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Exploring Employment Spatial Structure Based on Mobile Phone Signaling Data: The Case of Shenzhen, China

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Abstract: Debate on the shift from a monocentric to polycentric urban structure has been extensive. Polycentricity generally refers to the co-existence of several centers in a city. Existing studies regarding China have mainly focused on the morphological characteristics of urban centers, but few recent studies have focused on functional dimensions of urban centers. Emerging big data sources provide new opportunities to explore the morphological and functional perspectives of urban spatial structure. This study uses mobile phone signaling data and develops a new methodology to measure urban centers' functional centrality. The study area focuses on Shenzhen City, which has rapidly transformed from a village into a metropolitan city in the past few decades. As the first economic special zone in China, Shenzhen has adopted a polycentric urban plan since the beginning of the urbanization process. This study explores the spatial employment structure of the city from the morphological and function dimensions. Based on the findings, this study discusses the role of urban planning in forming an urban spatial structure and provides implications for future planning.

Keywords: urban spatial structure; morphological centrality; functional centrality; urban planning; mobile phone signaling data; Shenzhen; China

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1. Introduction

Rapid urbanization has led to the transformation of urban spatial structures. Many cities in the world have adopted polycentric urban planning as an important spatial strategy toward sustainable development [1], in order to solve urban problems, such as traffic congestion and excessive pressure on resources and the environment [2,3]. A polycentric urban structure is considered a more compact urban form that is conducive to more effective urban space organization [4]. Traditionally, urban spatial structure is measured on the basis of morphological indicators, such as population distribution and urban physical form attributes [5–7]. The theory of 'space of flows', proposed by Castell (1996), provides a new perspective for measurement and emphasizes the importance of urban networks and urban flows. Urban spatial units may be physically separated, but they can be linked by commuting and resource flows [8]. Based on this pool of theoretical literature, some empirical studies have been conducted to measure urban spatial structure from the perspective of functional connections [9,10].

However, related concepts and measurement methods of urban spatial structures are still vague [11,12]. Most of the existing studies on urban spatial structures have focused on western cities, and the research on Chinese urban polycentric spatial structures is still in the preliminary stage. Although many studies have measured the polycentric urban spatial structure from the perspective of morphology, studies on functional connection between centers in a city are limited [3,13]. Investigations on the relationship between morphological and functional centrality are also lacking [14]. This study investigates the urban spatial structure of Shenzhen, a large Chinese city, to fill these gaps. This study analyzes the morphological distribution and functional connections of the employment spatial structure. The relations between the morphological and functional centrality of employment centers are further analyzed. Since it became the first special economic zone in China in the 1980s, Shenzhen has implemented polycentric urban planning for its urbanization. Urban planning and public policies have played important roles in the rapid development of the city. However, the extent to which the polycentric spatial structure has developed is unclear. A better understanding of the urban spatial structure of Shenzhen provides a useful reference for the development of other Chinese cities and basis for the formulation of future urban planning.

The collection of data that represents functional linkages, such as population movements within cities, is a prerequisite for measuring spatial structure from functional perspective. The progress of information and communications technology and emergence of big spatial data, such as bus smart card data, taxi GPS trajectories, and mobile phone signaling data, have provided new possibilities for obtaining information about people's mobility activities [15–19]. Compared with traditional survey data, these new datasets have a much higher accuracy to provide a better tool for measuring urban spatial structure. Especially, mobile phone signaling data has wide coverage that can capture the travellers' travel track information during a whole day and has a unique advantage in the study of urban spatial structure [16,20].

The remainder of this paper is structured as follows. Section Two reviews the related concepts and theories on urban spatial structure and existing methods for identifying and analyzing urban centers. Section Three introduces the research methods and data sources. Section Four analyzes the research results. Section Five discusses the role of urban planning, based on a comparison analysis of the identified urban spatial structure and planned urban spatial structure in the master urban planning of Shenzhen. The last section draws the major conclusions of this paper.

2. Literature Review

2.1. Concept of the Spatial Structure

A considerable number of debates on urban spatial structure have been conducted. Foley (1964) indicated that the spatial attributes of urban spatial structure included cultural value, functional activities, and physical environment. Weber (1964) illustrated the form and process of the city and pointed out that urban space can be divided into adapted space (e.g., architecture) and channel space (e.g., traffic network). Bounre (1971) used system theory to understand the urban system, which includes three elements, namely urban form (the spatial layout mode of urban elements), urban internal interaction (the internal formation), and urban spatial structure (the organization mechanism). To sum up, the urban spatial structure can be summarized into two aspects: the various distributions of urban elements and functional connection amongst them. According to the literature review, the scale, influence, and spatial distribution of urban centers are the core contents for defining the characteristics of urban spatial structure [11,21,22].

The research on urban centers can be traced back to the central place theory presented by Christaller (1933), which lays the foundation for the definition of urban centers. According to central place theory, the central place refers to the location that provides goods and services for the surrounding residents. However, the definition and measurement of centrality are still vague. Some scholars argue that the essence of the center is a spatial unit with significantly higher attribute value than its surrounding units [23,24]. According to the method for measuring urban center, urban centers can be defined from morphological and functional perspectives [9,11,25]. The indicators for measuring the morphological centrality include regional area, population, density, and the construction of the centrality index. Grounded in the case study in Los Angeles, Giuliano and Small (1991) defined employment centers as having an employment density that is greater than 10 people/acre, as well as a total employment number greater than 10,000 people. Based on the land use map and urban construction data, Yue et al. (2019) identified the high-value areas of development intensity as morphological centers. According to the population and share of employment, Sun and Lv (2020) defined the employment centers as the central clusters, where the employment number met the minimum employment threshold and total amount of employment exceeds 20,000. Based on the literature review, this paper defines the morphological centers as spatial units that have a higher number of employees than the surrounding areas, as well as those that can have an impact on the surrounding areas.

