomerations	Hangzhou–Ningbo	136.47	YRD
	Hangzhou–Taizhou	69.93	YRD
	Shenzhen–Huizhou	46.94	GBA
	Beijing–Shijiazhuang	14.30	BTH
	Beijing–Tianjin	13.56	BTH
	Hangzhou–Jinhua	12.31	YRD
	Hong Kong–Shenzhen	8.60	GBA
	Guangzhou–Dongguan	6.67	GBA
	Beijing–Langfang	5.69	BTH
	Shanghai–Suzhou	5.45	YRD
	Shenzhen–Dongguan	4.46	GBA
	Shanghai–Hangzhou	4.32	YRD
	Beijing–Baoding	4.06	BTH
	Beijing–Xingtai	3.74	BTH
	Guangzhou–Shenzhen	3.52	GBA
	Beijing–Cangzhou	3.33	BTH
	Nanjing–Hangzhou	3.06	YRD
	Shijiazhuang–Xingtai	2.99	BTH
	Guangzhou–Foshan	2.70	GBA
	Guangzhou–Jiangmen	2.45	GBA
Innovation networks between cities within and beyond urban agglomerations	Suzhou–New Taipei	63.23	YRD–Other
	Hangzhou–Nanchong	29.91	YRD–CHC
	Shenzhen–Changzhou	23.26	GBA–YRD
	Changzhou–Huizhou	16.06	YRD–GBA
	Beijing–Wuhan	15.59	BTH–MRY
	Beijing–Hefei	14.94	BTH–YRD
	Beijing–Nanjing	14.39	BTH–YRD
	Beijing–Shenzhen	11.96	BTH–GBA
	Beijing–Changsha	10.46	BTH–MRY

Table 4. *Cont.*

Geographical Scales	City Pairs	Innovation Linkages	Urban Agglomerations
Innovation networks between cities within and beyond urban agglomerations	Beijing–Chongqing	9.54	BTH–CHC
	Shenzhen–Langfang	9.50	GBA–BTH
	Shenzhen–New Taipei	9.26	GBA–Other
	Beijing–Suzhou	9.18	BTH–YRD
	Hangzhou–Xiangtan	8.16	YRD–MRY
	Beijing–Chengdu	8.02	BTH–CHC
	Beijing–Hangzhou	7.66	BTH–YRD
	Wuxi–Changchun	7.60	YRD–Other
	Chongqing–Hefei	7.21	CHC–YRD
	Shenzhen–Suzhou	7.09	GBA–YRD
	Nanchang–Taiyuan	6.79	MRY–Other

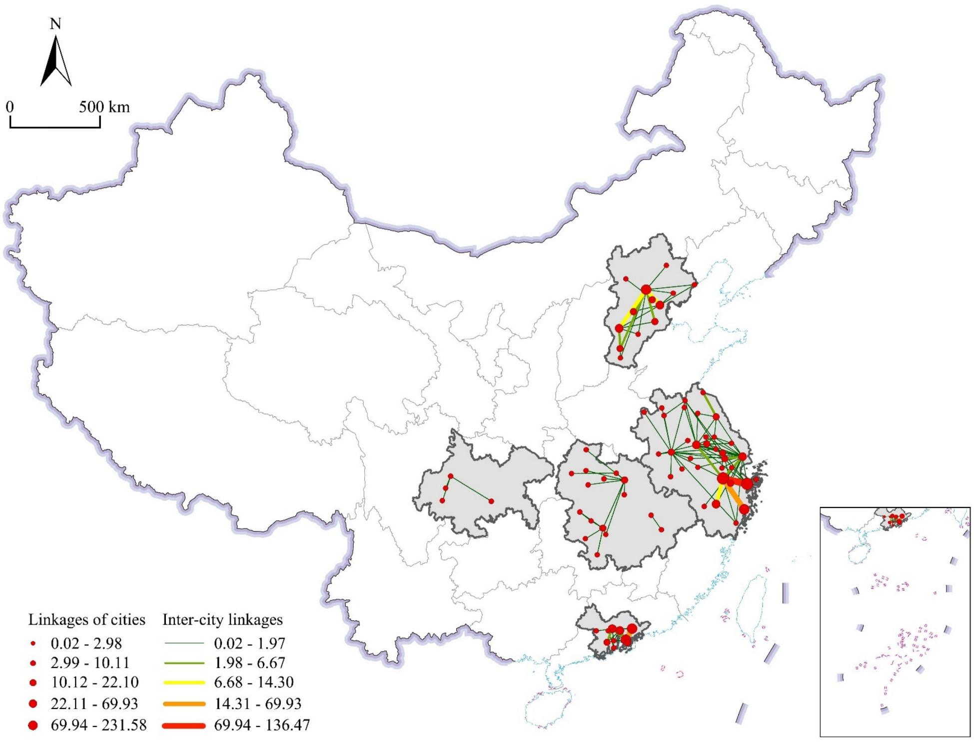

Figure 2. Urban innovation network of automobile manufacturing industry of the five urban agglomerations at the urban agglomeration scale.

