

Article

Measuring Intra-Urban Innovation Space from the Unit-Network Perspective: A Case Study of Guangzhou

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Abstract: Three spatial turns have occurred in innovation research, including focuses on regional, urban, and intra-urban scales. The primary focus of this study was to determine the spatial distribution of innovation and the innovation networks within urban areas based on a unit-network analytical framework. ArcGIS Pro was applied to identify innovation space units and to build a collaboration matrix among these units. Subsequently, Gephi 0.9.2 was used to analyse the networks. Guangzhou was used as a case study for empirical analysis, and the main conclusions are as follows. Guangzhou contains 53 innovation space units covering 495 grids and an area of 123.75 km² (1.67% of the land area). The 53 innovation space units encompass 231,698 patents, accounting for 72.28% of the total patents in Guangzhou. The 53 innovation space units can be categorised into three levels—innovation agglomeration zones (IAZs), innovation agglomeration sub-zones (IASZs), and innovation agglomeration nodes (IANs)—which can be further classified into nine types. The spatial distribution of innovation and the innovation networks in Guangzhou form a core–periphery structure, with the Wushan–Shipai Science and Education Innovation Zone, Tianhe Centre–Yuexiu East CBD Zone, and Guangzhou Science Town Innovation Zone forming three poles at the core. The weighted degree centrality of the three poles ranked among the top 3 of the 53 innovation space units, and the link frequency between poles was among the top 3 in the 143 pairs of connections between the 53 innovation spatial units.

Keywords: innovation space; innovation networks; GIS; spatial measurement; urban innovation; Guangzhou



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1. Introduction

Since the technological revolution, innovation has become a critical factor in driving economic growth and influencing economic cycles. Schumpeter first captured and theorised innovation in the 20th century [1], and argued that economic change revolves around innovation, entrepreneurial activity, and market forces [2]. However, innovation theory has not attracted much attention. It was not until after the 1950s that the microelectronics technology revolution brought about economic growth that could no longer be explained by traditional economic factors such as capital and labour; at this point, economists revisited and reflected on Schumpeter's innovation theory [3], leading to the emergence of Neo-Schumpeterian economics [4]. Schumpeter's followers use innovation to explain economic

development, as exemplified by the Solow model, which pioneers the incorporation of technological progress into economic growth variables [5]. In addition, they have explored the mechanisms of innovation, proposing the national innovation system theory [6] and triple helix model of innovation [7].

However, innovation activities exhibit distinct spatial characteristics that manifest as the formation of spatial agglomerations [8] and spatial networks [9]. Consequently, innovation has attracted the attention of geographers and urban researchers. Their research on innovation geography [10] and space [11] make up spatial turns of innovation research resulting in three primary perspectives, including focuses on regional, urban, and intra-urban scales. This study focuses on the intra-urban scale. Current research on intra-urban innovation spaces has effectively characterised the spatial distribution of innovation activities and analysed the types and patterns of innovation spaces within urban areas [12]. Existing studies have focused primarily on the spatial agglomeration dimension of innovation. However, spatial networks of innovation within urban areas have not yet been explored in current research. Therefore, this study explored the way in which spatial innovation networks can be measured beyond identifying the spatial distribution characteristics of innovation within urban areas.

2. Literature Background

Initially, innovation was the subject of economic research. However, since the 1970s, distinct spatial characteristics of innovation have been recognised, including regional, urban, and intra-urban innovation scales.

2.1. Regional Innovation Research

Since the 1970s, regional innovation has attracted the attention of scholars of regional economics and economic geography [13]. These researchers have been dedicated to explaining why innovative activities tend to agglomerate in certain regions, or in other words, the mechanisms that drive innovation within a particular region. Regional innovation research that focuses on innovation within regional spatial boundaries can be considered the first focus area following the initial spatial turn in innovation research, and primarily includes two theoretical sources and research trajectories.

The first is research on innovation in industrial districts/clusters. In his 1890 *Principles of Economics*, Marshall first introduced the concept of industrial districts, arguing that they are an alternative organizational mode to large-scale production by big corporations, and are characterised by a geographic agglomeration of numerous small and medium-sized enterprises (SMEs) [14]. However, with the rise of Fordism, characterised by large-scale production dominated by large corporations, the theory of industrial districts has not received widespread attention [15]. It was not until the 1970s, with the rise of the “Third Italy”, that a group of Italian scholars revived Marshall’s industrial districts to explain this phenomenon [16,17]. In the 1990s, Porter proposed the theory of industrial clusters, similar to the theory of industrial districts, to explain the competitive advantage of nations and regions [18]. Concurrent with these developments was research on flexible specialisation, new industrial spaces, and innovative milieux [19,20]. Initially, these studies emphasised the effects of localised collective learning [21]. Geographic proximity, knowledge, technology, and information flows within industrial districts/clusters promote innovation among local enterprises [22]. However, with the development of economic globalisation, subsequent research has recognised the role of multi-scale linkages between global and local networks to innovation in industrial districts/clusters [23,24].

The second is the research on regional innovation systems. Since the 1980s, scholars such as Lundvall, Freeman, and Nelson have emphasised a systems approach to studying

innovation, leading to the development of innovation system theory [25,26]. In the 1990s, Cooke proposed the concept of regional innovation systems [27], and Morgan introduced a concept called learning regions [28]. Research on regional innovation systems posits that regional organizational systems comprising interconnected enterprises, research institutions, universities, government agencies, and intermediary organisations support and promote innovation. Innovation drives regional economic growth and development. These studies also highlight the importance of multiscale interactions among global, national, and local regions in shaping regional innovation [29].

2.2. Urban Innovation Systems Research

Following the focus on regional innovation research, innovation has increasingly captured the attention of geographers and urban researchers. Pioneering research on urban innovation systems [30,31] can be considered the second spatial turn in innovation research, and can be categorised into two main streams.

The first is research on urban innovation hierarchies, which originates from the central place theory paradigm of urban geography [32]. Pred was among the first to introduce the diffusion of innovation through urban hierarchies [33]. Subsequently, scholars such as Hall and Florida introduced concepts like innovative cities and the creative class [34,35]. They argued that the function of urban areas has evolved from production and exchange centres in industrial societies, to service and management centres in post-industrial societies, and innovation and creativity centres in the knowledge economy. They posit that innovation is the core of urban competitiveness. This stream of research involves constructing appropriate evaluation indicators to assess urban innovation capacity at global, national, and regional levels, and further uncovering the factors influencing the strength of urban innovation capacity [36,37].

The second is research on urban innovation networks, with its theoretical foundation rooted in the network turn in urban geography research [38,39]. Castells first argued that in the information age, flows of information and other elements constitute a form of social organisation [40]. Taylor further called the various flows between cities the second nature of cities, emphasising that urban areas are not only place spaces in the traditional sense but also network nodes of flow spaces. This work was extended to analyse and visualise the World City Network [41]. Research on urban innovation networks has emerged as a significant direction against the backdrop of a rise in urban network studies [42]. These studies involve constructing appropriate methods to measure urban innovation networks at the global, national, and regional levels, characterising (evolution) features, and further uncovering the factors influencing the formation of urban innovation networks [43–45].

2.3. Intra-Urban Innovation Space Research

Concurrent with research on urban innovation systems, geographers and urban researchers have delved into the study of urban innovation spaces, further refining their focus to the intra-urban scale. This research has involved, on the one hand, deconstructing the spatial distribution of innovation within urban areas and, on the other hand, exploring the types and models of urban innovation spaces.

