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Study on Spatial-Temporal Evolution and Proximity Mechanism of Technological Innovation Network: Evidence from Specialized and Sophisticated SMEs in China

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ABSTRACT

This study focuses on the dynamic transmission of knowledge and technology by the innovation cooperation in the technological innovation network of specialized and sophisticated small and medium-sized enterprises (SMEs) that produce novel and unique products in China. Based on their cooperation patent data from 2001 to 2020, uses the methods of spatial analysis, social network analysis and negative binomial regression analysis to explore the evolution of the network structure and impact of multi-dimensional proximity on innovation cooperation. The empirical results were as follows. First, the network density and clustering degree have been increasing, and the majority of innovation cooperation occurs between private enterprises mostly. Second, the innovation cooperation focus on the industry of telecommunication technology, electronic information, petrochemical and equipment manufacturing, and Shanghai has gradually replaced Beijing to be in the first position in the innovation network. Third, institutional, economic, social and technological proximity have significant positive effects while geographic proximity has a negative effect on the innovation network. This study contributes to the literature on innovation network and highlights the issues of proximity-related innovation cooperation decision, and sheds light upon the innovation practice of specialized and sophisticated SMEs in China.

1.Introduction

Since the 2010s, with the rapid development of market and technology, the innovation investment of specialized and sophisticated SMEs in China has significantly increased (Huang et al., 2023; Cao et al., 2022). Data from the Ministry of Industry and Information Technology of China shows that the R&D investment intensity of manufacturing industry has increased from 0.85% in 2012 to 1.54% in 2021, while the average R&D intensity of specialized and sophisticated SMEs is as high as 10.3%.

As the innovation environment changing rapidly, more and more specialized and sophisticated SMEs begin to focus on seeking available innovation resources outwardly (Xi et al.,2022). The uncertainty of technology, market and institutional environment and the scarcity of innovation resources make the innovation cooperation inevitable (Khanna&Guler,2022;Zhao et al.,2022), which promotes the combination of various factors required for technological innovation of specialized and sophisticated SMEs in China, and formation of network organizations with common technological innovation objectives(Mao et al.,2021; Matray,2021), helping to use external advantageous resources to strengthen SMEs' core technology capability(Shen et al., 2023; Wang et al.,2022).

Innovation outcome is the main goal of innovation cooperation, and innovation cooperation is the key mechanism of innovation network. Innovation network is a formal and informal connection between enterprises through exchange and acquisition of knowledge, documents, etc (Nonaka& Takeuch, 1995). Interlaced innovation networks contribute to complex and systematic innovation behaviors (Freeman,1991). The structure of technological innovation network undergoes a certain pattern of evolution with the addition of external innovative enterprises, the increase of inter enterprise relationships within the network, and the regeneration of inter enterprise relationships within the network (Pan et al.,2020; Noonan et al.,2021).

With the development of research on innovation network in the field of economic geography, proximity has become a new perspective for scholars to explore the evolution dynamics and mechanism of innovation network (Argyres et al.,2020). Geographical proximity is considered as the primary factor driving innovation, which can adjust the impact of innovation network on knowledge novelty and knowledge transfer (Fernandez et al., 2021;

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Yang et al.,2019). In the process of research, scholars have gradually realized that geographical proximity is not the only form of proximity, nor is it a sufficient and necessary condition for mutual learning and cooperative innovation among organizations (Boschma,2005). In recent years, the shackles of space concept have been gradually broken, expanding from geography to organization (Liu et al., 2020), technology (Liu & Ma, 2019; Noonan et al.,2021), institution (Fernandez et al., 2021), society (Capone & Zampi, 2019; Cao et al.,2019).

This study expands the forms of proximity, focusing on the following research questions: First, what is the evolution characteristics of the technological innovation network of specialized and sophisticated SMEs in China, and what is the distribution characteristics of innovation subjects; Second, whether the multi-dimensional proximity has a homogeneous effect on the technological innovation network, and what is the change trend.