The cities with higher innovation linkages in the intra-city innovation networks are all core cities of urban agglomerations or cities with higher levels of economic development (Table 3). Furthermore, we can observe that those cities are mainly located in the YRD and GBA. Specifically, among the top 20 cities, 11 are core cities of urban agglomerations, and 15 have a GDP of over RMB 1 trillion. There are 15 cities located in the YRD and GBA, with nine and six in the YRD and GBA, respectively. This is in line with our expectations. The YRD and GBA are the catchment areas of China's automobile manufacturing clusters, and the core cities of urban agglomerations and cities with higher levels of economic development cluster a larger number of automobile manufacturing enterprises and their upstream and downstream service enterprises, universities, research institutes, and productive service organizations, providing the basis for the formation of the automobile manufacturing innovation network. Meanwhile, these cities have attracted many talents, with rich knowledge, well-developed transportation and communication facilities, which support the development of dense innovation networks within the cities.

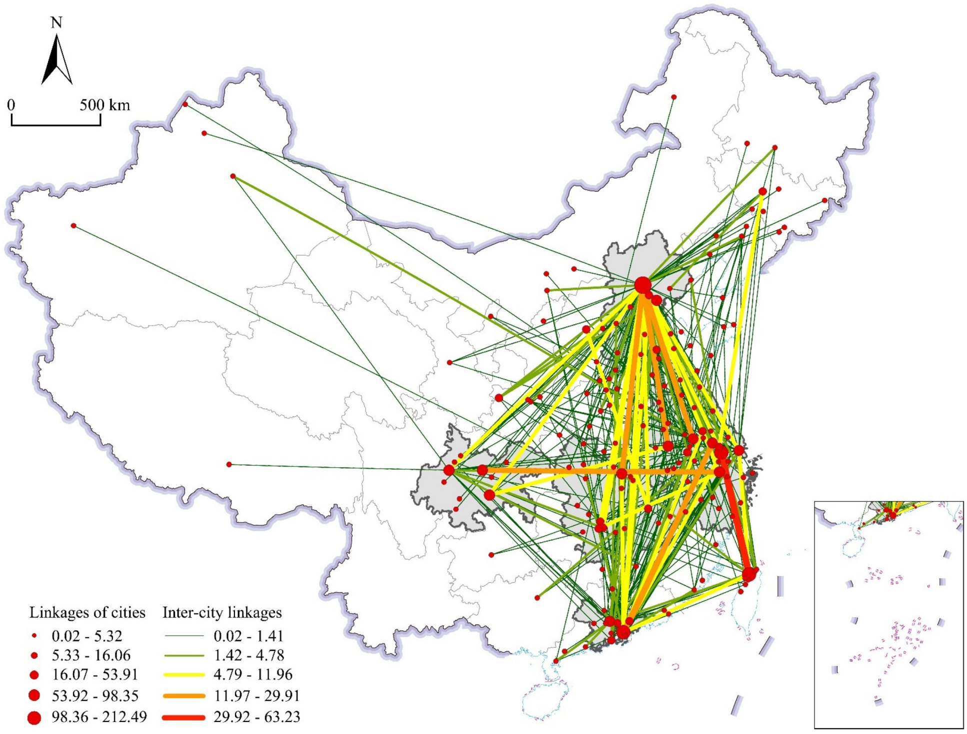

Figure 3. Urban innovation network of automobile manufacturing industry of the five urban agglomerations at the national scale.

For inter-city innovation networks within urban agglomerations, the cities with strong innovation linkages are mainly located in the YRD, BTH, and GBA, and the network density of these urban agglomerations is significantly higher than that of the other two. Showed as Tables 3 and 4, the top 20 cities in terms of innovation linkages are all located in the YRD, BTH, and GBA, with the numbers of nine, six, and five, respectively, and the top 20 city pairs of innovation linkages are also all located in the YRD, BTH, and GBA, with the numbers of six, seven, and seven, respectively. The results are mainly due to the fact that compared with the cities within CHC and MYR, the cities within BTH, YRD, and GBA are widely well endowed with rich talents, stock of knowledge and excellent infrastructure. Moreover, since the Chinese government has paid earlier attention to the three urban agglomerations of BTH, YRD, and GBA, their cooperation system is also more developed which weakens barriers to cross-city cooperation within urban agglomerations.