The study of the spatial distribution of innovation in urban areas has been significantly facilitated by the development of big data analysis methods in recent years. Relevant studies typically use the locations of patents [46] or innovative enterprises [47] to represent the spatial distribution of innovation activities within urban areas. Such studies employ various methods such as kernel density analysis [46], spatial grid counting [48], and postal block counting [49] to map the spatial distribution of patents and innovative enterprises within urban areas. Some studies specifically explore the spatial distribution characteristics of

different innovative enterprises/industries [50,51] or carriers of innovation (e.g., coworking spaces, maker spaces, and business incubators) [52].

In research on the types and models of intra-urban innovation spaces, various classifications can be made on the basis of different perspectives. Intra-urban innovation spaces can be categorised into high technology-intensive, creative, and knowledge-intensive service types [53]. According to their physical features, intra-urban innovation spaces can be classified as corridors, clumps, cores, comprehensive campuses, technology subdivisions, and scattered technology sites [54]. Regarding models of urban innovation spaces, relevant research has captured the evolution from science/technology/creativity parks (such as Silicon Valley) in the 1980s and 1990s, to innovation districts (such as Barcelona's 22@ and Boston's Seaport Innovation District) [55,56] in the 21st century. The former are typically located away from urban amenities and residential areas and have relatively single functions, whereas the latter are situated in downtown areas and suburbs, providing work–live–learn–play environments [57].

Rammer's study of Berlin offers a quintessential example of contemporary research on intra-urban innovation spaces. Based on unique panel data covering all legally independent enterprises with five or more employees in manufacturing and knowledge-intensive services in Berlin, and geocoding the enterprises' addresses to determine the precise locations, the research employed kernel density analysis to identify innovation agglomeration areas. Three types of innovation spaces were categorised: anchor plus areas (e.g., the Charlottenburg area around the Technical University), re-imagined urban areas (e.g., Friedrichshain), and urbanized science park areas (e.g., the Adlershof and Buch areas) [12].

2.4. Literature Overview and Research Implications

Initially, economists captured innovation as an economic phenomenon. As innovation has distinct spatial attributes, spatial turns emerged in innovation research. Regional innovation research can be regarded as the first faction of the spatial turns. Related studies explore the mechanisms of innovation occurrence within the spatial scope of regions and industrial districts, involving multiple spatial scales from global to local. Urban innovation system research regards cities as spatial nodes of innovation to measure and analyse urban innovation hierarchy and urban innovation networks in the world, country, or region, which can be considered the second faction of the spatial turns. Intra-urban innovation space research can be attributed to the third faction of the spatial turns, which is the field of this study. Current studies on intra-urban innovation space can have depicted the spatial distribution of innovation within urban areas, but this is rooted in the spatial agglomeration attributes of innovation. Innovation also has spatial network attributes, and innovation can also form spatial networks within urban areas, similar to the innovation networks between cities in the world, nation, or region. However, there is currently little literature exploring intra-urban innovation networks. This study aimed not only to identify the spatial distribution of innovation within urban areas but also to measure the spatial networks of innovation within the urban area, which deepens the research on intra-urban innovation spaces. It is necessary to construct new research methods based on existing studies.

Firstly, current intra-urban innovation space research primarily uses patents and innovation enterprises (in China, mainly national high-tech enterprises recognised by the Ministry of Science and Technology of China) as indicator data. The data of innovation enterprises have geographical location information, which can be used to depict the spatial distribution of innovation, but it is insufficient for constructing innovation networks. However, in addition to containing address information that can be translated into geographic coordinates, patents also include the information of joint applicants, which can be used

to construct collaboration networks. Therefore, we choose patents as the indicator data. Secondly, current research methods on intra-urban innovation space mainly include kernel density analysis and spatial grid analysis. Kernel density analysis can intuitively display the spatial agglomeration characteristics of innovation, but it cannot be used to establish nodes for network analysis. In comparison, spatial grid analysis can be used to delineate the innovation space units proposed in this study, and using these units as nodes can enable network analysis. Therefore, using patents and adopting spatial grid analysis, this study innovatively proposes a unit-network analysis method and conducts the following research using Guangzhou as a case study.

3. Materials and Methods

3.1. Study Area

Guangzhou, the capital of Guangdong Province, China, is one of five nationally central cities. Guangzhou is located on the Pearl River Delta and is at the forefront of China's reform and opening-up process. Guangzhou is divided into 11 districts (Tianhe, Yuexiu, Liwan, Haizhu, Guangzhou Development Zone, Panyu, Nansha, Baiyun, Zengcheng, Huadu, and Conghua) [58], covering a total area of approximately 7434.40 km² (Figure 1).

Since its reform and opening-up, Guangzhou has experienced rapid economic growth and population expansion. The regional GDP of Guangzhou soared from RMB 4.3 billion in 1978 to RMB 303,557.3 billion in 2023, an approximately 700-fold increase. Guangzhou's population grew from 4.83 million in 1978 to 10.57 million in 2023. Consequently, innovation in Guangzhou has become increasingly vibrant. According to the Innovation CitiesTM Index by 2thinknow (for detailed information, please refer to Appendix A), Guangzhou's global ranking rose from 232nd in 2011 to 51st in 2022. According to the Guangzhou Statistical Yearbook, internal expenditure on R&D increased from RMB 2.906 billion in 2000 to RMB 104.299 billion in 2023, and the number of R&D personnel rose from 99,100 in 2010 to 349,900 in 2023 [59].

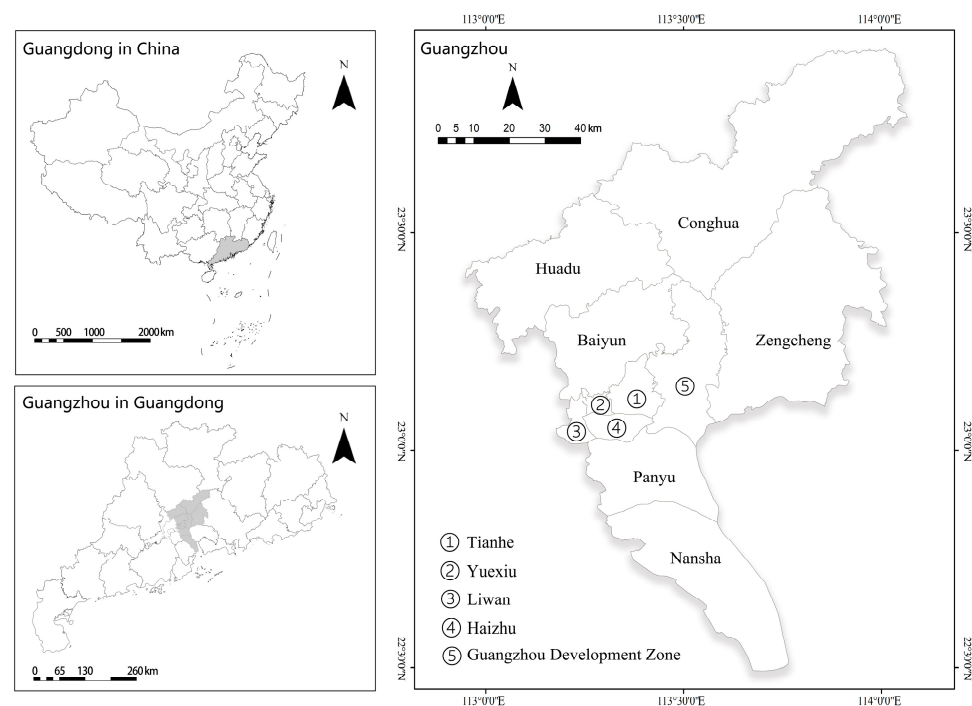


Figure 1. Geographical location of the study area.

