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Characteristics of Coupling between Multi-scale Community Living Circles Public Service Facilities Supply and Spatial Centers

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Abstract. In response to changing demand structures due to slower population growth and economic shifts, this study examines the coordination between public service facilities and urban spatial centers, crucial for people-centered community development and spatial agglomeration laws. Utilizing crystal-growth algorithms and spatial autocorrelation, the research algorithmically interprets spatial centers, and conducts kernel density and natural break classification analyses on public service facilities. The case of Guangzhou's central urban area reveals: 1) The spatial centers are in Liwan, Yuexiu, and Haizhu districts; 2) Centers are dispersed within a five-minute range but cluster over thirty minutes; 3) Analysis of coupling at different scales highlights areas needing more public service facilities. This methodology elucidates the relationship between spatial elements and structure, enriching community living circle theory and contributing to urban high-quality development.

Keywords: Community Living Circles; Spatial Center; Crystal Growth Algorithm; Coupling Analysis.

1. Introduction

Data, as a new factor of production, has become inseparable from people's lives. In 2022, China's digital economy reached 50.2 trillion-yuan, accounting for 41.5% of the total GDP, roughly equivalent to the scale of the secondary industry (Research Report on the Development of China's Digital Economy (2023), China Academy of Information and Communications Technology (CAICT)). Against the backdrop of rapid digital transformation in urban planning, China has introduced multiple policies, clearly defining the direction and content of urban digital construction. The 2023 "Digital China Construction Overall Layout Plan" proposes to promote the inclusiveness of digital public services, popularize intelligent digital life, and create smart, convenient living circles, new digital consumption patterns, and future-oriented intelligent immersive service experiences. Urban space will be digitized as elements, forming a "base map" database, and elements need to be organized through algorithms to achieve digital transformation in urban construction. However, current information practices have not yet formed a clear and widely applied path. The sharing of data resources and the capacity for socialized services still fall short of expectations, and much work remains to be explored in guiding urban construction through data and algorithms.

Traditional public service facility supply is arranged through control-detailed planning units from a larger spatial region [1]. In 2018, the Ministry of Housing and Urban-Rural Development approved the "Urban Residential Area Planning and Design Standards" (GB50180-2018), introducing living circle theory into residential community planning, specifying facilities configuration content and requirements for different scales of living circles [2]. In July 2023, the Ministry of Housing and Urban-Rural Development and other departments released a notice on the pilot construction of complete communities in several cities, exploring paths to improve community service functions and fill gaps in service facilities. Simultaneously, the Ministry of Commerce and other departments formulated the "Three-Year Action Plan for Fully Promoting the Construction of Urban 15-Minute Convenience Living Circles," aiming to enhance the convenience and quality of living circle services, planning to create community business districts where multiple business formats gather within a 15-minute living circle. These plans and notices indicate that residents' needs for public service facilities have shifted from basic support to the pursuit of service quality improvement. Therefore, in the context of an aging society and the new normal of economic development, the homogeneous spatial layout of public service facilities can no longer meet these requirements. Based on spatial economic laws, it is essential to explore how to allocate services around spatial centers, thereby enhancing spatial use efficiency and fostering product innovation and upgrades.

In this context, how to use new digital technologies to integrate the top-down spatial pattern of cities and the bottom-up governance model of communities, and coordinate public service facilities with spatial structure, is an urgent problem to be solved. Therefore, this study uses crystal-growth algorithms to simulate the internal structure of community living circles in multi-scale travel scenarios and spatial autocorrelation methods to identify spatial centers. It focuses on the coupling of public service facilities and spatial centers, exploring planning strategies for building "cores" in community living circles, which is of great significance for constructing people-centered and efficient urban systems.