This paper contributes to the theory and practice. First, we reveal the dynamic impact of proximity on the innovation network by dynamic analysis at different stages of the network. The impact of proximity on innovation network is not constant, and proximity has a threshold at different stages of the network (Wang&Hu,2021). Second, analyzing from geographical proximity, institutional proximity, economic proximity, social proximity, and technological proximity is of substantial value in revealing the impact mechanism of multi-dimensional proximity on the technological innovation network. There are differences in the selection of proximity dimensions, and the neglect of some dimensions may lead to the deviation of the research results. This contribution should be of interest to the study of impact on innovation network more comprehensively. Finally, previous studies have mainly explored the impact of proximity on the enterprises classified by industry, such as equipment manufacturing (Ye et al.,2017), biomedicine (Ma, et al., 2022), new energy vehicles (Su & Cao,2022), logistics (Sun et al.,2021), etc., whether it has a similar effect on the innovation network of specialized and sophisticated SMEs in China needs to be further demonstrated. By acquiring the patent cooperation data of China's specialized and sophisticated SMEs and using big data technology, this study constructs technology innovation network and reveal the evolution characteristics and the impact mechanism of innovation network. It provides some reference for how to promote the innovation integration of specialized and sophisticated SMEs in China.

2.Literature review

2.1 Innovation network

Innovation networks are considered to be the access to get heterogeneous resources from the outside beyond the organizational boundaries (Degbey & Pelto, 2013). Complex technological innovation cannot be completed by a separate enterprise. With the development of science and technology, the traditional closed, single linear innovation model has gradually evolved into a complex innovation network (Cao et al., 2022). As an important transmission mode of implicit knowledge and technology, innovation network has unlimited potential in making innovation by reducing innovation risks and utilizing external resources of the enterprise. Innovation cooperation forms the main connection mechanism of the network architecture, and the interrelationship among the innovation participants constitutes an interlocking innovation network (Freeman,1991).

The formation of intra-organizational cooperative relationship determines the results of partner’ selection and cooperation, and reflects the beginning of the evolution process of the innovation network (Sun et al.,2021). The change of cooperative relationship is of great significance for revealing the evolution law of the innovation network (Shi&Dang,2015). In the construction of innovation networks, joint patent applications and mutual citations are widely used in extant literature to build network connections between nodes (Cai&Li,2019; Zacchia,2019). In terms of analysis method, social network analysis method is widely used in the research of innovation network (Liu et al.,2016).

2.2 Multi-dimensional proximity

Faced with the complexity and diversity of technology, proximity is very important for the integration of knowledge from different fields, which will affect the cooperative relationship of innovation subjects and the evolution of innovation network (Balland et al.,2015). On the basis of external economic theory, proximity is defined as the proximity of each subject in the spatial position, and the knowledge transmission between subjects has obvious geographical characteristics, which explains the important position of geographical proximity in innovation activities (Amin,1999).

Previous studies have shown that the proximity of geographical location is driving the formation of cooperative relations between subjects, the closer the subjects are, the more likely they are to cooperate (Howells, 2002; Shaw,2000). Scholars have also used the proximity theory to analyze the impact of geographical distance on the evolution of innovation network (Gluckler,2007), which has provided a new theoretical framework for analyzing the complexity of innovation networks and evolution mechanisms. However, organizations will have different degrees of proximity at other levels over time (Boschma,2005). On the basis of geographical proximity, the French Proximity Dynamics School considered the impact of organizational proximity and institutional proximity on innovation from the perspective of interaction and institution (Li&Luo,2013). Subsequently, scholars have explored the multi-dimension of proximity and its impact mechanism on innovation.

There is different analytical framework of proximity. Kirat and Lung (1999) divided proximity into geographical proximity, organizational proximity and institutional proximity; Knoben and Oerlemans(2006) expanded proximity into seven dimensions, institutional proximity, cultural proximity, social proximity, technological proximity, cognitive proximity, organizational proximity and geographical proximity; Boschma(2005) pointed out that proximity includes cognitive proximity, social proximity, institutional proximity, organizational proximity and geographical proximity. Among the above dimensions of proximity, Boschma's five-dimension division has been widely recognized by scholars (Lazzeretti & Capone, 2016).

Based on Boschma's five-dimensional division, Cognitive proximity, social proximity, institutional proximity, organizational proximity and geographical proximity affect the change of cooperative relationship in terms of knowledge learning, personal relationship, institutional norms, organizational integration and geographical agglomeration (Balland et al., 2015). Proximity promoted the formation of industrial technology innovation strategic alliance network, and organizational proximity played a greater role than geographical proximity and cognitive proximity (Cao et al., 2019). However, the impact of proximity on innovation networks is changing, and proximity has a threshold at different stages of the network (Zhao et al., 2016). Now the study of proximity mainly focuses on geographical proximity, institutional proximity, economic proximity, technological proximity, and geographical proximity on innovation networks (Sun et al., 2021; Noonan et al., 2021; Wang & Hu, 2021). And it is demonstrated that geographical, economic and technological proximity have a differentiated impact on innovation cooperation network (Pan et al., 2020).