On the one hand, the employment centers are identified to measure the morphological centrality based on the employed population. On the other hand, it measures the centrality of urban spatial units through the dynamic functional connections, such as the amount and density of commuting. The most important urban center is not necessarily the most populous place, but one that is located in the most critical position in the transportation network [10,25,26]. Burger and Meijers (2012) argued that the functional connectivity of urban spatial structure plays a key role in the urban system. They measured the intra-urban centrality based on the shopping and commuting flows. Based on flows, Sarkar et al. (2020) defined three indicators (e.g., trips, density, and accessibility) to measure functional centrality. The larger the index value is, the stronger the centrality is. Wei et al. (2020) measured the importance of each spatial unit by relative centrality, based on check-in and -out taxi GPS data. The functional centrality of the center is defined as the strong functional connections between the spatial unit and surrounding area, and it is in a key position in the urban network.

At the beginning of an urbanization process, the urban core area is the main space carrier that reflects a monocentric urban structure [27,28]. With the development of the city, the city expands outward because of land scarcity, traffic congestion, and pollution in the urban core area [29,30]. To adapt to the development of cities, western countries began to formulate policies of polycentric spatial structure. For instance, the urban structure of many western countries, such as Chicago [22], Finland [10], and England [2], have the characteristics of polycentric urban spatial structures. Previous studies on polycentric spatial structures focused on the geographical distribution characteristics of cities with different scales from a morphological perspective [5,28,31]. However, recent studies have emphasized that a better understanding of spatial structures would also include attention paid to the functional connections amongst different nodes in the urban system [2,32]. Research in this area usually includes the measurement of flows between the centers of a city. Each (sub) center is considered to be connected with other (sub) centers through multidirectional flows [10,25].

Drawing on the experience of western countries, China has introduced the polycentric development of urban planning [33] and issued different polycentric urban planning at various urban scales, such as the regional [34] and city scales [5]. Many foreign studies have measured centrality from the morphological and functional perspectives and explored the relationship between them. Most foreign cities tend to be more functionally polycentric than morphologically polycentric [10,25]. However, existing studies regarding China have mainly focused on the morphological. Studies on the measurement of functional centrality by functional connection within cities are few. Shenzhen, which is representative of Chinese cities, has implemented polycentric urban planning since its establishment. Therefore, we use the case study of Shenzhen to reflect on morphological and functional perspectives.

2.2. Network City Approach

Some scholars apply the theory of the 'space of flows' proposed by Castells (1996) to analyze the urban spatial structure from the perspective of the network city [35,36]. According to Castells (1996), the spatial units may be separated based on their physical forms, but they can be connected with each other through different kinds of flows. Based on the theory of the space of flows and the concept of the network city, social network analysis has been applied to measuring functional centrality [37]. Green (2007) proposed the principle of functional polycentricity and defined the ratio of the total number of actual connections and potential connections in the network as network density. Wang et al. (2020)

used GPS taxi trajectory data to construct a commuter network and applied social network analysis to measure the functional centrality with four indicators, namely, network density, intermediate centrality, point centrality potential and center periphery index. The higher these indexes are, the stronger their functional centrality will be. These studies reflect that network density and centrality are two important indicators for social network analysis.

Other methods can also be used to measure the polycentricity of the urban spatial structure. The evaluation of the relative balance between centers according to the 'importance' of centers are crucial by the number of centers, the ratio method and the rank-size method. The number of centers can reflect the distribution of centers and the development degree of polycentricity most intuitively through the number of centers. The more the number of centers is, the higher the development degree of polycentricity will be [5,38]. The ratio method directly reflects the relationship between main centers and subcenters by comparing their attribute values. The closer the ratio is to 1, the more balanced the size distribution between main centers and subcenters is, and the higher the degree of polycentricity will be [10]. In recent studies, the rank-size method is the most common method for measuring polycentricity. This method reflects the relative status of each center in the urban system. The flatter the slope of the fitting line is, the higher the degree of polycentricity is [25,39].

3. Research Data and Methods

3.1. Study Area and Data Sources

Shenzhen is one of the most prosperous cities in China, and it is located south of Guangdong Province. This research takes Shenzhen as the study area for the following reasons. First, Shenzhen provides a good example for studying urban development in China because it is the first special economic zone that has developed from a small fishing village into one of the most prosperous cities in the past few decades. Second, since the beginning of its urbanization process, Shenzhen has implemented polycentric urban planning as an important spatial development strategy. However, systematic studies on the spatial structure of the city are limited. Third, the Shenzhen government proposed a polycentric urban spatial structure with two main urban centers, five subcenters, and eight community-level centers in the 'master plan of Shenzhen City (2010–2020)' (hereinafter referred to as the '2010 master plan'). The examination of the effect of this planning guidance on the formation of urban spatial structures is helpful for formulating better strategies to improve urban planning in the future. As of October 2019, Shenzhen has 10 administrative districts, with a total area of 1997.47 square kilometers, as well as a built-up area of 927.96 square kilometers and population of 13.4388 million. The administrative region of Shenzhen, excluding all areas within the ecological control line, is defined as the study area.