3.2. Analytical Methods

The overall analytical method was as follows. Using patent data, innovation spatial units were identified via spatial clustering analysis based on a 500×500 m spatial grid. Second, with innovation spatial units as nodes, network analysis was conducted using joint applicant information from the patents.

3.2.1. Identifying Innovation Space Units

The identification method was as follows: (a) the address information of patents was converted into geographic coordinates through the Gaode map API; (b) ArcGIS Pro was used to divide Guangzhou into spatial grids of 500×500 m; (c) the number of patents in each grid was counted and the result was assigned to each space grid; and (d) ArcGIS Pro was used to perform cluster analysis on the spatial grids to identify spatial agglomeration areas of innovation. Among these steps, the scale of spatial grids and the cluster analysis are crucial. The following details provide further explanation.

Firstly, the selection process for the scale of spatial grids needs to be explained. In related research, standard scales of spatial grids usually include 500×500 m [60], 1000×1000 m [61], and 2000×2000 m [62]. During the research process, we conducted experimental analysis using spatial grids of all three scales. The comparative results revealed that 1000×1000 m and 2000×2000 m spatial grids were too coarse, particularly in the central urban area, making them challenging to delineate innovation space units. Ultimately, we chose to use 500×500 m spatial grids for analysis. The potential reason why the 500×500 m spatial grids are relatively suitable is that this scale is close to the density of arterial roads in Guangzhou. According to the 2023 Guangzhou Transportation Development Annual Report, the density of arterial roads (excluding branch roads) in the central urban area of Guangzhou is 7 km/km^2 , which is close to the density of 500×500 m spatial grid side length. Taking the central zone of Zhujiang New Town (bounded by Linjiang Avenue to the south, Huangpu Avenue to the north, Liede Avenue to the east, and Guangzhou Avenue to the west) as an example, the average spacing of the arterial roads is close to 500 m. From south to north, the spacing between Linjiang Avenue and Huacheng Avenue is approximately 600 m, between Huacheng Avenue and Jinsui Road is approximately 480 m, and between Huacheng Avenue and Huangpu Avenue is approximately 450 m. From east to west, the spacing between Liede Avenue and Xiancun Road is approximately 560 m, between Xiancun Road and Huaxia Road is approximately 680 m, and between Huaxia Road and Guangzhou Avenue is approximately 620 m.

Secondly, the method of cluster analysis needs to be explained in detail. The Cluster and Outlier Analysis (Anselin Local Moran's I) tool in ArcGIS Pro was used for analysis; this tool is commonly used to identify statistically significant hot spots, cold spots, and spatial outliers (a low value surrounded by high values or a high value surrounded by low values). The Local Moran's I statistic of spatial association was given as:

$$I_i = \frac{x_i - \bar{X}}{S_i^2} \sum_{j=1, j \neq i}^n w_{ij} (x_j - \bar{X})$$

where x_i is an attribute of feature i , $\bar{X}$ is the mean of the corresponding attribute, w_{ij} is the spatial weight between features i and j , and:

$$S_i^2 = \frac{\sum_{j=1, j \neq i}^n (x_i - \bar{X})^2}{n - 1}$$

where n equates to the total number of features.

The z_{I_i} scores were computed as:

$$z_{I_i} = \frac{I_i - E[I_i]}{\sqrt{V[I_i]}}$$

where:

$$E[I_i] = -\frac{\sum_{j=1, j \neq i}^n w_{ij}}{n-1}$$

$$V[I_i] = E[I_i^2] - E[I_i]^2$$

Statistical significance was set at a default confidence level of 95%. Four grid types were identified: high–high (HH), low–low (LL), high–low (HL), and low–high (LH). HH and HL grids were initially considered as spatial agglomeration areas of innovation. Subsequently, manual adjustments were made based on natural boundaries, transportation barriers, administrative boundaries, and industrial park boundaries to comprehensively delineate the innovation space units in Guangzhou.

3.2.2. Characterizing Innovation Space Networks

The characterisation method was as follows: (a) taking the innovation space units as the scope, patents were screened to identify those with multiple institutions or companies within the units; (b) using the names of the cooperating institutions or enterprises, geographic coordinates were converted through the Gaode map API and a pairwise link matrix was determined where both parties fell within the innovation space units; (c) the Gephi 0.9.2 software was used to characterise topology networks and space networks of innovation. The construction of a pairwise relationship matrix between units and the characterisation of networks are key aspects, and the relevant details are elaborated below.

Firstly, the principles and details of constructing a pairwise link matrix between units need to be explained. We first filtered out patents jointly applied for by multiple institutions/companies within the innovation space units. Assuming that a patent was jointly applied for by four institutions/companies, A, B, C, and D, we could establish six pairs of collaborative relationships: A–B, A–C, A–D, B–C, B–D, and C–D. Based on this principle, all filtered patents were established as pairwise relationship matrices, resulting in a dataset with two columns of applicant institution/company names, designated as column X and column Y. We converted the institutions/companies in column X and column Y into geographical coordinates and performed spatial association with the innovation space units, respectively. Assuming there were N innovation space units, A was located in unit N1, B was located in unit N2, C was located in unit N3, and D was not located in any unit. In this way, one link could be established between N1–N2, one between N1–N3, and one between N2–N3. After aggregation and calculation, the link frequency between the N innovation space units could be obtained.

Secondly, the characterisation of networks needs to be explained in detail. Gephi 0.9.2 can be used to analyse indicators, such as link frequency and weighted degree centrality, and to achieve visualisation presentations in graphical and map formats. Link frequency refers to the number of collaborations between innovation space units. Weighted degree centrality is an indicator of the centrality of an innovation spatial unit within the network and is calculated as follows:

$$O_i = \sum_{j=1}^n T_{ij}, i \neq j$$

where O_i is the weighted degree centrality of unit i , n is the number of units, and T_{ij} is the frequency of collaboration between unit i and unit j .

3.2.3. Data Collection

This study utilised patent application data rather than granted patent data. In China, applicants can freely submit patent applications, while grants require examination by the China National Intellectual Property Administration. Grants have a time lag compared to applications. If an institution or enterprise files a patent application, it indicates that they have invested resources and costs to conduct technical research or product design. In other words, regardless of government approval, the act of filing a patent application signifies the occurrence of innovation [49].

This study primarily utilised data on patents obtained from the China Patent Announcement website of the China National Intellectual Property Administration (<http://epub.cnipa.gov.cn>, accessed on 30 March 2024). A total of 320,080 patents with Guangzhou application addresses were collected, covering the period from 2000 to 2023. In addition, this study employed Guangzhou maps sourced from ArcGIS Pro, as well as administrative and industrial park boundaries of Guangzhou, obtained from the Guangdong Province Public Map Service website (<https://guangdong.tianditu.gov.cn>, accessed on 30 October 2024).