Proximity is an important factor affecting the formation of innovation network relationships (Capone & Zampi, 2019). Although scholars have studied the structure of innovation networks at different scales, there remains a lack of exploration of their formation mechanisms of specialized and sophisticated SMEs in China. In order to study the difference of the influence of proximity at different levels, this paper will analyze the impact mechanism of multi-dimensional proximity on innovation networks of specialized and sophisticated SMEs in China from five perspectives of geographical proximity, institutional proximity, economic proximity, social proximity, and technological proximity.

3.Data Methodology

3.1 Data sources

Cooperation patent serves as an important method for building the innovation network. This study builds the innovation network with patent cooperation data of specialized and sophisticated SMEs in China from 2010 to 2020 by using big data mining technology from the patent information service platform of China National Intellectual Property Administration. First, 520710 patent data were obtained by retrieving the application time, applicant type, patent type, International Patent Classification number and other attributes of the qualified applicant. Second, we extract the patents for joint application and screen out the data of 71521 from 2001 to 2020. Third, the subjects of innovation cooperation are divided into 8 types, state-owned enterprises, private enterprises, joint ventures, universities, research institutes, public institutions, hospitals and non-governmental organizations.

3.2 research methods

3.2.1 Social network analysis

The method of social network analysis is used to analyze the structure and attributes of technological innovation network involved in cooperation scale, network density, clustering coefficient, etc. The nodes of the network are the joint applicants and their geographical locations. The quantitative relationship of the cooperation patents between the nodes is the edge. The indicators and descriptions of innovation network structure and attribute are shown as follows and calculated with the formula by using the software of UCIENT, GEPHI and ARCGIS.

(1) Cooperation scale is the sum of the number of subjects connected to innovation subject i, indicating innovation cooperation scale among innovation subjects.

$$S_i = \sum_{j=1}^{N} a_{ij} \tag{1}$$

N is the total number of innovation subjects in the network; a_{ij} is the number of subjects connected to innovation subject i, S_i is the innovation cooperation scale of innovation subject i;

(2) Coefficient of variation is the ratio of weighted degree standard deviation to mean., indicating differentiation degree of innovation network.

$$CV = \frac{S}{\bar{E}}, \quad S = \sqrt{\frac{\sum_{i=1}^{N}\left(E_i - \bar{E}\right)^2}{N}} \tag{2}$$

CV is the coefficient of variation; S is the standard deviation; $\bar{E}$ is the mean value; N is the total number of innovation subjects in the network.

(3) Network density is the ratio of the number of actual connections between innovation subjects to the maximum number of possible connections, indicating how closely all innovation subjects are connected.

$$D = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} d(i,j)}{N(N-1)} \tag{3}$$

N is the total number of innovation subjects in the network; $d(i,j)$ is the number of connections between innovation subject i and innovation subject j.

Clustering coefficient is the ratio of the actual number of edges between the subjects directly adjacent to the innovation subject i to the maximum possible number of edges, indicating the overall cohesion of the innovation network.

$$C_i = \frac{2e_i}{k_i(k_i - 1)} \tag{4}$$

e_i is the number of edges between the k neighbors of innovation subject i; k_i is the number of edges owned by innovation subject i.

Average path length is the shortest path between innovation subject i and j, indicating the degree of cooperation between innovation subjects.

$$L = \frac{1}{2N(N-1)} \sum_{i \geq j} d_{ij} \tag{5}$$

N is the total number of innovation subjects in the network; d_{ij} is the distance from innovation subject i to innovation subject j.