This study collects the mobile phone signaling data (MPSD) of Shenzhen from China Unicom (the largest telecommunication company in China) from 1 June to 30 June 2019. We used the data of June 2019 in our study. June is a normal working month. No significant change was found in the mobility behavior or distribution characteristics of citizens in Shenzhen during this period. Thus, the data of June 2019 are appropriate to be used for the identification of urban spatial structure in 2019 [40]. The MPSD is generated when the mobile phone user is in the event of a call, SMS, or mobile location. The data include the time and location information of a person. This information can be used to deduce the travel path of users. As long as the user turns on the mobile phone, the travel information can be captured. Our actual sampling consisted of 4,467,500 people. Considering the market share of China Unicom, the age structure difference of mobile phone users, and other factors, this paper expands the sample and excludes the situation of non-human number cards, as well as one person with multiple cards, and obtains the expanded resident population. After sample enlargement, we obtained 19.825 million samples. The number of users in different districts in the MPSD has high similarity with that of the survey data in the Shenzhen statistical yearbook. This finding suggests that MPSD is appropriate for analysis.

The residence and employment locations are identified according to the time characteristics of employment and residence. The locations of residence correspond to places where mobile phone users stay in the same place for more than 4 h from 9:00 p.m. to 8:00 a.m. the next day and were observed for more than 15 days in a month. The employment locations correspond to places where mobile phone users stay in the same place for more than 4 h from 9:00 a.m. to 5:00 p.m. and were observed for more than 15 days in a month. Then, the population in employment and residence areas are defined as the employment and residential populations, respectively. To ensure a more accurate analysis, this paper allocates the mobile phone users into 250 m $\times$ 250 m grids.

The OD data are constructed by taking the place of residence as the original point and place of employment as the destination; thus, the residence–employment functional flows between spatial units are obtained. For example, mobile phone users live in place A and work in place B; when they go to work and go home, the functional connections between A and B are observed. After counting these functional connections, we can obtain the inflows and outflows of each spatial unit. Each spatial unit is used as a node, and flows are used as connections to build a direct urban network. The research area is divided into 18,226 grids, as research units with 2,313,529 flows. This study excludes the grids without connections with other grids and flows, whose starting and ending points are in the same grid. A total of 16,761 grids and 2,152,384 flows are, finally, identified for analysis.

3.2. Identification of Employment Centers

The spatial auto-correlation analysis method is used to identify the spatial clustering, which can reflect the spatial attributes of different areas [10,39]. This method divides spatial agglomeration into four categories, namely high-high, high-low, low-low, and low-high. The high-high agglomeration area is identified as a hot spot area, a high-value aggregation area surrounded by other high values areas. In this study, employment centers are identified on the basis of employed density. First, we use the ArcGIS 10.3 software to carry out local spatial auto-correlation analysis on the employment density of spatial units, select the significance of 0.01 for hot spot analysis, eliminate the insignificant areas, and choose the high-high gathering areas as candidate centers. Then, a cut-off value is applied to eliminate the small and practically insignificant spatial clusters. To make the cut-off value sensitive to local variation in each area, the cut-off value is defined in relative terms, where areas having an employment less than 0.5% of Shenzhen's total employment are excluded [1,5]. Considering that a center should have significant impact on the surrounding areas, identified areas with more than 10 grids [11,41] are regarded as the final employment centers. After that, according to the employment population of the identified centers, combined with the natural discontinuity method, we divided the centers into three levels.

3.3. Measuring Functional Centrality

Social network analysis has been recently adopted to measure functional centrality [26,37]. Most existing studies have only considered a single factor in shaping the centricity of key nodes, such as network density, the number of nodes, and commuter traffic. Few studies have paid attention to the directions of functional connections because of data limitations. To overcome these limitations, this study not only considers the commuting traffic of node connections but also uses the number of nodes connected and directions of commuting traffic to measure functional centrality. We combine network density [26] and degree centrality [41,42] as important measures to quantify the functional connections amongst nodes and measuring functional centrality.

Theoretically, the functional connections of a node in the urban network may occur in the following situations: (1) a node is connected with a plurality of nodes, but the connection is weak (Figure 1a); (2) the connection between nodes is very strong, but the number of connected nodes is few or the inflows and outflows are very different (Figure 1b); (3) nodes are not only connected with multiple nodes but also have strong connection strength (Figure 1c).

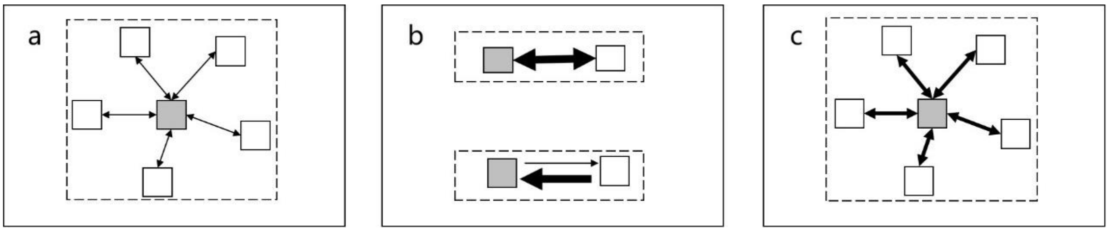

Figure 1. Different relations amongst nodes in an urban network. (**a**) A node is connected with a plurality of nodes, but the connection is not strong; (**b**) The connection between nodes is very strong, but there are few connected nodes or the inflows and outflows are very different; (**c**) Nodes are not only connected with multiple nodes, but also have strong connection strength.