1.1. Guiding Public Service Facility Construction with Living Circle Theory

Living circle theory, tracing its roots to the concepts of "wide-area living circles" and "settlement circles" [3], essentially aims to achieve "regional coordinated development" on a macro level and "people-centered space" on a micro level. The extensions of this theory, such as the "fifteen-minute living circle" and "community living circle", have been hot topics in planning research over the past decade. Through the development of time geography, this theory has gradually formed a research paradigm for guiding human settlement environment construction, "boundary delineation of living circle units" and "index evaluation for issues within the circle" [4]. Beyond the "Urban Residential Area Planning and Design Standards," extensive research has explored this field. Zhao [5] used POI data to calculate the accessibility levels of the elderly to different facilities within living circles at various levels. By combining multiple linear regression and geographically weighted regression, they summarized the characteristics of elderly living circles and facility configurations. Xia [6] used kernel density analysis and network analysis methods, focusing on the coverage rate of elderly population by elderly care service facilities as a core indicator to build a rationality evaluation standard for facility spatial configuration, revealing the spatial distribution characteristics of urban elderly care service facilities in Hefei.

However, public service facilities have always adopted an equalized layout approach, evident in boundary delineation methods and quantitative evaluation techniques [7]. For example, Wu [8] delineated 400 fifteen-minute living circles based on street boundaries, assessing the coverage of public service facilities in each circle from eight dimensions, thus identifying spatial units with facility configuration deficiencies. Zhang [9], based on a fifteen-minute walking isochrone from residential areas, delineated community living circles and constructed park green space exposure indices from four dimensions – quantity, area, distance, and quality – accurately depicting the interaction between living circle residents and green space resources. The boundary division across the entire study area treats residents in the center and the periphery of each unit differently. Since living circles center around the individual, boundaries based solely on a specific area's population are neither fair nor shared. In terms of evaluation systems, related studies use quantitative evaluation methods like equity performance [10] to identify shortcomings in facility provision in residential areas.

With societal development, the agglomeration effect of public service facilities and construction around the core of living circles should be a focus. Zhan [11] used contour line analysis methods to identify and analyze the agglomeration centers of public service facilities in Beijing, finding these centers have a significant negative impact on residents' satisfaction with public services. Liu [12], based on POI data, analyzed the agglomeration characteristics of public service facilities in Zhuhai. However, existing research lacks an analysis of agglomeration characteristics of public service facilities from different spatial scales and an exploration of the coupling between residential community spaces, which is a worthwhile issue to explore.

1.2. The Significance of Spatial Centers in Urban Construction

Spatial centers, as key elements of spatial structure, are continuous areas of high concentration of human activities [13]. In China, these centers are referred to as "Tianxin" or "Dixue," while in the West, they are described as "geometric centers" or "coordinate origins" [14]. Both Eastern and Western approaches to spatial studies and practices have consistently revolved around the concept of "center," as seen in theories like Thunnen's agricultural rings, Weber's industrial location theory, W. Christaller's central place theory, Bill Hillier's space syntax, and Saskia Sassen's global city. Depending on the factor, urban spatial centers can be categorized as commercial, cultural, landscape centers, etc., but most studies mainly focus on commercial centers [15], lacking in micro-perspective research and practice on residential community spatial centers.

Recognizing centers and establishing cores is a primary awareness in spatial planning and an effective method following the "core-periphery" law. From the perspective of spatial economics, spatial centers, compared to other areas, offer convenient accessibility. The "endogenous city theory" posits that the location and size of a city, enterprise spatial distribution, and infrastructure support significantly impact urban development. Emerging classical urbanization theories incorporate the efficiency gains brought about by social division of labor and spatial proximity into the explanation of urban formation [16]. As stated, as long as there are costs related to spatial distance, such as freight, time, convenience of communication, etc., there will exist spaces with central positions. However, once a center exists, the burden formed by a large volume of material and information flows needs to be supported by good form and structure. Therefore, the organization of spatial relationships cannot be separated from the interpretation of spatial centers, and establishing cores in space is also a thought process that should be adhered to when addressing public service facilities.

Table 1. Layered Characteristics of Living Circles

Authors	Year	Walkable Radius	Tool Commuting Radius	Random Travel Radius	Cross-City Radius
CHAI Yanwei	1996	Essential Living Circle	Low-Level Living Circle	High-Level Living Circle	—
YUAN Jiadong	2005	Essential Living Circle	Basic Living Circle	Opportunity Living Circle	—
ZHU Chasong	2010	Essential Living Circle	Primary Living Circle & Secondary Living Circle	Tertiary Living Circle	—
SUN Defang	2012	Primary Living Circle	Essential Living Circle & Daily Living Circle	—	—
CHAI Yanwei	2015	Community Living Circle	Basic Living Circle & Commuting Living Circle	Expanded Living Circle	Collaborative Living Circle
HUANG Jianzhong	2019	Community Living Circle	Expanded Living Circle	Opportunity Living Circle	—