3.2.2 Negative binomial regression model

In this study, the dependent variable is innovation cooperation network of specialized and sophisticated SMEs in China. Cooperation patents are used to measure the dependent variable and the negative binomial regression model is built to explore the impact of multi-dimensional proximity on the cooperation innovation network of specialized and sophisticated SMEs in China. Taking enterprises, universities, scientific research institutes, etc. as nodes, and based on the cooperation patents retrieved from the patent database, a symmetric weighted cooperation matrix is constructed using Python programming. Select the average value of cooperation patent applications between nodes as the threshold value. If the number of patents applied for by two node cooperation is greater than the threshold value, the corresponding matrix value is recorded as 1, otherwise it is 0, and the weighted cooperation matrix is converted into a binary symmetric cooperation matrix. The formula for the impact mechanism of multi-dimensional proximity is shown in Eq. (6).

$$\begin{aligned} P_{ij} = \alpha + \beta_1 Geo_{ij} + \beta_2 Reg_{ij} + \beta_3 Eco_{ij} \\ + \beta_4 Soc_{ij} + \beta_5 Tec_{ij} + \varepsilon_{ij} \end{aligned} \tag{6}$$

In the formula, α is a constant item, ε_{ij} is a random error item, β_i is an independent variable coefficient, and the dependent variable P_{ij} is the number of cooperation patent between nodes, that is, the corresponding strength between nodes in the innovation network. The independent variables are geographical proximity (Geo), institutional proximity (Ins), economic proximity (Eco), social proximity (Soc), and technological proximity (Tec).

Geographic proximity (Geo) refers to the geographical distance between the innovation subsectors as measured by Euclidean distance of the city (Li et al.,2021). The closer distance is conducive to the efficient transmission and reception of knowledge.

(2) Institutional proximity (Ins) are the proximity of the innovation subjects to the binding force of the rules which is usually measured by urban administrative level and the system values of municipalities directly under the central government, sub-provincial cities, provincial capital cities and prefecture-level cities are respectively 4, 3, 2 and 1(Gui et al.,2021).

$$Ins_{ij} = \left| r_i - r_j \right| \tag{7}$$

In the formula, Ins_{ij} refers to the institutional distance between city i and j, respectively, r_i, r_j represents the institutional value of the city i, j.

(4) Economic proximity (Eco) refers to the degree of difference in economic strength between innovation subjects. A relatively balanced economic strength between cities contributes to the surge of innovation elements and the interaction of technological knowledge, enabling innovation cooperation between subjects.

$$Eco_{ij} = \frac{min\left(e_i, e_j\right)}{max\left(e_i, e_j\right)} * \frac{e_i + e_j}{2} \tag{8}$$

In the formula, e_i, e_j refers to GDP per capita of city i and city j respectively.

(5) Social proximity (Soc) is derived from the relationship established between innovation subjects in formal or informal form. The more frequent interaction between subjects, the more knowledge dissemination will be promoted. This paper uses the method of Schengell and Barber (2009) to measure the social proximity of technological innovation cooperation between cities using the Jaccard index.

$$Soc_{ij} = \frac{P_{ij}}{C_s(i) + C_s(j) - P_{ij}} \tag{9}$$

In the formula, $C_s(i), C_s(j)$ are the intensity centrality of city i and city j, that is, the sum of the cooperation between two cities.

(5) Technical proximity(Tec) indicates the degree of adaptation and similarity of the technological basis between the innovation subjects. The Jaffe index is used to measure technical proximity (Jaffe et al.,1993). The technical proximity formula is:

In the formula, P_{ik}, P_{jk} are the number of patent applications

$$Tec_{ij} = \frac{\sum_{k=1}^{8} P_{ik} P_{jk}}{\sqrt{\sum_{k=1}^{8} P_{ik}^2 P_{jk}^2}} \tag{10}$$

under city i and city j under kth international patent classification number.

4.Characteristics of spatial-temporal evolution

4.1 Expansion in the scale of innovation networks

Fig.1 illustrates the cooperation patent data of specialized and sophisticated SMEs in China from 2001 to 2020, which has gradually increased since 2001, reaching 13236 in 2020. To summarize the evolution characteristics of the innovation network in different periods, it is divided into four years intervals: 2001-2005, 2006-2010, 2011-2015, and 2016-2020.

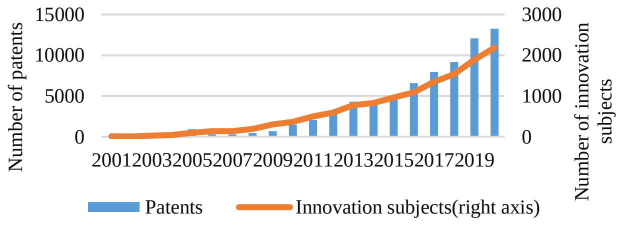

Fig.1. 2001-2020 Overview of Technological Innovation of China's SRCI enterprises

Table1 shows the scale of the technological innovation network of specialized and sophisticated SMEs in China is increasing, and the transmission of knowledge and technology is becoming more frequent. The number of innovation subjects have increased from 167 in 2005 to 4697 in 2020 and the scale of cooperation increase from 1031 to 49021. The network density has increased from 0.013 to 0.597, and the clustering coefficient increased from 7.747 in 2005 to 20.768 in 2020, indicating that the local network has been formed.