This study uses the relative degree centrality of social network analysis to measure the frequency between nodes (Equation (1)), where N_i^{in} is the number of all nodes connected with node i as the ending point (indegree), and N_i^{out} is the number of all nodes connected with node i as the starting point (outdegree). Then, we divide the relative degree centrality of each node by the maximum value to normalize (Equation (2)).

$$\text{Relative Degree } (\mathrm{AD_i}) = \left(\mathrm{N_i^{in}} + \mathrm{N_i^{out}}\right)/(2n-2), \tag{1}$$

$$\mathrm{AD_i}' = \mathrm{AD_i}/\mathrm{AD_{imax}}. \tag{2}$$

We divide the inflow/outflow population of node i by the number of nodes that flows into/out of node i to indicate the connection strength between node i and other nodes; then, we take the mean value (Equation (3)). Then, we divide the commuting density of each node by the maximum value to normalize (Equation (4)).

$$\text{Commuting Density } (\mathrm{CDi}) = \left[\left(\mathrm{POP_i^{in}}/\mathrm{N_i^{in}}\right) + \left(\mathrm{POP_i^{out}}/\mathrm{N_i^{out}}\right)\right]/2 \tag{3}$$

$$\mathrm{CD_i}' = \mathrm{CD_i}/\mathrm{CD_{imax}}. \tag{4}$$

We assigned 50% weight to the relative degree centrality and commuting density of each node to construct the FCI to measuring functional centrality (Equation (5)). The larger the FCI value of the center is, the stronger the functional centrality is, which implies that the center is in an important position in the urban network. After that, according to the FCI value of the identified center, combined with the natural discontinuity method, we divided the center into three levels.

$$\mathrm{FCi} = \frac{1}{2}\mathrm{AD'_i} + \frac{1}{2}\mathrm{CD}_i' \tag{5}$$

4. Employment Spatial Structure of Shenzhen

4.1. Morphological Characteristics of Employment Centers

From a morphological perspective, we have identified eight employment centers (Figure 2). Based on the employment population, the centers are graded by a natural discontinuity method. Figure 2 shows the morphological levels of the identified centers, among which, 1–8 is the area order of centers: 1 is Futian–Luohu center, 2 is Kejiyuan center, 3 is Chegongmiao center, 4 is Songhe center, 5 is Fuhai center, 6 is Aviation City center, 7 is Longhua center, and 8 is Dengliang center. The results show that the eight employment centers include one first-level morphological center (with an employment population of 2,001,404), one second-level morphological center (with an employment population of 1,072,720), and six third-level morphological centers (with an employment population of less than 270,317). The employment centers are mainly distributed in the central and western parts of Shenzhen. No center has been identified in the east, indicating that the development of the employment centers in the east of Shenzhen are behind those of the central and western regions. Four centers, namely Futian–Luohu, Kejiyuan, Chegongmiao, and Dengliang, are distributed inside the special economic zone (SEZ); the four remaining centers (i.e., Songhe, Longhua, Fuhai, and Aviation City) are located outside SEZ. The first- and second-level morphological centers are distributed in Futian–Luohu and Nanshan within SEZ. The third-level center around the two centers suggests that the first- and second-level centers play a leading role in the development of the surrounding areas. The area of the employment centers outside the SEZ is smaller and more scattered than that inside the SEZ.

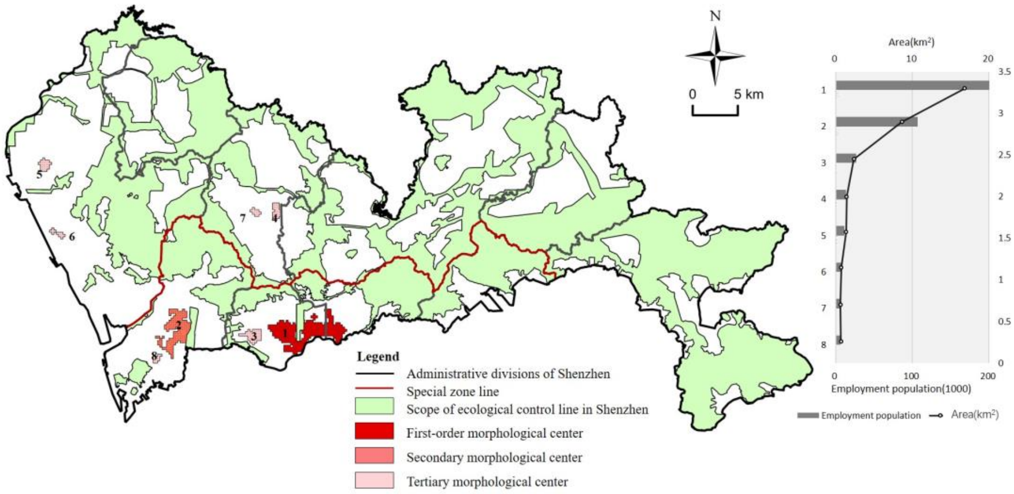

Figure 2. Identified employment centers.

Overall, in the SEZ centers, the total number of employment is 3,018,169, with an average employment density of 94,588 people/km^2 and total area of 28.648 square kilometers. In the non-SEZ centers, the total number of employees is 277,353, with an average employment density of 65,568 people/km^2 and total area of 4.251 square kilometers. The number of employees, average employment density, and centers' areas inside the SEZ are much larger than those outside the SEZ. The Futian–Luohu center has the largest area of 17.008 square kilometers, accounting for 51.70% of the total area of all the centers, as well as the largest number of employees, 1,820,679, accounting for 55.25% of the total employment of the centers. The Kejiyuan center takes the second place, with an area of 8.640 square kilometers, accounting for 26.26% of the total area of all the centers, with the number of employed people at 931,073, accounting for 28.25% of the total number of employed people of all the centers. Regarding the third-level centers, Chegongmiao has a higher number of employees (222,837) and a higher area (2.375 km^2) than other centers.