Living circle theory focuses on the central spaces of human activities. However, unlike individual living circles centered around a person's fixed residence, the spatial center of a living circle is the main travel area for all residents, representing the greatest common denominator found in the same space. It exhibits tiered characteristics, divided into four types based on travel scale: walkable layers, tool-commuting layers, random travel layers, and cross-city layers (Table 1). These layers each have unique characteristics due to different transportation modes and travel frequencies, but the walkable layer at the center is more important, stable, and worthy of exploration. This is because it is the layer most closely related to residents, where factors like the accessibility of facilities and services, comfort of street space, and shareability of leisure space all impact residents' well-being. With further research, this layer has been studied in more detail, for instance, Lin [17] categorized the elderly's slow walking circle into core, basic, expanded, and opportunity layers based on walking duration.

2. Methods

We simulate the internal structure of community living circles using the crystal-growth algorithm, followed by spatial autocorrelation analysis to precisely define the boundaries of these centers. The final step involves a regression analysis, examining the relationship between the quantity of public service facilities in community grids and their centrality, to better understand the interplay between facility distribution and spatial center structures.

2.1. Study Area

Our study focuses on the central urban area of Guangzhou City (**Fig 1**). Located in the subtropical monsoon region, Guangzhou boasts an annual average temperature above 20°C and stands as a comprehensive gateway city with advanced economic development in China. Ranking third in the country in terms of the number of top-tier hospitals, just after Beijing and Shanghai, Guangzhou offers superior medical facilities, making it one of the most suitable mega cities for the elderly to live in. Considering the distribution and spatial accessibility of the elderly population in Guangzhou, we selected Liwan, Yuexiu, Tianhe, and Haizhu districts as our study areas. These areas encompass a total of 79 streets, covering an area of 323.3 square kilometers. According to the Seventh Population Census data, the permanent population in this area is 6.3379 million, accounting for 33.93% of the city's total population. Of this, the elderly population aged 60 and above totals 929,300, representing 15.45% of the permanent residents.

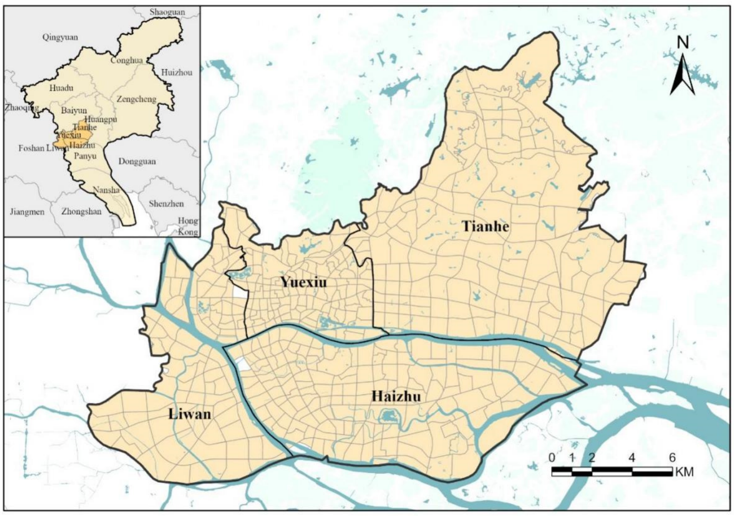

Fig 1. Research Scope of Guangzhou City Center

2.2. Crystal-growth Algorithm for Simulating the Structure of Living Circles

In this study, we generated a hexagonal grid system to construct Context-Based Hexagonal Accessibility-Weighted Planes, referencing the creation of hexagonal codes. Compared to square grids, hexagonal grids offer uniform centroid distances between adjacent units, providing superior performance in path analysis problems. Drawing on the modeling classification method for spatially weighted planes [18] and the walking speed of healthy elderly people, approximately 50m/min, as mentioned in "Research and Practice of Shanghai's 15-Minute Community Living Circle," our study categorized grid units into three types and assigned corresponding walking speed attributes to the spatial grid: obstacle, impedance, and accessible classes (Table 2)