Tabel 1.Statistics on the eigenvalues of the innovation network

Period	Innovation subject	Cooperation scale	Coefficient	network density	Clustering coefficient
2001—2005	167	1031	0.638	0.013	7.747
2006—2010	780	3221	1.289	0.040	2.138
2011—2015	2266	18248	0.939	0.222	9.964
2016—2020	4697	49021	0.683	0.597	20.768

4.2 Innovation cooperation between private enterprises has dominated

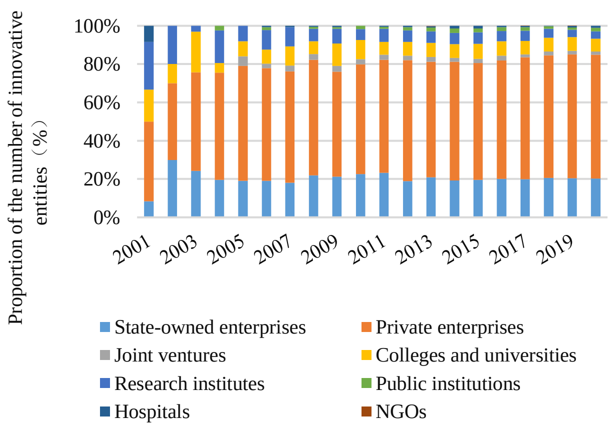

Fig 2. Evolution of the structure of innovation subjects

Fig.2 shows the changes have taken place in the innovation cooperation subjects since 2001. The proportion of private enterprises that participated in innovation cooperation constantly increased to 65% in 2020. The proportion of colleges and universities, research institutes declined from 42% in 2001 to 10% in 2020. The state-owned enterprises accounted for the stable ratio of about 20%. The public institutions, non-governmental organizations, and other organizations have remained small ratio relatively.

The number of innovation subjects continued to increase and the scale of the network grew rapidly, the innovation cooperation was frequent, as shown in Figure3. Although the private enterprises were the main source of knowledge and the innovation cooperation between private enterprises was the primary form, the subjects of innovation cooperation gradually spread to private enterprises and universities, such as Tsinghua University, East China University of Technology, Hefei University of Technology. The network showed a diversified trend and the innovation cooperation spread to the industry of telecommunication technology, electronic information, petrochemical industry, and equipment manufacturing, while the innovation cooperation in new materials, composite materials, composite technology, biomedical and other industries becoming prosperous gradually More private enterprises, science and engineering universities, and research institutes with the innovation advantage promote the cooperation of industry-university-research actively.