The cities with higher innovation linkages in the innovation networks between cities within and beyond urban agglomerations are the cities with stronger levels of development and specialized cities dominated by automobile manufacturing. Specifically, core cities of urban agglomerations account for 13 of the top 20 cities in terms of innovation linkages. These cities not only have gathered a large number of automobile manufacturing enterprises, innovative talents, universities, and research institutions, but also have stronger knowledge reserves and innovation capabilities, thus becoming the main objects of cooperation for other cities. Small and medium-sized cities such as Nanchong and Langfang have stronger innovation linkages mainly because they are deeply embedded in the production network of China's automobile manufacturing industry, creating a competitive advantage of specialization. For example, with Zhejiang Geely Holding Group, a leading automobile manufacturing company headquartered in Zhejiang, having invested in a plant in Nanchong in 2014, Nanchong has gradually developed into one of the key manufacturing bases for new energy vehicles in China. Figure 3 suggests that the cities with strong innovative connections with cities within an urban agglomeration are mainly located in the other four urban agglomerations. Statistically, the number of city pairs with inter-city innovation cooperation within the five urban agglomerations accounts for 65.1% of the total number of city pairs in five urban agglomerations.

4.2. The Knowledge Spillover Effect of Multi-Scale Innovation Networks on the Development of Automobile Manufacturing Industry

Table 5 lists the estimated results of the OLS model with fixed effects at the urban agglomeration level. Models 1–3 test the relationship between multi-scale urban innovation networks and the development of the automobile manufacturing industry. Models 4–6 examine the synergistic effect between urban innovation networks on three different geographical scales by adding interaction terms to regression models. Models 7–9 focus on the moderating role of the industrial agglomeration level in the process of the influence of multi-scale urban innovation networks on industrial development by introducing the interaction terms between multi-scale urban innovation networks and the agglomeration level of the automobile manufacturing industry.

Table 5. The estimation results.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
CITY	0.453 *	0.332 **	0.358 **	0.457 **	0.566 ***	0.389 **	0.827 ***	0.287 *	0.278 *
	(0.235)	(0.163)	(0.170)	(0.184)	(0.214)	(0.166)	(0.275)	(0.171)	(0.156)
MEG	0.206 *	0.642 ***	0.203 *	0.363 ***	0.208 *	0.424 ***	0.227 **	0.666 ***	0.236 **
	(0.113)	(0.219)	(0.115)	(0.119)	(0.112)	(0.111)	(0.097)	(0.212)	(0.097)
COU	0.243 **	0.238 **	0.521 ***	0.263 **	0.341 ***	0.384 ***	0.292 **	0.300 **	0.831 ***
	(0.121)	(0.119)	(0.190)	(0.123)	(0.129)	(0.127)	(0.116)	(0.119)	(0.232)
CITY × *CITY*	−0.033								
	(0.052)								
MEG × *MEG*		−0.094 **							
		(0.041)							
COU × *COU*			−0.078 *						
			(0.044)						
CITY × *MEG*				−0.086 **					
				(0.043)					
CITY × *COU*					−0.090 **				
					(0.044)				
MEG × *COU*						−0.118 ***			
						(0.039)			
CITY × *EPAMI*							0.200 **		
							(0.085)		
MEG × *EPAMI*								0.162 **	
								(0.077)	
COU × *EPAMI*									0.196 ***
									(0.067)
EPAMI	0.881 ***	0.875 ***	0.862 ***	0.856 ***	0.858 ***	0.835 ***	0.808 ***	0.771 ***	0.759 ***
	(0.081)	(0.076)	(0.081)	(0.078)	(0.080)	(0.077)	(0.092)	(0.109)	(0.092)
PGDP	0.337	0.246	0.341	0.326	0.329	0.333	0.293	0.298	0.304
	(0.249)	(0.252)	(0.238)	(0.246)	(0.245)	(0.244)	(0.239)	(0.235)	(0.238)
SE	0.807	0.639	1.040	0.834	0.960	0.982	0.756	0.886	0.748
	(0.722)	(0.693)	(0.706)	(0.715)	(0.706)	(0.696)	(0.700)	(0.701)	(0.692)
SGDP	0.581	0.760	0.352	0.391	0.274	0.261	1.104 *	0.859	1.055 *
	(0.586)	(0.536)	(0.535)	(0.547)	(0.553)	(0.523)	(0.565)	(0.523)	(0.535)
FDI	0.149 *	0.160 **	0.143 *	0.148 *	0.146 *	0.149 *	0.126	0.152 *	0.123
	(0.081)	(0.078)	(0.081)	(0.079)	(0.080)	(0.078)	(0.082)	(0.083)	(0.080)
Cons	3.222	2.984	4.253 *	3.846	4.550 *	4.395 *	1.259	2.397	1.104
	(2.624)	(2.513)	(2.504)	(2.495)	(2.535)	(2.467)	(2.418)	(2.477)	(2.470)
Megalopolis FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	107	107	107	107	107	107	107	107	107
R^2	0.848	0.854	0.851	0.852	0.852	0.857	0.854	0.853	0.856