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Table 2. Cost Grid Weighted Classification of Different Spatial Elements

Categories	Spatial Elements	Walking Speed	Datas
Barrier Category	Buildings	—	Baidu Building Data
	Highways	—	OSM Road Data
	Expressways & Arterial Roads	—	OSM Road Data
	Railway Land	—	Planning Control Vector Data
	Industrial Land	—	Planning Control Vector Data
	Warehouse Land	—	Planning Control Vector Data
	Municipal Utility Land	—	Planning Control Vector Data
	Water Areas	—	Planning Control Vector Data
Impedance Category	Collector Roads	30m/min	OSM Road Data
	Local Roads	40m/min	OSM Road Data
	Intersections	25m/min	OSM Road Data
	Green Spaces	30m/min	Planning Control Vector Data
Accessibility Category	Pedestrian Zones	50m/min	—

The simulation process of the living circle's scope necessitates determining the starting points for growth, growth resources, and an algorithm for the consumption of growth costs. Since living circles are activity ranges formed around residences, the nearest walkable grid to the centroid of residential buildings is selected as the growth seed. Common growth resources are set at 5, 10, 15, and 30 minutes. Based on the speed differences in the impedance and accessible grids in spatial grid modeling, the process involves continuously searching adjacent grids and deducting corresponding time costs, ceasing growth only when the resources are exhausted.

The spatial distribution structure of people's travel activities requires weighting and overlaying the living circle ranges generated based on the residential population attributes of the growth starting points. Due to the high cost of GPS surveys [19], this study utilizes public data from the Seventh Population Census of streets. By spatially processing the elderly permanent population based on the proportion of residential building area to street building area, this information is used as the population attribute of the building vector [20].

2.3. Identification of Spatial Centers and Calculation of Centrality Attributes

Methods for identifying spatial centers include spatial autocorrelation [21], standard deviation threshold [22], contour tree [23], and breakpoint method [24]. Spatial autocorrelation is used to measure the degree of aggregation of spatial objects and their attributes in space. Commonly used indices include Moran's I and Getis Gi*, which provide a statistical interpretation of the First Law of Geography and are widely used in studies identifying urban centers.

In this study, the identification and calculation of spatial centers are divided into four steps: (1) Using the global Moran's Index to determine the distribution pattern (clustered, evenly distributed, or dispersed) of the internal structure of community living circles; (2) If the distribution is non-random, further calculation of the z-values of each grid can be conducted using local Moran's Index; (3) Average z-values are then spatially connected to community grid data as centrality attributes, and the natural break method [21] is used to categorize the community grid data into four levels, with the top two levels identified as communities with spatial center characteristics.

The formula for calculating the local Moran's Index is:

$$I_i = \frac{(n-1) \times z_i \sum_{j=1,j\neq i}^{n} w_{i,j} z_j}{\sum_{j=1,j\neq i}^{n} z_i^2} \tag{1}$$

where z_i is the deviation of the attribute x_i of grid i from its mean value $\bar{X}$, expressed as $x_i - \bar{X}$; $w_{i,j}$ is the spatial weight between elements i and j; and n is the total number of elements.

The formula for calculating the statistical significance z_i score is:

$$z_i = \frac{I_i - E[I_i]}{\sqrt{V[I_i]}} \tag{2}$$

where I_i is the local Moran's Index for grid i; $E[I_i]$ and $V[I_i]$ are the mathematical expectation and variance of the local Moran's Index for grid i.

2.4. Coupling Analysis of Multi-scale Living Circles and Facilities

In the classification of community grids, the top two categories are defined as "high" values, and the latter two as "low" values. Referring to the "Community Living Circle Planning Technical Guide" compiled by the Ministry of Natural Resources and the "14th Five-Year Public Service Planning" approved by the State Council, this study conducts a kernel density analysis of 9 types of facilities closely related to residents' quality of life, including education, medical, cultural, and sports facilities (**Table 3**). The Delphi method and the Analytic Hierarchy Process (AHP) are used to determine the weights of each type of facility. The aggregate kernel density values, weighted by facility importance, represent the concentration of public service facilities. This result is also divided into "high" and "low" categories using the natural break method. A bi-factor combination mapping method is employed to illustrate and observe the coupling results between public service facilities and spatial centers.