4. Results

4.1. General Overview

Statistical analysis by administrative district revealed that among Guangzhou's 11 districts, Tianhe had the highest number of patents (108,296), followed by the Guangzhou Development Zone (44,055), Panyu (38,604), Yuexiu (37,743), Haizhu (27,688), Baiyun (17,297), Nansha (12,586), Liwan (12,451), Huadu (11,296), Zengcheng (7926), and Conghua (2139). Kernel density analysis (for detailed information, please refer to Appendix B) of patent locations revealed five spatial agglomeration areas of innovation: Wushan–Shipai, Tianhe Centre–Yuexiu East, Guangzhou Science Town, Haizhu North (Xin Gang West Road), and Guangzhou University Town. However, this spatial analysis was not sufficiently granular (Figure 2).

The following results were obtained by identifying innovation space units. The total area of Guangzhou is 7434.40 km², divided into 30,142 grids of 500 × 500 m. There are 53 innovation space units in Guangzhou, covering 495 grids and an area of 123.75 km², and accounting for 1.67% of the total urban area. The 53 innovation space units encompassed 231,698 patents, accounting for 72.28% of the total patents in Guangzhou. Among the 53 innovation space units, the largest has an area of 18.00 km², whereas the smallest has an area of 0.25 km². The maximum number of patents within a unit was 57,952 and the minimum was 227. Among the units, the maximum weighted degree centrality was 1339 and the minimum was 1 (Table 1).

Table 1. Overview of 53 innovation space units in Guangzhou.

Unit Number	Unit Name	Number of Patents	Weighted Degree Centrality	Unit Area (km ²)
U-01	Wushan–Shipai Science and Education Innovation Zone	57,952	1339	18.00
U-02	Guangzhou Science Town Innovation Zone	33,645	1211	16.25
U-03	Tianhe Centre–Yuexiu East CBD Zone	24,512	1163	9.50
U-04	Xingang West Road Science and Education Innovation Zone	19,513	485	9.50
U-05	Guangzhou University Town Science and Education Innovation Zone	13,233	229	14.00

Table 1. Cont.

Unit Number	Unit Name	Number of Patents	Weighted Degree Centrality	Unit Area (km ²)
U-06	Huanghuagang–Dongfeng Middle Road Science–Education Innovation Zone	12,930	98	3.75
U-07	Yuxiu–Liwan CBD Zone	9612	163	8.00
U-08	Tangxia Industrial Park Zone	6133	46	3.25
U-09	Guangzhou Science Town East Zone	4732	67	3.75
U-10	Yunpu Industrial Park Zone	4409	21	2.88
U-11	Nansha Information Technology Park Research Zone	4369	119	1.75
U-12	Tianhe Wisdom Town Zone	3356	84	2.75
U-13	Nansha Jiaomen River Business Zone	3022	53	1.63
U-14	Southern Medical University	2232	12	0.75
U-15	Nancun Wanbo Business Zone	2037	0	1.00
U-16	West District of Guangzhou Development Zone	1920	37	1.63
U-17	Tian'an Energy Conservation Technology Park	1814	37	0.75
U-18	Guangzhou Biology Island	1794	13	0.50
U-19	Phoenix Lake District of China and Singapore Knowledge Town	1695	20	0.75
U-20	Huangcun–Zhuji Industrial Park Zone	1628	17	1.75
U-21	Fangcun North Industrial Park Zone	1578	3	0.75
U-22	Liwan E-commerce Park	1546	0	0.25
U-23	Cencun Industrial Park Zone	1444	1	1.00
U-24	Guangzhou Private Science–Technology Park	1318	14	1.25
U-25	Yantang Creative Park Zone	1293	140	2.00
U-26	China–Singapore Knowledge Town North Zone	1112	12	1.00
U-27	CSSC Huangpu Wenchong Shipbuilding Co., Ltd.	993	0	0.25
U-28	Chepi Industrial Park Zone	916	9	1.75
U-29	Nansha Zhujiang Industrial Park	913	2	1.75
U-30	Yuangang–Changtang Creative Park Zone	749	31	1.75
U-31	Huijiang Industrial Park Zone	747	1	1.50
U-32	Hanxi Changlong TOD Zone	729	0	0.25
U-33	Sanyuanli Science and Education Zone	723	5	0.75
U-34	LOTES Guangzhou Co., Ltd.	587	0	0.25
U-35	Panlong Industrial Park	542	0	0.25
U-36	Wanshengwei TOD Zone	508	8	0.50
U-37	Huangpu Village Creative Park Zone	504	2	0.75
U-38	Guangzhou–Foshan Digital Creative Park	426	0	0.25
U-39	Dantansha Optoelectronics Industrial Park Zone	369	0	0.50
U-40	Guangzhou Baiguoyuan Information Technology Co., Ltd.	366	0	0.25
U-41	Huachuang Industrial Park	359	3	0.75
U-42	Gaotang Industrial Park Zone	352	3	0.75
U-43	Guangzhou Guangri Elevator Industry Co., Ltd.	342	2	0.25
U-44	China Tobacco Guangdong Industrial Co Ltd.	311	12	0.25
U-45	Guangzhou Wenchong Shipyard Co., Ltd.	308	0	0.25
U-46	Guanhao Science–Technology Park	290	19	0.25
U-47	Dongfeng Nissan Passenger Vehicle Company	284	0	0.25
U-48	Pazhou TOD Zone	281	2	0.50
U-49	Guangdong Hotata Technology Group Co., Ltd.	280	0	0.25
U-50	Guangzhou College of SCUT	264	2	0.25
U-51	Guangzhou Shipyard International Co., Ltd.	260	0	0.25
U-52	Yuzhu Zhigu Industrial Park	239	0	0.25
U-53	Guangzhou Panyu Polytechnic	227	1	0.25
Sum		231,698	-	123.75
Proportion in Guangzhou		72.28%	-	1.67%