4.2. Functional Centrality of Employment Centers

Based on the FCI value, the identified employment centers are graded by the natural discontinuity method (summary statistics for the variables shown in Table 1). Figure 3 shows the functional centrality levels of the identified centers. The results show that the eight employment centers include two first-level functional centers (FCI values of 0.996 and 0.561), three second-level functional centers (FCI values of 0.177, 0.135, and 0.135), and three third-level functional centers (FCI values of 0.069, 0.066, and 0.077). From the perspective of spatial distribution, the first-level functional centers are distributed in Futian District and Nanshan District, whereas the second- and third-level functional centers are scattered, showing that, as they are affected by the location advantages of Nanshan District and Futian District, Futian–Luohu center, and Kejiyuan center, they have a strong functional connection within the whole region and the greatest influence on other areas. Furthermore, the functional centrality of the centers distributed inside and outside the special zone is quite different, which means that the functional connection of each employment center is unbalanced. In other words, the functional centrality in the special zone is stronger than outside the special zone, and the employment centers distributed inside the special zone have a stronger functional influence. From the level of each center, we can find differences in the morphological and functional levels of some centers, such as the Kejiyuan, Chegongmiao, Songhe, and Aviation City centers. Specifically, the morphological level of Kejiyuan center is the second, whereas the functional level is the first. The morphological level of the Chegongmiao, Songhe, and Aviation City centers are third, whereas the functional level is second, showing a mismatch between the employment population aggregation and functional connections of these centers. The distributed employment population can generate stronger commuter flows, which leads to the functional level of these centers, being one level higher than the morphological level.

Table 1. Summary statistics for the variables to construct FCI.

Centers	N_{in}	N_{out}	C_i	C_i'	POP_{in}	D_{in}	POP_{out}	D_{out}	D_i	D_i'	FCI
Futian–Luohu	1571	1462	0.090	0.994	2,001,404	1,274.0	1,287,879	881.1	644,380	0.999	0.996
Kejiyuan	1293	1114	0.072	0.789	1,072,720	830.0	430,239	386.2	215,313	0.334	0.561
Chegongmiao	387	384	0.023	0.252	270,317	699.3	130,086	339.1	65,213	0.101	0.177
Songhe	301	327	0.019	0.206	134,312	446.9	82,431	252.4	41,342	0.064	0.135
Fuhai	278	338	0.018	0.202	117,751	423.1	86,600	256.2	43,428	0.067	0.135
Aviation City	148	161	0.009	0.101	73,415	495.4	46,555	288.9	23,422	0.036	0.069
Dengliang	142	147	0.009	0.095	68,006	479.3	47,538	323.3	23,931	0.037	0.066
Longhua	143	154	0.009	0.097	66,189	462.1	71,756	465.1	36,111	0.056	0.077

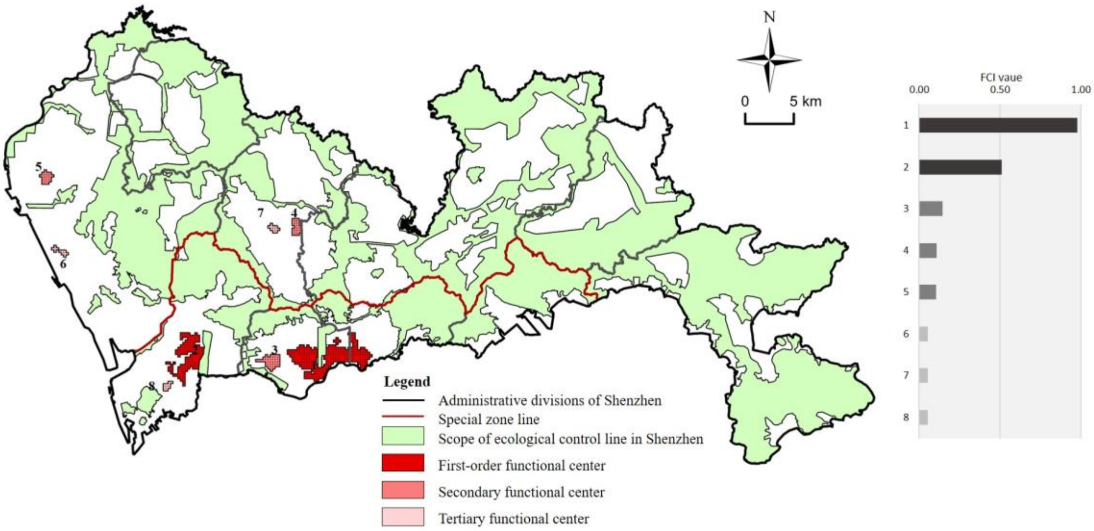

Figure 3. Functional centrality of the identified centers.

Based on the OD data, we further investigated the functional centrality of the first-level functional centers, including Futian–Luohu center and Kejiyuan center. Residence-employment connections whose starting and ending points are all distributed in Futian–Luohu center and Kejiyuan center are excluded. Figures 4 and 5 show the influence area of Futian–Luohu center and Kejiyuan center, respectively. According to the results, the Futian–Luohu employment center has many functional connections to the whole city. Many people lived in the midwest of Shenzhen and some people in the east worked in Futian–Luohu employment center. The affected area is mainly located in four districts: Nanshan District, Bao'an District, Longhua District and Longgang District. Nanshan District is the closest to Futian–Luohu center in space, and has the advantage of a short commuting distance. Many residential areas, such as urban villages, are found near the special zone line in Bao'an District and Longhua District, showing that Futian–Luohu center provides many jobs for the population lived in these areas. The influence area is mainly distributed along the metro line in the westernmost part of Bao'an District and Longgang District.