Table 3. Categorization of Public Service Facilities in Community Living Circles

Facility Types	Facility Content	Weights
Education Services	Schools, Training Institutions, Driving Schools	0.2
Cultural Services	Museums, Media Institutions, Archives, Exhibition Centers, Science and Technology Museums, Science and Education Cultural Sites, etc.	0.05
Sports Services	Sports Venues, etc.	0.05
Medical Services	Disease Prevention Agencies, Specialized Hospitals, General Hospitals, Animal Medical Facilities, Emergency Centers, etc.	0.2
Elderly Care Services	Wellness Centers, Wellness Service Stations	0.15
Recreational Services	Parks and Plazas	0.05
Shopping Services	Supermarkets, Clothing and Accessories Stores, Personal Care/Cosmetics Stores, Flower and Pet Markets, etc.	0.1
Food and Beverage Services	Tea Houses, Pastry Shops, Cafés, Fast Food Restaurants, Ice Cream Parlors, Dessert Shops, Foreign Restaurants, etc.	0.1
Lifestyle Services	Travel Agencies, Information Consultation Centers, Ticket Offices, Telecommunication Service Centers, Service Agencies, Talent Markets, etc.	0.1

3. Results and Discussion

In this research, we utilized a fine resolution of 5 meters, deploying approximately 14.95 million hexagonal grids to cover the central urban area of Guangzhou City. Among these grids, obstacle types account for 41.6%, impedance types for 16.6%, and accessible types for 41.8%. This cost grid approach establishes a robust foundation for the subsequent simulation of the internal structure of community living circles, identification of spatial centers, and classification of community grids.