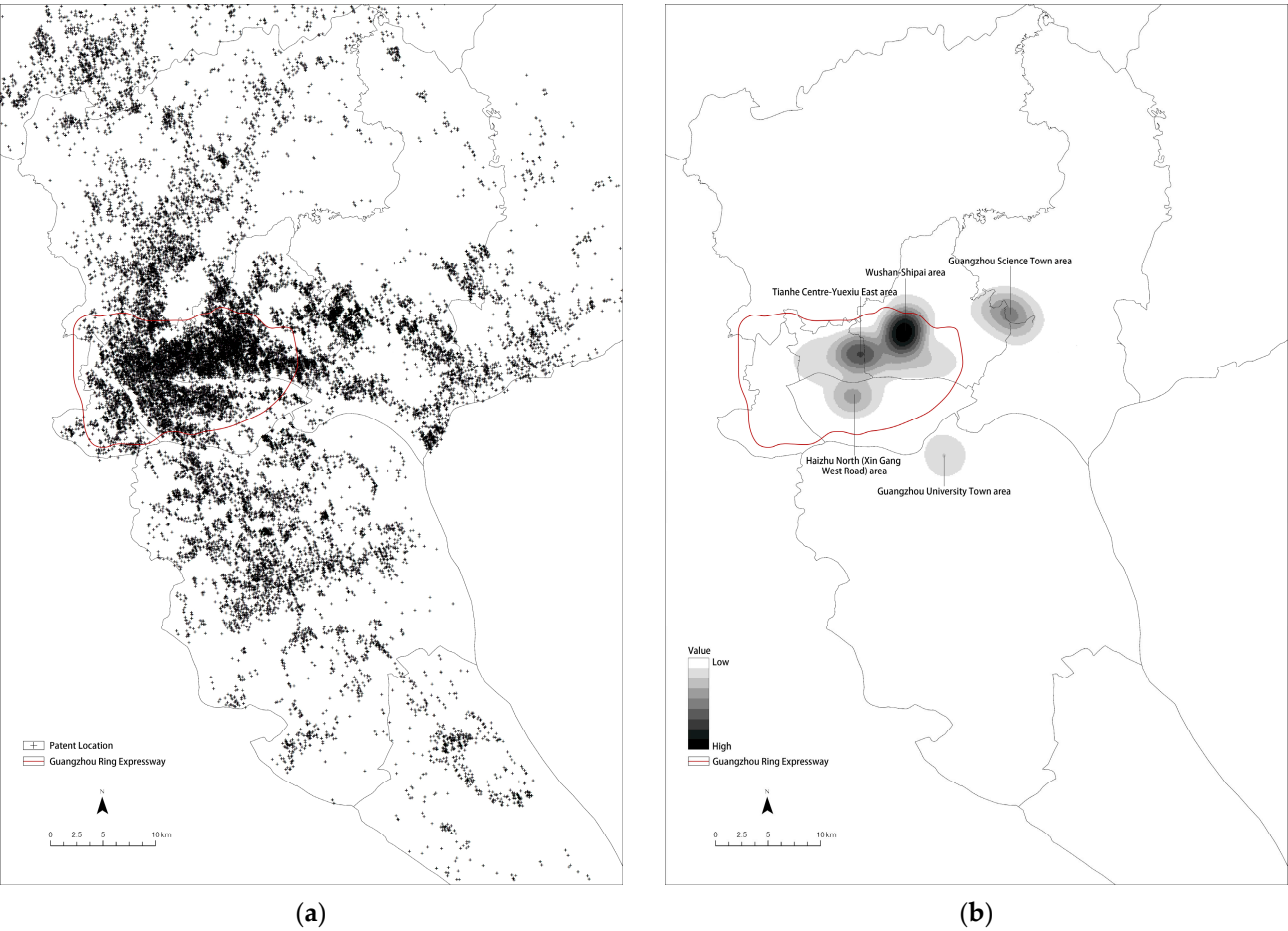


Figure 2. Spatial distribution of patents in Guangzhou. (a) Location; (b) kernel density analysis.

4.2. Spatial Distribution of Innovation in Guangzhou

The 53 innovation space units can be categorised into three levels—innovation agglomeration zones (IAZs), innovation agglomeration sub-zones (IASZs), and innovation agglomeration nodes (IANs)—which exhibit a core–periphery structure, extending from the urban centre to the suburbs and then outskirts. IAZs are located in the urban centre or suburbs, IASZs are found in the suburbs, and IANs are found on the outskirts. The 53 spatial innovation units can be further classified into nine types: IAZs, Science and Education-Led; IAZs, Incubation-Led; IAZs, CBD-Oriented; IASZs, Science and Education Zone; IASZs, Industrial Park Zone; IASZs, Business Zone; IANs, Institute/Enterprise; IANs, Industrial Park; and IANs, TOD Node (Table 2 and Figure 3).

Table 2. Three levels and nine types of innovation space units in Guangzhou.

Three Levels	Nine Types	Typical Cases
IAZs	IAZs, Science and Education-Led IAZs, Incubation-Led IAZs, CBD-Oriented	Wushan–Shipai Science and Education Innovation Zone Guangzhou Science Town Innovation Zone Tianhe Centre–Yuexiu East CBD Zone
IASZs	IASZs, Science and Education Zone IASZs, Industrial Park Zone IASZs, Business Zone	Nansha Information Technology Park Research Zone Tangxia Industrial Park Zone Nancun Wanbo Business Zone
IANs	IANs, Institute/Enterprise IANs, Industrial Park IANs, TOD Node	Guangdong Hotata Technology Group Co., Ltd. Tian’an Energy Conservation Technology Park Wanshengwei TOD Zone

its historic urban centre, concentrating on business and office functions along Dongfeng Road, Zhongshan Road, and Huanshi East Road, forming the Yuexiu–Liwan CBD. From the 1990s onwards, Guangzhou continued to expand eastward, further creating a new agglomeration zone of business and office functions around Tianhe Road, Tianhe North Zone, and Zhujiang New Town, leading to the formation of the Tianhe Centre–Yuexiu East CBD. The numerous office buildings in these CBDs house many enterprises, including the headquarters of state-owned enterprises and research institutes, which apply for multiple patents. Additionally, Guangzhou’s CBDs are home to some technology companies, which are also active participants in innovation.

Third, Guangzhou Science Town is a distinct category among the seven IAZs in Guangzhou. In the early 1990s, the Guangzhou municipal government planned to construct Guangzhou Science Town to create a science and technology park similar to Silicon Valley. After several years of preparation, the Government of Guangzhou Municipality officially entrusted the development of Guangzhou Science Town to the Guangzhou Development Zone in 1998. The Guangzhou Development Zone is dedicated to building Guangzhou Science Town into an endogenous innovation development zone. After over two decades, Guangzhou Science Town has become one of the seven IAZs and the only IAZs incubated in Guangzhou, presenting the characteristics of local entrepreneurial small and medium-sized enterprises (SMEs) as the primary innovation entities [63].

4.3. Spatial Networks of Innovation in Guangzhou

Between the 53 innovation space units in Guangzhou, if any two units have collaborations, a theoretical maximum of 1378 pairs of links could exist. However, there are no joint patent applications between all units. Empirical analysis shows 143 pairs of units with varying relationship frequencies of joint patent applications. Furthermore, this study analyses topological networks and spatial networks. The topological network is a purely logical connection between units, which ignores spatial attributes. Through topological network analysis, we can derive the types of network entities, the types of links, the weighted centrality of nodes (innovation space units), and the link frequencies of edges (between innovation space units).

Regarding the types of network entities, private enterprises account for approximately 46.52%, whereas universities, research institutes, and state-owned enterprises account for approximately 52.66%. There are three main types of links in the network: between private enterprises (accounting for approximately 36.55%), between state-owned enterprises (accounting for approximately 27.72%), and between university/research institutes and private enterprises (accounting for approximately 12.24%).

Regarding the weighted centrality of innovation space units, the Wushan–Shipai Science and Education Innovation Zone, Guangzhou Science Town Innovation Zone, and Tianhe Centre–Yuexiu East CBD Zone are significantly higher than other units. The Wushan–Shipai Science and Education Innovation Zone has the highest weighted degree centrality (1339), with universities and research institutes as the primary actors in the networks, among which South China University of Technology ranks first. The Guangzhou Science Town Innovation Zone ranks second, with a weighted degree centrality of 1211, and with locally incubated private enterprises as the primary network actors. The Tianhe Centre–Yuexiu East CBD Zone ranks third, with a weighted degree centrality of 1163; its networks are dominated by state-owned enterprises, with the China Southern Power Grid and its subsidiaries and research institutes as typical representatives.