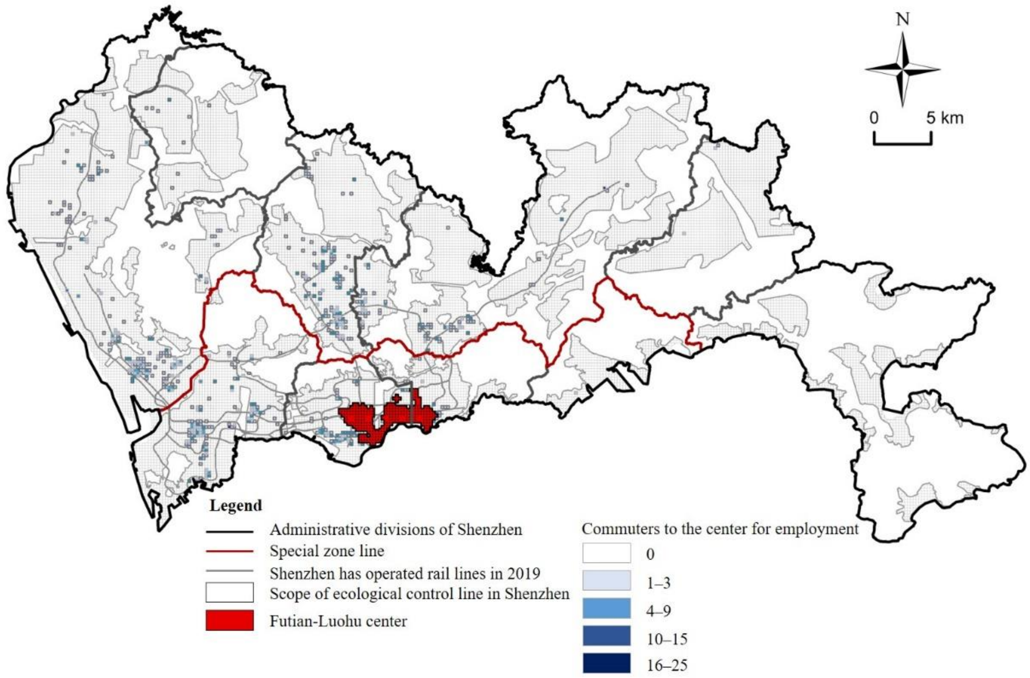

Figure 4. The influence area of Futian–Luohu center.

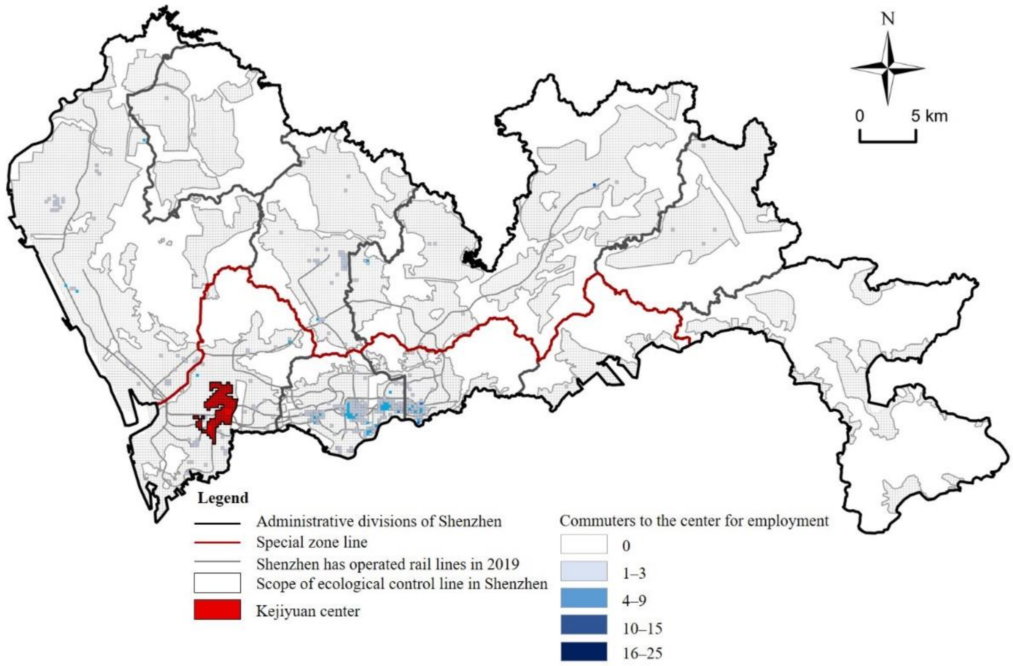

Figure 5. The influence area of Kejiyuan center.

According to Figure 5, although the functional centralities of the Kejiyuan and Futian–Luohu centers are at the first level, the influence area of Kejiyuan center is much smaller than that of Futian–Luohu center. The influence area of Kejiyuan center is mainly distributed at the south of Kejiyuan center, the boundary area of the Futian and Luohu Districts, as well as scattered in Longhua District and west of Bao'an District. According to the results, Kejiyuan center has a strong connection to Futian–Luohu area, indicating a spatial interaction between the Futian–Luohu and Kejiyuan centers. Many science parks and high-tech zones are located in Kejiyuan center and have attracted many people residing in Futian and Luohu to work in this employment center.

4.3. Comparison of Morphological Centrality and Functional Centrality

We use R1 to measure the morphological centrality of each employment center, which is the ratio of employment population of each center to the sum of the employment population of all employment centers. We use R2 to measure the functional centrality of each employment center, which is the ratio of the FCI value of each center to the sum of the FCI value of all employment centers. Then, by comparing the ratio of R1/R2 and 1, we can evaluate the strength of morphological and functional centrality of each employment center. R1/R2 > 1 means that the morphological centrality of the center is stronger than its functional centrality. R1/R2 < 1 means that the functional centrality of the center is stronger.