Note: 1. Robust standard errors are in parentheses; 2. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Model 1 shows that the coefficient of intra-city innovation networks is significantly positive, while its square term is negative but not significant, indicating that intra-city innovation networks do not exhibit nonlinearity and that the impact of intra-city innovation networks on the development of the automobile manufacturing industry is monotonically positive. This is inconsistent with H1, but supports this viewpoint on the importance of buzz for urban economics [52,53]. Buzz may promote industrial development in these ways by facilitating the absorption of local knowledge by innovators and reducing risks and transaction costs in the innovation process. In Models 2 and 3, the coefficients of inter-city innovation networks within urban agglomerations and innovation networks between cities within and beyond urban agglomerations are significantly positive, and their square terms are significantly negative. The results show that inter-city innovation networks within urban agglomerations and innovation networks between cities within and beyond urban agglomerations have an inverted U-shaped effect on the development of the automobile manufacturing industry, which is consistent with H1. The result suggests that although inter-city innovation networks within urban agglomerations and innovation networks between cities within and beyond urban agglomerations play a positive role in the development of the automobile manufacturing industry, the intensity of cooperation will limit further development of the automobile manufacturing industry when it reaches a certain limit, which is mainly due to the fact that overly intensive external links will, on the one hand, increase the difficulty of knowledge integration and reduce the marginal output of innovation, and on the other hand, increase the city's external dependence on innovation and industrial development, causing it to lose its initiative and dominance in industrial development.

Models 4–6 in Table 4 show that the interactions between urban innovation networks on different geographical scales have a negative impact on the development of the automobile manufacturing industry. The results reflect the substitution effects among urban innovation networks on different geographical scales on the development of the automobile manufacturing industry, which is in line with the findings of Operti and Kumar [37] and Zhang et al. [44]. For the automobile manufacturing industry, excessive urban innovation connections may increase the cost of innovation actors, leading to "information overload", "decision-making difficulties", and "mobilization failure", which is detrimental to industrial innovation and thus limits the development of industries.

Models 7–9 show that the coefficients of the interaction terms between urban innovation networks at different geographical scales and the agglomeration level of the urban automobile manufacturing industry are all positive and have statistical significance, which verifies H3. The results indicate that with the improvement of the agglomeration level of the urban automobile manufacturing industry, the impact of urban innovation networks at different geographical scales on the development of automobile manufacturing industry is constantly increasing. The improvement in the agglomeration level of the urban automobile manufacturing industry, promoting the accumulation of talents, knowledge, and technology in related fields, can enhance the ability and efficiency of identifying, absorbing, and restructuring knowledge input through multi-scale urban innovation networks. Simultaneously, it can reduce the operation and maintenance costs of multi-scale urban innovation networks.

4.3. Robustness Tests

In this paper, we test the robustness of the results by replacing the core variables. Specifically, we use the average of co-patents in the automobile manufacturing industry on the three different geographical scales from 2016 to 2018 as the core explanatory variable for the robustness test. Table 6 presents the results of the robustness test, which support the previous conclusions.