The link frequencies between the Wushan–Shipai Science and Education Innovation Zone, Guangzhou Science Town Innovation Zone, and Tianhe Centre–Yuexiu East CBD Zone are also the highest. The Guangzhou Science Town Innovation Zone and Tianhe

Centre–Yuexiu East CBD Zone have the most links, with a total of 662. The primary type of collaboration is that between enterprises, including state-owned and private enterprises. The Wushan–Shipai Science and Education Innovation Zone and the Tianhe Centre–Yuexiu East CBD Zone have 346 links, ranking second, with collaborations mainly between universities/research institutes and state-owned enterprises. The Wushan–Shipai Science and Education Innovation Zone and Guangzhou Science Town Innovation Zone have 316 links, ranking third, with collaborations mainly between universities/research institutes and private enterprises. (Table 3)

Table 3. Top 20 link frequencies between innovation space units in Guangzhou.

	Unit Name A	Unit Name B	Links
1	Guangzhou Science Town Innovation Zone	Tianhe Centre–Yuexiu East CBD Zone	662
2	Wushan–Shipai Science and Education Innovation Zone	Tianhe Centre–Yuexiu East CBD Zone	346
3	Wushan–Shipai Science and Education Innovation Zone	Guangzhou Science Town Innovation Zone	316
4	Wushan–Shipai Science and Education Innovation Zone	Xingang West Road Science and Education Innovation Zone	188
5	Wushan–Shipai Science and Education Innovation Zone	Yantang Creative Park Zone	136
6	Guangzhou Science Town Innovation Zone	Xingang West Road Science and Education Innovation Zone	83
7	Tianhe Centre–Yuexiu East CBD Zone	Xingang West Road Science and Education Innovation Zone	75
8	Wushan–Shipai Science and Education Innovation Zone	Yuexiu–Liwan CBD Zone	70
9	Guangzhou Science Town Innovation Zone	Huanghuagang–Dongfeng Middle Road Science and Education Innovation Zone	59
10	Xingang West Road Science and Education Innovation Zone	Nansha Research Zone	54
11	Wushan–Shipai Science and Education Innovation Zone	Guangzhou Science Town East Zone	50
12	Wushan–Shipai Science and Education Innovation Zone	Guangzhou University Town Science and Education Innovation Zone	44
13	Guangzhou Science Town Innovation Zone	Nansha Jiaomen River Business Zone	43
14	Tianhe Centre–Yuexiu East CBD Zone	Yuexiu–Liwan CBD Zone	37
15	Guangzhou Science Town Innovation Zone	Xingang West Road Science and Education Innovation Zone	34
16	Tianhe Wisdom Town Zone	Tian'an Energy Conservation Technology Park	30
17	Wushan–Shipai Science and Education Innovation Zone	Nansha Information Technology Park Research Zone	28
18	Guangzhou University Town Science and Education Innovation Zone	Huanghuagang–Dongfeng Middle Road Science and Education Innovation Zone	25
19	Wushan–Shipai Science and Education Innovation Zone	West District of Guangzhou Development Zone	25
20	Wushan–Shipai Science and Education Innovation Zone	Tangxia Industrial Park Zone	21
Sum of top 20			2326
Total of Guangzhou			2734
Proportion of top 20 in Guangzhou			85.08%

Mapping the topological networks into geographic space results in spatial networks, which visually display the spatial structure of innovation networks within urban areas. This study sets the geometric centre of innovation space units as the nodes of spatial networks.

Empirical analysis reveals that innovation networks form a core–periphery spatial structure within Guangzhou, with the Wushan–Shipai Science and Education Innovation Zone, Guangzhou Science Town Innovation Zone, and Tianhe Centre–Yuexiu East CBD Zone constituting the core three poles. This result realistically depicts the spatial structure of innovation within Guangzhou. Comparing this result to the innovation axis planned by Guangzhou in recent years, which is the strategic space for the future development of innovation and industry in Guangzhou, connecting the Guangzhou Development Zone, eastern Panyu, and Nansha from north to south, reveals a notable discrepancy between the current reality and the intended vision, suggesting that realizing the planned vision requires substantial effort. (Figure 4).

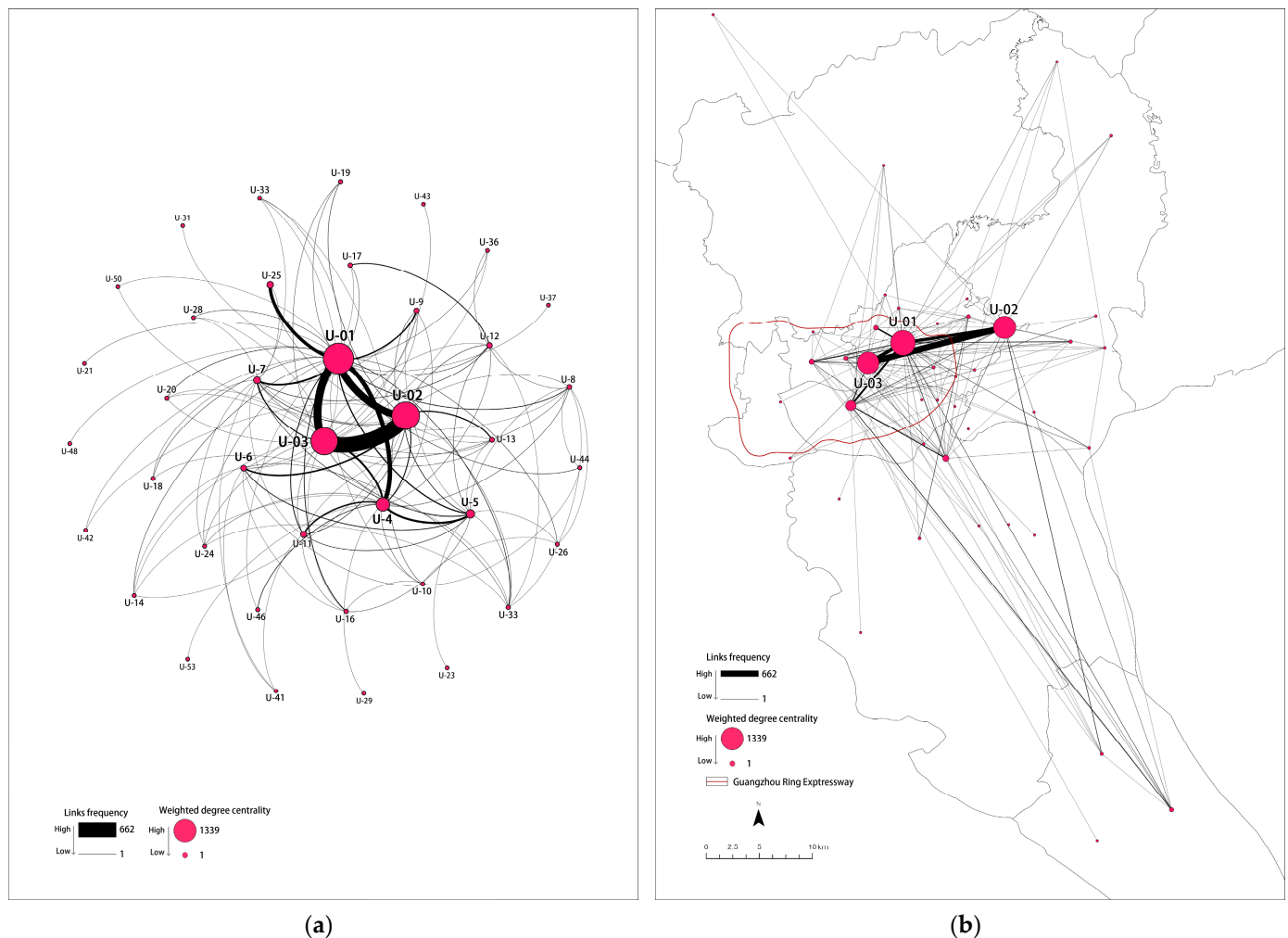


Figure 4. Innovation networks in Guangzhou. (a) Topological structure of networks; (b) spatial structure of networks.