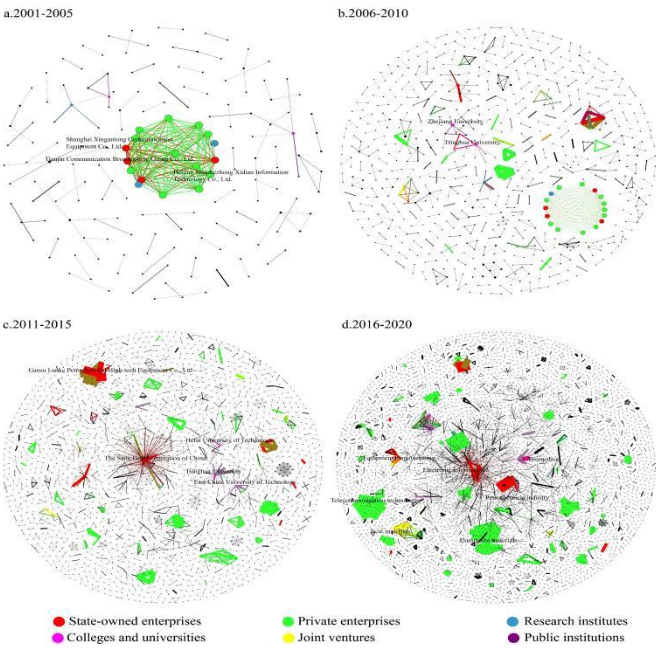

Fig 3. Map of innovation cooperation network

4.3 Structural changes at urban scale

FIG.4 shows innovation cooperation of specialized and sophisticated SMEs in China mainly occurs in Beijing, Shanghai, and some coastal cities. At the local-external level, the all-embracing ability of innovation cooperation in Shenzhen, Guangzhou, Tianjin, Chengdu, Chongqing is gradually strengthened. Correspondingly, Xi'an, Dongguan and other cities are typical representatives of the externality and liquidity of innovation knowledge. The coastal provinces with good R&D investment, technology accumulation, innovation environment and industrial foundation are more dependent on intra-provincial innovation cooperation, and the scale of innovation cooperation in the eastern, central and western provinces has hierarchical characteristics; At the same time, important nodes are closely connected, and innovation cooperation between Guangdong and Shaanxi has broken through geographical boundaries, with obvious spatial differences. Coastal regions have more advantages in the scale of local-external innovation cooperation.

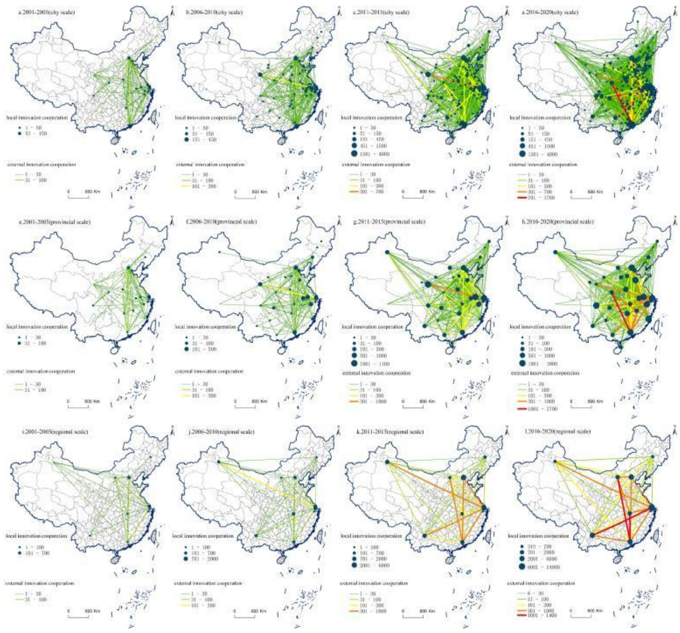

Fig 4. Multi-scale innovation cyberspace pattern from 2001 to 2020

5. Proximity mechanism of technology innovation networks

This study constructs a model of negative binomial regression as shown in Eq.(6) to estimate the panel data from the year of 2001 to 2020 and explores the factors influencing on the technology innovation network of specialized and sophisticated SMEs in China. The dependent variable is the number of cooperation patent between nodes and the independent variables are geographical proximity (Geo), institutional proximity (Ins), economic proximity (Eco), social proximity (Soc), and technological proximity (Tec).In order to ensure the feasibility of the estimated results, the hierarchical regression method is used to analyze.

5.1 Regression results and analysis

Table4 shows that geographical proximity has a negative and significant effect on the innovation cooperation, and the greater the geographical distance is, the less conducive to inter-city innovation cooperation. Geographic proximity can promote the interaction and exchange of innovation subjects and the dissemination and diffusion of invisible knowledge. Therefore, geographical proximity provides convenient conditions for inter-city innovation cooperation, and with the increase of geographical distance, the cost of interaction and contact increases, which further hinders inter-city innovation links. This is inconsistent with Friedman' assertion that "geography is dead" (Friedman,2005)。

Table4 shows that the institutional environment of cities at different administrative levels is different, which will lead to institutional barriers for innovation cooperation, while cities at the same administrative level have similar institutional frameworks, scientific norms or codes of conduct, which is conducive to reducing institutional barriers, enhancing mutual trust, reducing unnecessary cost factors, and improving the possibility of achieving consensus in innovation cooperation. This is similar to the research of Maillat and Kebir (2011). The similar institutional basis is the basis of inter-city innovation cooperation.