Table 6. The estimation results of robustness tests.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
AVCITY	0.848 **	0.427 *	0.491 **	0.699 **	0.922 ***	0.569 **	1.141 ***	0.349	0.343
	(0.349)	(0.216)	(0.234)	(0.275)	(0.319)	(0.231)	(0.421)	(0.257)	(0.237)
AVMEG	0.211	1.082 ***	0.210	0.527 ***	0.221	0.612 ***	0.260 **	0.915 ***	0.272 **
	(0.153)	(0.322)	(0.161)	(0.148)	(0.154)	(0.127)	(0.123)	(0.309)	(0.130)
AVCOU	0.299 *	0.286 *	0.933 ***	0.365 **	0.535 ***	0.604 ***	0.411 **	0.418 **	1.132 ***
	(0.174)	(0.159)	(0.239)	(0.169)	(0.171)	(0.170)	(0.160)	(0.168)	(0.353)
AVCITY × *AVCITY*	−0.130								
	(0.087)								
AVMEG × *AVMEG*		−0.231 ***							
		(0.073)							
AVCOU × *AVCOU*			−0.217 ***						
			(0.071)						
AVCITY × *AVMEG*				−0.231 ***					
				(0.067)					
AVCITY × *AVCOU*					−0.243 ***				
					(0.075)				
AVMEG × *AVCOU*						−0.303 ***			
						(0.064)			
AVCITY × *EPAMI*							0.310 **		
							(0.136)		
AVMEG × *EPAMI*								0.253 **	
								(0.118)	
AVCOU × *EPAMI*									0.277 **
									(0.108)
EPAMI	0.896 ***	0.891 ***	0.861 ***	0.858 ***	0.858 ***	0.824 ***	0.848 ***	0.816 ***	0.816 ***
	(0.085)	(0.079)	(0.084)	(0.082)	(0.084)	(0.082)	(0.094)	(0.106)	(0.096)
PGDP	0.438 *	0.351	0.421 *	0.414 *	0.411 *	0.394 *	0.455 *	0.445 *	0.460 *
	(0.248)	(0.253)	(0.231)	(0.242)	(0.240)	(0.235)	(0.236)	(0.230)	(0.234)
SE	0.922	0.678	1.279 *	0.981	1.161 *	1.167 *	0.927	1.072	0.895
	(0.732)	(0.694)	(0.704)	(0.712)	(0.698)	(0.679)	(0.714)	(0.712)	(0.706)
SGDP	0.486	0.919	0.258	0.323	0.157	0.195	1.160 *	0.920	1.111 *
	(0.601)	(0.585)	(0.541)	(0.567)	(0.551)	(0.526)	(0.621)	(0.582)	(0.603)
FDI	0.145 *	0.178 **	0.120	0.146 *	0.128	0.141 *	0.130	0.154 *	0.130
	(0.081)	(0.081)	(0.082)	(0.079)	(0.080)	(0.077)	(0.084)	(0.084)	(0.083)
Cons	2.906	1.614	4.190	3.566	4.555 *	4.399 *	−0.061	1.263	−0.099
	(2.760)	(2.568)	(2.625)	(2.586)	(2.623)	(2.534)	(2.543)	(2.605)	(2.599)
Megalopolis FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	107	107	107	107	107	107	107	107	107
R^2	0.841	0.851	0.849	0.850	0.849	0.858	0.845	0.844	0.846

Note: 1. Robust standard errors are in parentheses; 2. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

5. Conclusions and Discussion

5.1. Conclusions

Knowledge spillovers and urban innovation networks have received increasing attention from scholars, but there are still few studies that combine them to explore the knowledge spillover effect of multi-scale innovation networks. Thus, taking the automobile manufacturing industry in China's five urban agglomerations as an example, this paper examines the knowledge spillover effect of multi-scale urban innovation networks on industrial development based on the "buzz-and-pipeline" model.

In this paper, based on the 2018 Form of Correlation and co-patent data, we firstly construct urban innovation networks on three different geographical scales for the automobile manufacturing industry, including intra-city innovation networks, inter-city innovation networks within urban agglomerations, and innovation networks between cities within and beyond urban agglomerations. Compared with existing studies [18,20], we synthesize three different geographical scales. Here, intra-city innovation networks are deemed analogous to ''local buzz', while innovation networks between cities within and beyond urban agglomerations are deemed analogous to ''global pipelines" and inter-city innovation networks within urban agglomerations are deemed to have dual characteristics of buzz and pipelines. In China, it is more realistic to consider the impact of urban innovation networks on three different geographical scales. On the one hand, the administrative boundaries of cities still play an important role with regard to the flow of elements in China. In fact, time and institutional cost of elements flow within city is significantly lower than that of inter-city. On the other hand, with the rapid development of China's economy and the continuous improvement of reginal infrastructure since 2000, cooperation between cities has become increasingly close. Simultaneously, the Chinese government pays great attention to the integration of urban agglomerations, and continuously breaks down the institutional barriers to facilitate mobility. Therefore, urban agglomerations nowadays have become an important economic spatial entity in China.