Figure 6 shows the results of comparing the morphological and functional centrality of each employment center. The result shows that the ratio of R1/R2 of the Futian–Luohu and Kejiyuan centers is greater than 1, meaning the morphological centrality is stronger than the functional centrality. The remaining centers are morphological tertiary employment centers, showing that the functional centrality is stronger than the morphological centrality. Furthermore, influenced by the employment population gathering, the larger the center is, the more employed people can be gathered, which leads to the morphology centrality being stronger than the functional centrality.

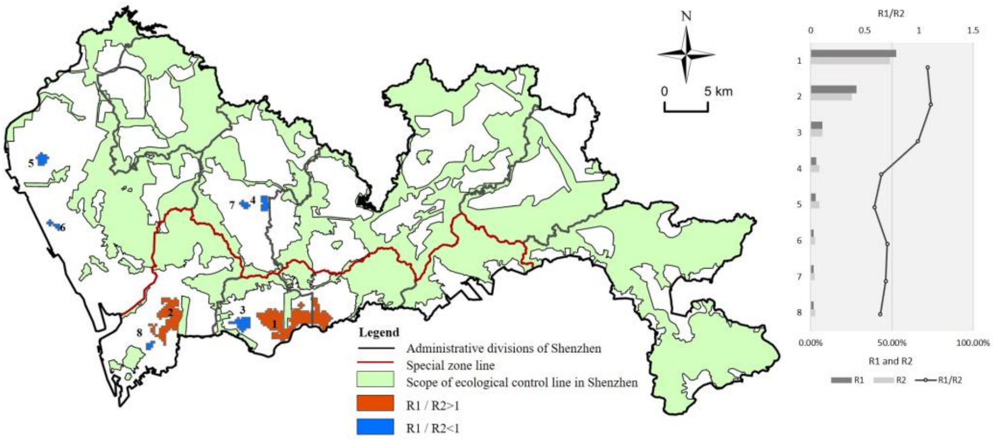

Figure 6. Comparison of morphological centrality and functional centrality.

This study curve fit the employment population and FCI value of different employment centers to measure the distribution equilibrium degree of each employment center's morphological and functional centrality. The method is applied as follows. The logarithm is taken as the horizontal axis for the ranking of each center. Then, the logarithm of the employment population and FCI values of each center are taken as the vertical axis for linear fitting. Next, the logarithm is taken. According to Figure 7, the fitted curve is shaped like an "L", and the absolute value of the slope is greater than 1, which shows the unbalanced morphological and functional centrality of the centers, as well as a monocentric employment spatial structure. In other words, Futian–Luohu center still concentrates most on the employment population and is in the dominant position of the employment–residence network in the city. We further compared the slope of the two fitting lines to understand the distribution of the morphological and functional centrality of the identified employment centers. The results show that the distribution of morphological centrality in employment centers is even more concentrated than that of functional centrality. According to the results, the employment spatial structure of Shenzhen is still monocentric in the morphological and functional perspectives.

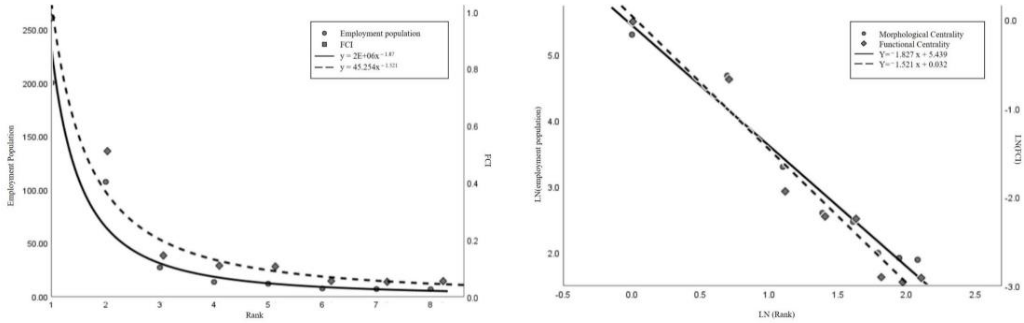

Figure 7. Relationship between functional and morphological centrality.

5. The Role of Urban Planning in the Formation of Spatial Structure

China's urban development is deeply affected by the intervention of urban planning and relevant policies [43]. Since its establishment of a special economic zone, the Shenzhen government has adopted polycentric development as an important spatial strategy. The Shenzhen 2010 master plan proposed building a '2 + 5 + 8' three-level polycentric urban spatial structure system that includes two main centers, five subcenters, and eight cluster centers (Figure 8). Our study shows that the master plan has played an important role in the formation of the spatial structures of Shenzhen. Figure 9 shows the center, subcenters, and cluster centers that were formed, or not formed, during the planning period. The urban development of Shenzhen is generally in line with the planning. The identified eight employment centers are all located within the planned urban centers. This finding reflects Sorensen's (2001) argument that the powerful structure plan contributed to the trend of urban spatial structure development. Strong government intervention measures and planning policies can promote the growth of employment centers in metropolitan areas, in order to cope with urban sprawl [44]. For example, Futian–Luohu and Kejiyuan were planned to become a R&D center that developed high-tech industries and became the hub of industrial clusters in Shenzhen. As a consequence, a large number of enterprises have been attracted to be located in Futian–Luohu and Kejiyuan, thereby promoting employment and local economic development.

Figure 8. The Shenzhen master plan (2010–2020).