Tabel 4. Regression results of the impact of multidimensional proximity on technology innovation networks

Variable	Model(1)	Model(2)	Model(3)	Model(4)	Model(5)
Geo	-0.0011***	-0.0012***	-0.0006***	-0.0003***	-0.0003***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Ins		0.9187***	1.0376***	1.2486***	1.0868***
		(0.0325)	(0.0211)	(0.0181)	(0.0178)
Eco			1.8936***	1.7484***	1.2238***
			(0.2233)	(0.0217)	(0.0211)
Soc				291.0799***	206.0202***
				(4.5095)	(3.5679)
Tec					3.5850***
					(0.0789)
_Cons	-2.0403***	-2.4648***	-34.1979***	-35.0075***	-28.3981***
	(0.0418)	(0.0389)	(0.3625)	(0.3717)	(0.03553)
Lnalpha	6.7149***	6.5924***	5.4411***	3.2332***	2.9875***
_cons	(0.0153)	(0.0156)	(0.0178)	(0.0171)	(0.0173)
N	1.6e+06	1.6e+06	1.6e+06	1.6e+06	1.6e+06
Pseudo R2	0.0152	0.0247	0.1130	0.3517	0.3770
LR chi2	1770.40	2881.04	13153.50	40941.60	43888.35
Prob	0.0000	0.0000	0.0000	0.0000	0.0000

Note: 1. Standard error in brackets; 2. Significance level,* p < 0.1， ** p < 0.05，*** p < 0.01。

Table4 illustrates that economic proximity has a significant positive impact on innovation cooperation. The industrial structure of cities is related to the level of economic development to a certain extent, and similar industrial structures will be formed when the economy is close, which indicates that economic proximity can promote inter-city innovation cooperation, and the closer the level of economic development, the more opportunities for innovation cooperation between cities. This conclusion confirms the statement of Sun and Liu (2016) on economic proximity. Inter-city economic proximity has a relatively similar level of technological development and industrial structure, making technological innovation cooperation more likely to occur.

Table4 illustrates that social proximity is the key factor of technology innovation cooperation. The subjects of innovation cooperation are more inclined to choose the subjects of social proximity to establish cooperative relations, and the closeness of social relations is an important factor to improve innovation cooperation. Social proximity is based on cooperation practices and trust mechanisms to reduce the uncertainty risk of innovation cooperation, reduce unnecessary processes, improve the flow and acceptance of innovation elements, and enhance the path dependence of inter-city innovation cooperation.

Table4 shows that technological proximity has a positive effect on innovation cooperation. The more consistent the similarity and adaptability of innovation technology are, the more similar the invisible knowledge structure between innovation subjects is, the more conducive to the subjects' understanding of the acquisition of diversified knowledge base and rare resources, so as to make the inter-city technology innovation cooperation smooth and efficient.

5.2 Robustness test and discussion

The robustness of the regression model results is tested from both the sample and the method. From the test of sample selection, considering that the cooperation relationship of technology innovation cooperation between the cities with a scale of 1 is relatively sporadic, and the innovation cooperation may not be restricted by multi-dimensional proximity, the cities are eliminated, and the model is re-used for stepwise regression. From the test of model regression method, the Tobit model is used to conduct empirical calculation again. The regression results of the two test methods are shown in TABLE 5, and there are no contradictory conclusions in the regression results.

TABLE5. Results of robustness test

Variable	Model(1)	Model(2)	Model(3)	Model(4)	Model(5)	Model(6)	Model(7)	Model(8)	Model(9)	Model(10)
Geo	-0.0011***	-0.0012***	-0.0006***	-0.0002***	-0.0003***	-0.0234***	-0.0250***	-0.0185***	-0.0110***	-0.0112***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(-0.0000)	(0.0005)	(0.0005)	(0.0005)	(0.0004)	(-0.0004)
Ins		0.9094***	1.0030***	1.2495***	1.0969***		18.0906***	15.6366***	15.5753***	14.0301***
		(0.3858)	(0.0247)	(0.0207)	(0.0205)		(0.3048)	(0.2988)	(0.2843)	(0.2949)
Eco			1.8923***	1.7568***	1.2506***			33.7060***	30.3454***	21.3664***
			(0.0258)	(0.0248)	(0.0242)			(0.4452)	(0.4014)	(0.3873)
Soc				302.5883***	218.4761***				442.7345***	386.4619***
				(5.1225)	(4.1396)				(5.8595)	(5.6041)