This empirical study finds that the cities with stronger innovation linkages in the intra-city innovation networks are mainly the core cities of urban agglomerations and cities with higher levels of economic development. The cities with higher innovation linkages in the inter-city innovation networks within urban agglomerations are mainly located in the BTH, YRD, and GBA. For the innovation networks between cities within and beyond urban agglomerations, in addition to the core cities of urban agglomeration, small and medium-sized cities with the advantage of specialization in automobile manufacturing also show higher innovation linkage intensity. The knowledge spillover effect of urban innovation networks varies with different geographical scales. Intra-city innovation networks have a facilitating effect on industrial development, while both inter-city innovation networks within urban agglomerations and innovation networks between cities within and beyond urban agglomerations have an inverted U-shaped impact on industrial development. The interactions between urban innovation networks at three different geographical scales are has a negative effect on industrial development. Simultaneously, the agglomeration level of urban industry plays a positive moderating role in the process of multi-scale urban innovation networks acting on industrial development.

5.2. Discussion

The "buzz-and-pipeline" model provides a good theoretical framework for the study of the knowledge spillover effect of multi-scale urban innovation networks, while relevant empirical studies are still scarce. Although some studies have analyzed the impact of urban innovation networks on urban innovation [18] and industry-specific innovation [20] based on this model, few studies have focused on the knowledge spillover effect of urban multiscale innovation networks on industrial development. In this paper, we deepen the existing research based on the "buzz-and-pipeline" model to explore the impact of multi-scale urban innovation networks on industrial development. In terms of the construction method of industrial innovation networks, we all know that the commonly used four-digit code patents may appear in different industrial categories, and it tends to overestimate the level of innovation cooperation in industry based solely on the correspondence between the industry and four-digit code patents to construct industrial innovation networks [20,49]. Therefore, Ren et al. [20] reduce the effect with a more detailed categorization. In this paper, we employ a new approach to reduce the influence through a structured interpretation of the 2018 Form of Correlation. On this foundation, based on the actual situation in China, we simultaneously incorporate three different geographical scales into the "buzz-and-pipeline" analytical framework to investigate the knowledge spillover effect of urban multiscale innovation networks on industrial development.

The empirical findings have some policy implications. Firstly, urban industrial agglomeration level and opening up level play a positive role in the development of urban automobile manufacturing industry. Therefore, local governments should continuously improve the agglomeration level and opening-up level of the urban automobile manufacturing industry. Secondarily, all urban innovation networks on three different geographical scales have a positive impact on the development of the urban manufacturing industry. Policymakers should pay attention to building an ecological environment that is conducive to the development of urban innovation networks in the automobile manufacturing industry on three different geographical scales. Thirdly, among the urban innovation networks on three different geographical scales, our results show that the intra-city innovation networks provide motivation for the development of the manufacturing industry, and there is a lot of room for this positive effect to grow. Thus, more attention should be paid to enhance intra-city automobile manufacturing industry innovation networks through measures of promoting the construction of transportation and information facilities, establishing innovative action subject cooperation organizations and reducing the transaction costs of knowledge and technology industries within cities. Thirdly, when strengthening the inter-city innovation networks within urban agglomerations and innovation networks between cities within and beyond urban agglomerations, it is important to enhance the quantity and quality of automobile manufacturing talents, research institutions, and service organizations within the city, which can reduce the negative impact of excessive connectivity by enhancing the city's ability to integrate, absorb, and transform knowledge.

Of course, this paper also has some limitations in the research methods and ideas, which need to be constantly updated with the application of new technologies and means and the enrichment of data types. For instance, there are many data types used to construct urban innovation networks, while we only applied the widely used co-patents. In the meantime, we only consider the knowledge spillover effect of three different geographical scales, but we do not take into account the impact of global scale innovation networks. Additionally, the improvement of the basic theory of the knowledge spillover effect of urban innovation networks, the optimization of the measurement methods and the impact of urban innovation networks on different dimensions such as economy, society, and environment will also be the focus of subsequent research.

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Data Availability Statement: The data in the paper are all open source and from the statistical data from the China National Intellectual Property Administration (SIPO), the fourth economic census yearbook of China and the province where each city is located and the China Urban Statistical Yearbook in 2018, with a few cities with missing data supplemented by the statistical yearbook of the city.

Conflicts of Interest: The authors declare no conflicts of interest.

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