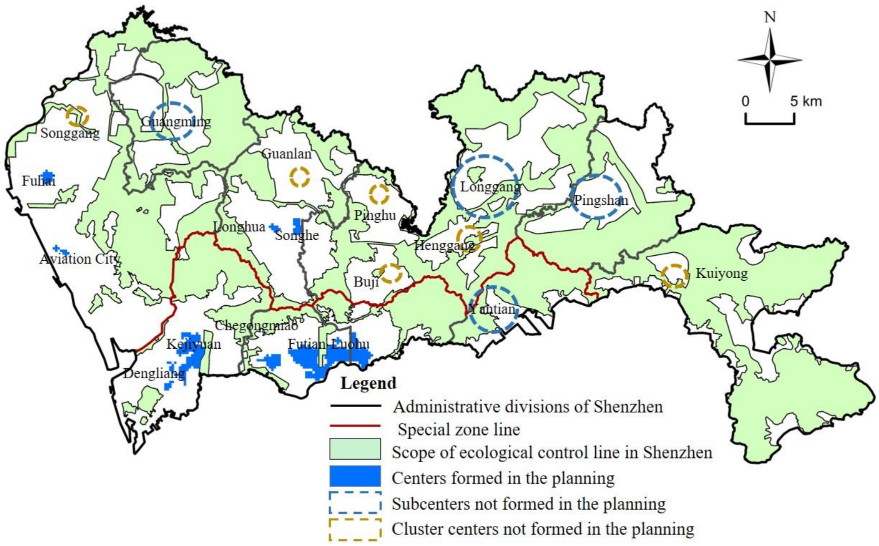

Figure 9. Classification of centers compared to the planning.

However, the planned polycentric spatial structure has not yet formed. The previous results have revealed that the spatial structure is still monocentric from the morphological and functional perspectives. The planned centers have not yet been formed in many areas, such as Yantian, Guangming, Pingshan, and Kuichong. These areas have a single industrial structure and relatively backward economic development. For example, Yantian's development is restricted by the functional orientation of the city. It is expected to develop a port logistics industry with few types of industries. In addition, a large part of these areas (e.g., Yantian and Kuichong) are located in the ecological control line, wherein development and construction are not allowed. As such, economic and spatial development are constrained, thereby hindering these areas from becoming centers. The public investment in service infrastructure and large-scale urban projects has a direct impact on the positioning of settlements and activities and is one of the driving factors for the formation and change in spatial structure [45]. Therefore, in order to improve the implementation performance of urban planning, strengthening infrastructure construction and land development in these areas in the future is necessary to help form the planned urban centers.

6. Conclusions

This study uses mobile phone signaling data to explore Shenzhen's employment spatial structure from the morphological and functional dimensions. Eight employment centers have been identified, all of which are located in the city's central and western parts. The analysis shows the differences between each center's morphological and functional centrality. It shows that the two biggest centers' morphological centrality(Futian–Luohu center and Kejiyuan center) are stronger than their functional centrality. Both of them are located in the SEZ area. On the contrary, the other centers' morphological centrality are weaker than their functional centrality. Most of these centers are located in the non-SEZ area. The findings suggest that, although Shenzhen has implemented polycentric urban planning since its foundation, its employment spatial structure is still monocentric in the morphological and functional terms. Further investigation shows that the distribution of morphological centrality in employment centers is even more concentrated than that of functional centrality.

Based on the results, this work discusses the role of urban planning in the forming of spatial structures in Shenzhen and provides implications for future urban planning. We find that the master plan has played an important role in the formation of the polycentric spatial structures of Shenzhen. Globally, the shift of the urban structure from monocentric to polycentric has been widely recognized in the literature. Several cities in Europe, America, and Japan have formed polycentric urban spatial structures [7,46,47]. Recently, studies on the relationships between morphological and functional urban spatial structures have been performed. These studies reflect that some western countries (e.g., Finland and Netherlands) are more polycentric, in terms of the functional perspective, compared to the morphological perspective [10,25].

Like western cities, many Chinese cities have adopted polycentric urban planning as an important spatial strategy for sustainable development. However, the extent to which these Chinese cities have been polycentric remains inadequately explored. This study explores the polycentricity of Shenzhen from the morphological and functional perspectives. The finding shows that, as influenced by the significant advantages of the Futian–Luohu center, most employment population and employment–residence connections are still concentrated in the Futian–Luohu center. Although eight employment centers have been identified, the employment spatial structure of Shenzhen remains monocentric, from the morphological and functional perspectives. Shenzhen's polycentric urban planning has not yet guided the city to form polycentric urban spatial structures.

Furthermore, this study contributes to the methodological approach. The method of measuring centrality has been improved. Previous studies often use a single factor, such as traffic density or the number of nodes, to measure functional centrality. Based on mobile phone signaling data, the present study combines social network analysis with GIS for analysis. The number of connected nodes, traffic density, and direction of population flow have been considered, in order to construct the FCI to measure functional centrality, thus providing a new perspective for analyzing the functional contact characteristics of the centers. Moreover, this study shows that the mobile phone signaling data, which can reflect the track of people in the city, is valuable for identifying the urban centers and reflecting on the spatial structure. These findings contribute to the recent studies using new and big datasets for urban analysis. Although the empirical analysis has focused on Shenzhen city, the proposed approach can be used to identify other cities, as long as the relevant data are available. The FCI index constructed in this study considers the number of connected nodes, traffic density, and direction of population flow to measure the functional centrality of the identified urban centers. Thus, the application of this research method requires datasets covering the information about the studied population and origin-destination of their commutes.

This study has some limitations that point to the directions for the future research. First, this study only explores the urban spatial structure of Shenzhen in 2019. However, investigating the evolution of the spatial structure during a certain period can help us understand how the city has been developed step-by-step. By examining the evolution of the spatial structure for many years, we can reveal whether the planning policy affects the overall trend of urban development and provide a policy-based explanation for the spatial evolution trajectory. Second, this research only explores the polycentric spatial structure of Shenzhen City, but the performance and efficiency of the formed spatial structure are still unknown. More research is required to understand the performance of polycentric spatial structures for Chinese cities and whether it is conducive to sustainable development.

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