Tec					3.5892***					56.2111***
					(0.0927)					(1.3550)
_Cons	-2.0817***	-2.4940***	-34.2640***	-35.4930***	-29.1933***	-124.0214***	-133.5906***	-663.8840***	-607.1930***	-495.3627***
	(0.0490)	(0.0457)	(0.4180)	(0.4253)	(0.4076)	(1.4071)	(1.5172)	(8.2042)	(7.4240)	(7.1472)
N	1.6e+06	1.6e+06	1.6e+06	1.6e+06	1.6e+06	1.6e+06	1.6e+06	1.6e+06	1.6e+06	1.6e+06
LR chi2	1313.75	2091.30	9608.37	32440.06	34593.71	4247.18	9486.86	24961.04	33845.91	37507.39
Prob	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Note: 1. Standard error in brackets; 2. Significance level,* $p < 0.1$， ** $p < 0.05$，*** $p < 0.01$

6. Conclusions and recommendations

6.1 Conclusions

This study explores the evolution of the technological innovation network structure and impact of multi-dimensional proximity on innovation cooperation of specialized and sophisticated SMEs in China to reveal the characteristics of dynamic transmission of knowledge and technology in the network.

First, the network density and clustering degree are increasing, the number of innovation subjects is increasing, and the interaction between various subjects is frequent, among which the transmission of knowledge and technology between private enterprises is the most important form of cooperation, and comprehensive universities and science and technology universities become important knowledge exchange nodes. The state-owned enterprises such as the State Grid Corporation of China as the core of the network become the priority cooperation subjects gradually. The high-frequency interaction between some controlling or being controlled subjects forms the local network.

Second, the transmission of knowledge and technology focused on the industry of telecommunication technology, electronic information, petrochemical industry, and equipment manufacturing, while the innovation cooperation in new materials, composite materials, composite technology, biomedical and other industries becoming prosperous gradually. More science and engineering universities and research institutes with the advantage of innovation assist the cooperation of industry-university-research actively.

Third, Shanghai, Beijing and the coastal cities play a leading role in the transmission of knowledge and technology. At the local-external level, Shenzhen, Guangzhou, Tianjin, Chengdu, Chongqing and other cities have gradually strengthened the "all-embracing" ability of innovation cooperation. Xi'an, Dongguan and other cities are typical representatives of the externality and liquidity of innovation knowledge. At the provincial level, the coastal provinces with good R&D investment, technology accumulation and industrial foundation are more dependent on intra-province innovation cooperation. At the regional scale, coastal regions with excellent resource endowments have more advantages in the scale of local and external innovation cooperation, and the level difference between regions is obvious.

Finally, it is found that geographical proximity, institutional proximity, economic proximity, social proximity and technological proximity have significant effects. Geographical distance is still a constraint factor for the technological innovation cooperation. The order of the forces affecting the innovation network is social proximity, technological proximity, economic proximity, institutional proximity, and geographical proximity respectively, of which the social proximity is the strongest force to drive the flow of knowledge and technology across regions.

6.2 Recommendations

Based on the above findings, the following countermeasures and suggestions are proposed to promote the technology innovation cooperation of technology innovation of specialized and sophisticated SMEs in China.

First, strengthen the awareness of cooperation among the private enterprises and construct the mechanism of collaborative development and spatial linkage. Encourage the construction of innovative industry alliances, and provide targeted technical assistance. The guiding function of the government should be exerted to guide state-owned enterprises to deepen their participation and openness to participate in technological innovation exchanges widely and actively.

Second, establish a professional talent team, create a technological innovation financial platform, integrate key core technologies into the industrial chain, activate the endogenous driving force of technological innovation, and force the development of high-tech industries to keep up with market demand.

Third, position the core areas of technological innovation, promote the construction of technological innovation spillover channels, exert technological spillover effects on areas with technological potential differences, and promote the sharing of innovation resources. Promote the flow of innovative elements such as funds, manpower, and technology between regions, and activate the endogenous driving force of technological innovation.

Finally, improve infrastructure construction, improve reach-ability between innovation regions, and reduce transaction costs in terms of distance and time. Social proximity is a key factor in promoting the flow of innovative knowledge. It is necessary to accelerate the integration of institutional mechanisms with innovation centers, actively promote the integration of innovation systems, enhance trust, reduce interaction costs, ensure effective integration of technological needs, and promote the diffusion and dissemination of innovative knowledge.

6.3 Limitations and directions for future research

The patent cooperation data can be used as an indicator to measure the characteristics of the technological innovation network, but there are still a large number of patents for independent applications, so the follow-up research can be supplemented by the innovative topics represented by independent patents. In addition, this paper uses the data of cooperation patent applications to build a directed innovation network. Subsequent research can analyze the characteristics of the directed network based on the relationship data of patent authorization, transfer, and citation.

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