3.1. Distribution of Community Living Circle's Internal Structure

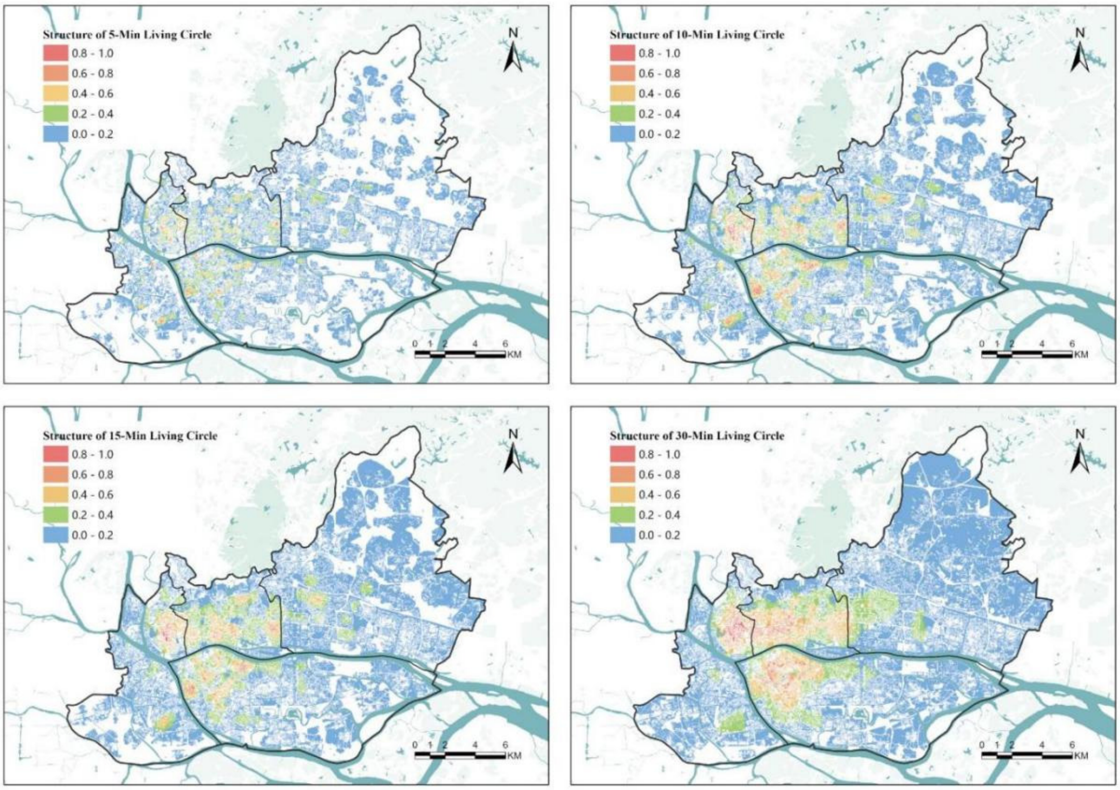


Fig 2. Multiscale Distribution of Internal Structure in Community Living Circles

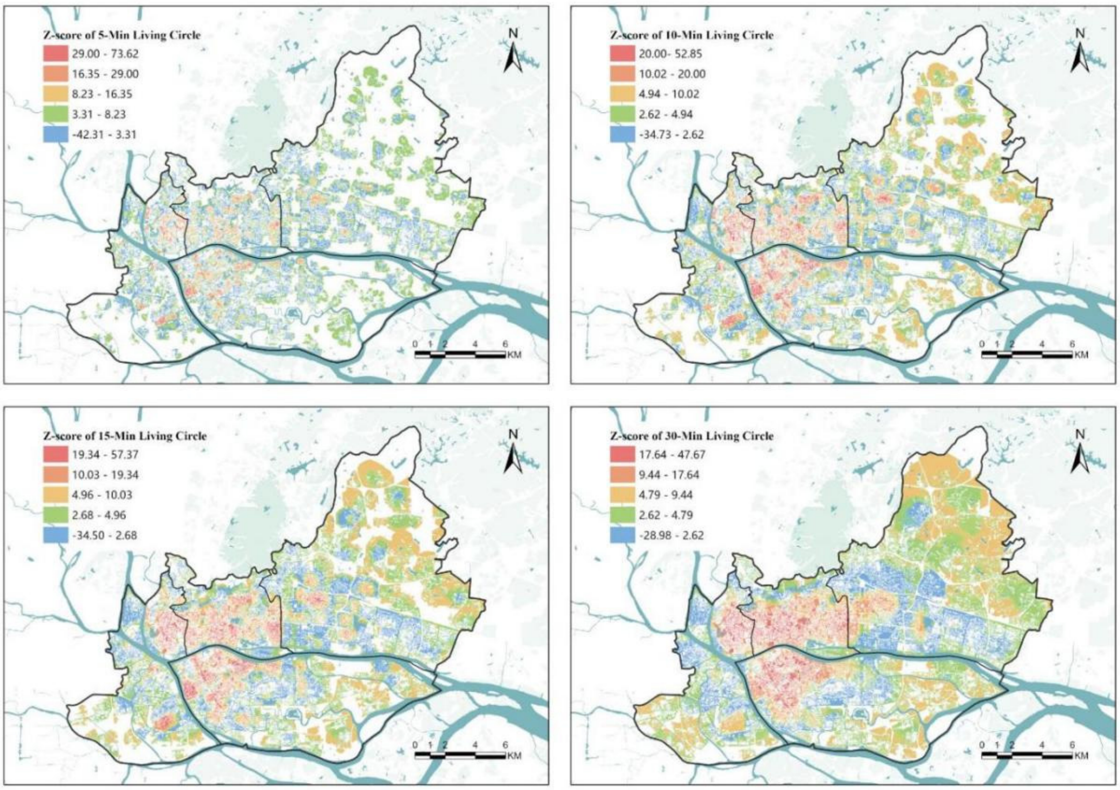


Fig 3. Z-score for Multiscale Spatial Center Identification

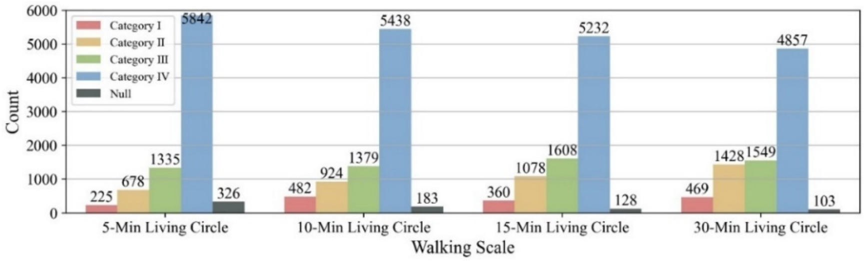
Our study obtained a distribution map of the internal structure of community living circles through simulation methods. This outcome reflects both the distribution of the resident population and the constraints imposed by spatial elements on residents' travel activities (**Fig 2**). At a five-minute walking scale, hotspot areas are scattered, located in communities like Beijing Road in Yuexiu District, Changshou Road and Baihedong in Liwan District, Shayuan and Haiyin in Haizhu District, and Huabiao in Tianhe District. At a ten-minute walking scale, hotspot areas are block-like, mainly found around Beijing Road in Yuexiu District, Changshou Road in Liwan District, and Jiangnan Avenue Middle in Haizhu District. Fifteen-minute walk scale hotspots are mostly connected, primarily in central and southern Yuexiu District, northern Liwan and Baihedong areas, northwestern Haizhu District, and southwestern Tianhe. At a thirty-minute walking scale, three main hotspot areas emerge: "Changshou Road-Beijing Road" hotspot, "Yangjichong" hotspot, and "Jiangnan Avenue Middle" hotspot.

3.2. Analysis of Local Spatial Autocorrelation

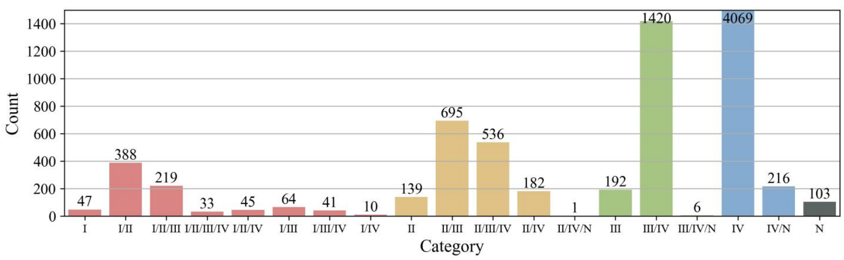
Our study initially conducted a global autocorrelation analysis of the internal structure of community living circles. The results show that at all scales, the z-scores are greater than 2.58 and the p-values approach zero, indicating a non-random clustering pattern. Further analysis using local autocorrelation categorized the z-score results into five classes based on natural breaks. It was observed that with changing scales, grids in the top two statistically significant levels formed a structural evolution from "point-block-sheet-area" (**Fig 3**). At a thirty-minute scale, hotspot areas developed around the old town area of Guangzhou City.

3.3. Classification of Community Grids

In the central urban area of Guangzhou City, there are a total of 8,406 community grids. Based on the natural break method applied to Moran's Index results, these grids are divided into four categories. The quantity of grids at each scale shows a stair-step pattern, with Category IV having the most grids (Fig 4 a). Notably, 47 community grids consistently fall under Category I across all scales, representing critical spatial areas with centrality at multiple walking scales. Meanwhile, 4,285 grids are consistently in Category IV across scales, indicating peripheral regions that require attention for the construction of essential service facilities. These grids cover all types at multiple scales, necessitating focus on grids containing only one category as well as those with three or four categories, as the latter represent more dynamic spaces (Fig 4 b).