5. Discussion

5.1. Mechanism Analysis

Firstly, we identified 53 innovation spatial units, covering 1.67% of the total land area and comprising 72.28% of the total patents in Guangzhou. This result raises the question of why innovation tends to spatially agglomerate in urban areas. Although this study cannot provide a direct answer, a literature review on innovation research offers the following explanations. First, the spatial agglomeration of innovation is primarily attributed to spatial proximity effects [64,65] with four underlying mechanisms. (1) Spatial agglomeration leads to economies of scale, allowing innovation actors (such as enterprises,

universities, and research institutes) to share infrastructure, public services, suppliers, and labour markets, thereby reducing the cost of innovation [66]. (2) Collective learning created by spatial agglomeration innovation actors form local networks that facilitate the flow and collaboration of knowledge, technology, and information [67,68]. (3) Spatial agglomeration generates positive externalities [69], such as local technological spillovers and spin-offs [70]. (4) Spatial agglomeration facilitates face-to-face communication and exchange of innovative ideas, particularly the sharing, dissemination, and diffusion of tacit knowledge [71,72]. The core three poles are the most agglomerated innovation space in Guangzhou. The following will qualitatively discuss their specific agglomeration mechanisms of innovation.

Wushan–Shipai Science and Education Innovation Zone emerged due to the agglomeration of universities and research institutes. In 1932, Sun Yat-sen University relocated to Wushan–Shipai, initiating the development of this zone. After 1949, the government continued to establish universities (such as South China University of Technology, South China Agricultural University, South China Normal University, and Jinan University) and research institutes (such as Guangzhou Institute of Energy Research of Chinese Academy of Sciences, Guangzhou Institute of Chemistry of Chinese Academy of Sciences, and Guangdong Academy of Agricultural Sciences) in the Wushan–Shipai area. They are among the top patent applicants in Guangzhou. After the reform and opening-up of China, the faculties and graduates of these universities and the researchers of these institutes founded enterprises nearby, and these universities and research institutes established affiliated enterprises. Meanwhile, considering the advantages of the high density of universities and research institutes, the government selected this location for the Guangzhou Tianhe High-Tech Industrial Development Zone, building Wushan Science and Technology Street and actively supporting the development of high-tech industries such as electronic information and software. Subsequently, the agglomeration of talents and enterprises gradually fosters the local ecosystem of innovation and entrepreneurship.

Guangzhou Science Town is a government-planned science and technology park. Its innovation is driven by entrepreneurial small and medium-sized enterprises (SMEs), which results from government support and market innovation. In 1998, the Guangzhou Development District took over the construction of Guangzhou Science Town. Initially, the Guangzhou Development Zone focused on attracting overseas talent and founded enterprises in Guangzhou Science Town. Subsequently, it began providing broader support for innovation and entrepreneurship, driving an increasingly diverse and extensive pool of entrepreneurial talent to support enterprises in Guangzhou. Guangzhou has several universities, research institutes, and state-owned enterprises. Their staff is an integral part of the entrepreneurship of Guangzhou Science Town. To meet the requirements of entrepreneurial enterprises, the Guangzhou Development Zone has built numerous state-owned incubators and encouraged private incubators in Guangzhou Science Town.

The innovation agglomeration in the Tianhe Centre–Yuexiu East CBD Zone is attributed to the affiliation and extension of CBD functions. This zone is the CBD formed in the context of the market economy after the reform and opening-up of China, primarily hosting corporate headquarters, financial institutions, professional service organizations, and high-end retail businesses, presenting the typical functional composition of a CBD. The high-density and high-intensity CBD is not a low-cost innovation place. However, the headquarters of many large state-owned enterprises and their subsidiaries are located in Tianhe Centre–Yuexiu East CBD Zone, such as the headquarters and subsidiaries of China Southern Power Grid, Sinopec Guangzhou Engineering Co., Ltd., and China Mobile Group Guangdong Co., Ltd., which are the top three patent applicants in Tianhe Centre–Yuexiu East CBD Zone. These state-owned enterprises generate numerous patent applications. This is attributed to Guangzhou’s advantage as a provincial capital. In addition, Tianhe

Centre–Yuexiu East CBD Zone has also gathered some technology companies, such as Guangzhou Kingsoft Network Technology Co., Ltd. and Guangdong Shuxiang Intelligent Technology Co., Ltd., which are also active innovation entities.

Secondly, we further measured the innovation networks within Guangzhou based on innovation space units. It was found that between the 53 innovation space units, there were 143 pairs of links. This result raises the question of why innovation forms networks. We also first explored the mechanisms through a literature review, and then specifically discussed the characteristics of Guangzhou. The literature suggests four mechanisms that drive the formation of innovation networks. (1) Collaborative innovation, including industrial chain collaboration, industry–university research collaboration, and collaboration among branches within the same enterprise [73,74]. (2) Specialised division of labour, generating technology outsourcing to contract research organisations (CRO) [75]. (3) Transactions on technological property rights such as patent assignments and technology acquisitions [76]. (4) The flow of innovation driven by talent mobility [77]. In this study, joint patent applications were used as an indicator to measure innovation networks, with collaborative innovation being the most direct mechanism. Collaborations between the Wushan–Shipai Science and Education Innovation Zone and Guangzhou Science Town Innovation Zone, and those between the Wushan–Shipai Science and Education Innovation Zone and Tianhe Centre–Yuexiu East CBD Zone are primarily driven by industry–university research collaboration. In contrast, collaborations between the Guangzhou Science Town Innovation Zone and Tianhe Centre–Yuexiu East CBD Zone are mainly driven by the industrial chain and collaboration among branches within the same enterprise (with headquarters in the CBD and subsidiaries in Guangzhou Science Town).

5.2. Comparison Analysis

The spatial patterns of innovation within many Chinese cities have been analysed in the existing literature, including Beijing, Shanghai, Shenzhen, Hangzhou, Nanjing, and Harbin. Analyses by Duan Dezhong et al. on Beijing and Shanghai found that Beijing consistently exhibits a core–periphery structure; Shanghai underwent an evolution from single-core to multi-core, simultaneously forming multiple innovation corridors [49]. Studies by Chen Qingyi et al. on Beijing, Shanghai, and Shenzhen suggested that both Beijing and Shanghai exhibit core–periphery characteristics, while Shenzhen displays a multi-group structure [78]. Wu Songtao et al. identified five innovation agglomeration zones within Harbin, distributing on both sides of the Songhua River and presenting a multi-group structure with connections through main roads [48]. Analyses by Tang Shuang et al. and Guan Manling et al. on Nanjing found that innovation is highly concentrated in the main urban area, and multiple agglomeration nodes are formed by surrounding industry/science/technology parks [47,79]. Studies by Wang Jiwu et al. and Zhao Peipei et al. on Hangzhou found that the spatial pattern of innovation exhibits a core–periphery structure (the urban central area, Binjiang High-Tech Development Zone, and Xiasha Education and Science Zone being the core three poles), adding point–axis (Chengxi Science and Technology Innovation Corridor) [80,81]. It is necessary to note that these studies are based solely on measuring the spatial distribution of innovation within urban areas. Furthermore, it should be pointed out that for the same city, the conclusions drawn by different studies may vary due to differences in the data and methods used or subjective differences in qualitative generalisation.

Our analysis of Guangzhou not only depicts the spatial distribution of innovation but also measures the spatial network of innovation. The results show that the innovation space within Guangzhou presents a core–periphery structure. Compared with other cities, it can be found that core–periphery, multi-centre/multi-group, and point–axis/corridor

are the basic forms of urban innovation spatial structures, which conform to the classical theoretical paradigms of geography and urban planning. About the core–periphery model, it is generally believed that Friedman comprehensively and systematically proposed this model in 1966 [82]. He argued that the core is the economic, political, and cultural centre, possessing highly concentrated resources and power; the periphery is in a subordinate position, relying on the core area. The core–periphery model is rooted in the classical location theory and the growth pole theory, providing a classic structure for regional/urban morphology [83]. Scholars such as Krugman further explained the mechanism of the core–periphery structure, including agglomeration effects, transportation costs, and cumulative causation [84]. Due to the spatial proximity effects, innovation has the attribute of spatial agglomeration, aligning with the basic principles of the core–periphery model.

Furthermore, comparisons with other cities have revealed that innovation agglomeration zones within urban areas can be categorized into similar items based on common characteristics. The first category is science and education-led areas, such as the Wushan–Shipai area in Guangzhou, the Zhongguancun area in Beijing, and the Jiangwan–Wujiaochang area in Shanghai. Their innovation development is attributed to natural spillover from university and research institutes, as well as the effect of government-initiated proximity planning of science/technology parks. The second category is new industrial spaces, such as development zones and science/technology parks formed after the reform and opening-up process, including Guangzhou Science Town in the Guangzhou Development Zone, the Zhangjiang High-Tech Industrial Development Zone in Shanghai, and the Binjiang High-Tech Industrial Development Zone in Hangzhou. The third category includes the CBD and urban central areas, such as Tianhe Centre–Yuexiu East area in Guangzhou, Wangjing area and Guomao area in Beijing, and Nanshan central area and Futian central area in Shenzhen.

5.3. Practical Application

Practical applications for measuring the spatial distribution and spatial networks of innovation within urban areas are also worth discussing. In the knowledge economy, innovation has become the global goal of urban development, and innovation space planning has emerged as a new component of urban planning and municipal experimentation [85]. The analytical framework and methods used in this study can be used to interpret the current situation of innovation spaces within urban areas, thereby providing support for urban innovation space planning. The results were applied to the Guangzhou Development Strategy Planning Research for 2049 (GDSPR2049). In July 2022, the Guangzhou 14th Five-Year Planning for Science and Technology Innovation proposed a vision for the innovation axis, which can be divided into three sections: a northern section centred around the Guangzhou Development Zone, a central section centred around eastern Panyu, and a southern section centred around Nansha. The GDSPR2049 is required to implement the innovation axis in depth. However, our results show that the current spatial pattern of innovation exhibits a core–periphery structure with three poles at the core of Guangzhou. The goal of an innovation axis from north to south remains to be achieved. Only the northern section, centred around the Guangzhou Science Town Innovation Zone, has achieved high-level innovation development. Therefore, in the GDSPR2049, the development strategy of “leveraging the advantages of the northern section and strengthening the weaknesses of the southern and middle sections” was proposed. Based on our results, we propose developmental ideas based on the qualitative characteristics of the three geographical zones. For the northern section, we suggest continuing along the existing path and focusing on cultivating and incubating entrepreneurial enterprises. In the southern section, there needs to be a focus on industrialisation of the existing Nansha Science Centre, which is essential for generating

widespread local innovation effects. The central section should be developed as a satellite platform and hub-and-spoke industrial district, attracting leading enterprises, institutions, and other enterprises along the industrial chain.

6. Conclusions

Based on a review of innovation literature, we identified three spatial turns in innovation research, from regional innovation research to urban innovation system research, and then to intra-urban innovation space research. Current research on intra-urban innovation spaces has effectively characterised the spatial distribution of innovation activities within urban areas and analysed the types and models of innovation spaces within urban areas. This study aimed to go beyond identifying the spatial distribution of innovation within urban areas and to measure the innovation network, including topological and spatial networks, within urban areas. Based on patent data, we constructed a unit-network analytical framework to achieve this goal. An empirical analysis was conducted using Guangzhou as a case study.

We identified 53 innovation space units in Guangzhou, covering 495 grids, an area of 123.75 km², and 1.67% of the total land area. The 53 innovation spatial units encompassed 231,698 patents, accounting for 72.28% of the total patents in Guangzhou. The 53 innovation space units can be categorised into three levels: IAZs, IASZs, and IANs, which can be further classified into nine types. Overall, the spatial distribution of innovation in Guangzhou exhibits a core–periphery structure, with most innovation agglomeration occurring in seven IAZs located in the urban centre or suburbs. The innovation networks also present a core–periphery structure, with the Wushan–Shipai Science and Education Innovation Zone, Tianhe Centre–Yuexiu East CBD Zone, and Guangzhou Science Town Innovation Zone forming three poles at the core. These three poles have the highest values of weighted degree centrality among the 53 innovation space units. The values of link frequency between the three poles also rank in the top 3 of the 143 pairs of connections among the 53 innovation spatial units. Finally, the mechanisms of the spatial agglomeration of innovation and the formation of innovation networks, as well as practical applications and limitations of this study, were discussed.

Finally, extensive discussions were conducted from three aspects: mechanism analysis, comparison analysis, and practical application. We discussed the mechanisms of innovation space agglomeration and innovation networks and analysed the core three poles in detail. A comparison analysis was performed with other cities, revealing that core–periphery, multi-centre/multi-group, and point–axis/corridor are the three basic forms of innovation spatial structures within urban areas, and finding that the innovation agglomeration zones similar to the core three poles also exist in other cities. Furthermore, practical applications were discussed. The analysis of Guangzhou in this study has been applied in GDSPR2049, revealing a notable discrepancy between the core–periphery reality and the planned innovation axis. The development strategy of “leveraging the advantages of the northern section and strengthening the weaknesses of the southern and middle sections” was proposed for the innovation axis. The methodology of this study can also be used in the innovation space planning of other cities, serving as a tool to deconstruct the reality of urban innovation spaces.

Of course, certain limitations are unavoidable. This study relied primarily on patent data, which may have some limitations as patents have several shortcomings as innovation indicators [86]. In particular, not all innovations are patentable, nor is every discovery patented out of fear of competition. Patents are sometimes used to deceive competition. The implementation value of some patents is negligible, and some do not express tacit knowledge, working hypotheses, or concrete ideas. Despite these limitations, patents

remain an essential indicator of innovation [87]. Joint patent applications are currently the most feasible data for measuring innovation networks in urban areas.

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

Appendix A

2thinknow is an innovation agency, established in 2006. 2thinknow began publishing Innovation Cities™ Index in 2007. Chinese cities (including Guangzhou) were included in 2010. Website: <https://www.innovation-cities.com/>, accessed on 30 October 2024.

Appendix B

Kernel density analysis of patent locations in Guangzhou was implemented using the Kernel Density Tool in the Spatial Analyst Tools of ArcGIS Pro, and the parameters were selected as default values. Since this analysis tool is commonly used and is not the primary method of this paper, the calculation formula is not described in detail.

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