(a) Bar Chart of Different Scale Community Types



(b) Bar Chart of Grid Types within the Same Community

Fig 4. Multiscale Classification Statistics of Community Grids

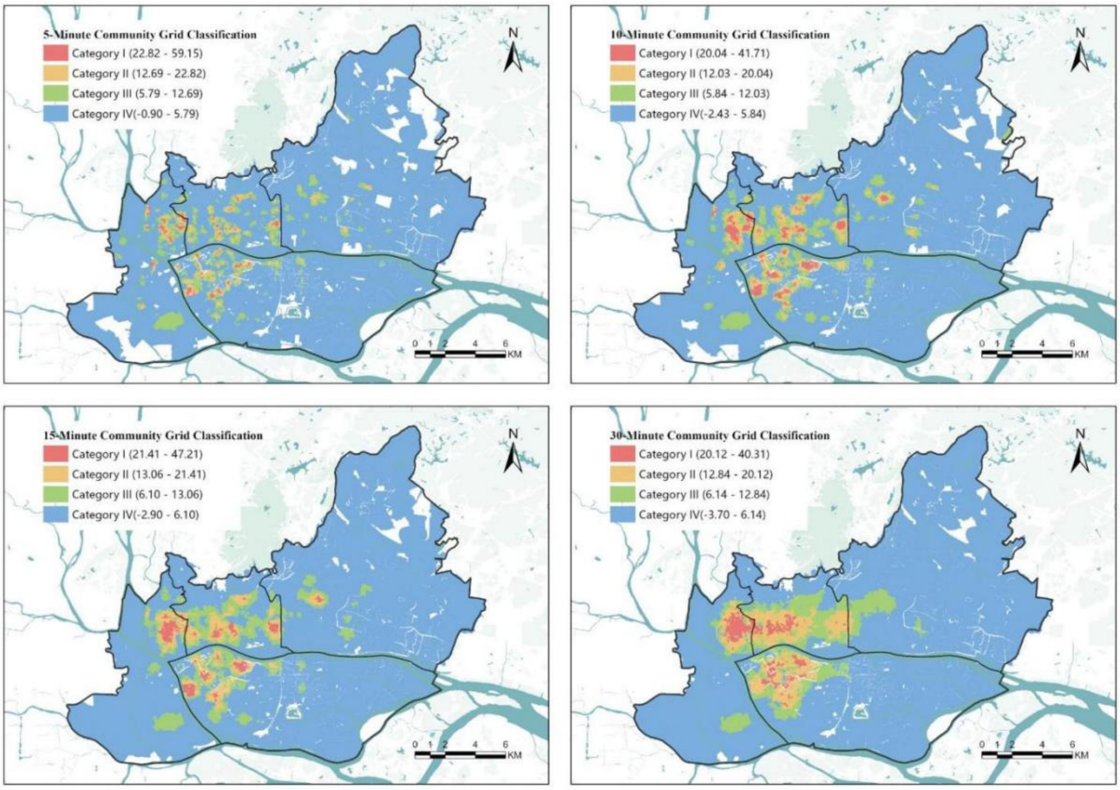


Fig 5. Multiscale Distribution of Community Grid Types

Linking Moran's Index results to Guangzhou's community grids (**Fig 5**), we observe four categories based on the natural break method. As the scale increases, the distribution of grids transitions from scattered small points to larger clustered areas. At the five-minute walking scale, Category I communities are represented as small dots, with minor hotspots like "Huijing" and "Lizhi Nanwan". Moving to the ten-minute scale, hotspots such as "Fangcaoyuan-Jindi" and "Taojin" communities rapidly expand. Moreover, hotspots in Yuexiu, Liwan, and Haizhu districts start to connect, seen in areas like "Fulixi-Houfu-Maji Yong" and "Xingxian-Zengxiang" in Liwan, "Haiyin Nan-Hailian Bei" and "Jinya-Jishi" in Haizhu, and "Dadongjie Dongli" and "Dadongjie Qinglongli-Dadongjie Qizheng" in Liwan. At the fifteen-minute scale, the primary hotspots from the ten-minute scale continue to expand, while smaller peripheral hotspots begin to fade, such as "Yuancun Jie Shanding" and "Heng Liwan Pan" communities. Finally, at the thirty-minute scale, large hotspots emerge in northern Liwan, western Yuexiu, and scattered areas in Haizhu.

3.4. Coupling Analysis of Public Service Facilities

The coupling analysis reveals (**Fig 6**) that the central areas of public service facility aggregation are primarily located in Guangzhou's old city area, Guangzhou Yuehui City, along Jiangnan Avenue Middle, Baogang Avenue, Xingang Subdistrict, along Guangzhou's new central axis, and Junjing Garden, among others. Four types of coupling relationships between spatial centers and public service facilities emerge at different scales. At a five-minute walking scale, due to the point-like distribution of spatial centers, several centers show dissimilar coupling with public service facilities, while most grids with similar coupling are in Liwan, Yuexiu, and Haizhu. As the scale increases, grids with spatial centers spread in public service facility aggregation areas, resulting in an increase in red areas (high concentration) and a decrease in green areas (low concentration). Of particular interest are the orange areas, which have spatial centers but lack sufficient public service facilities. These areas represent varying proportions across different scales: 4.9%, 6.8%, 6.0%, and 9.2%, respectively.

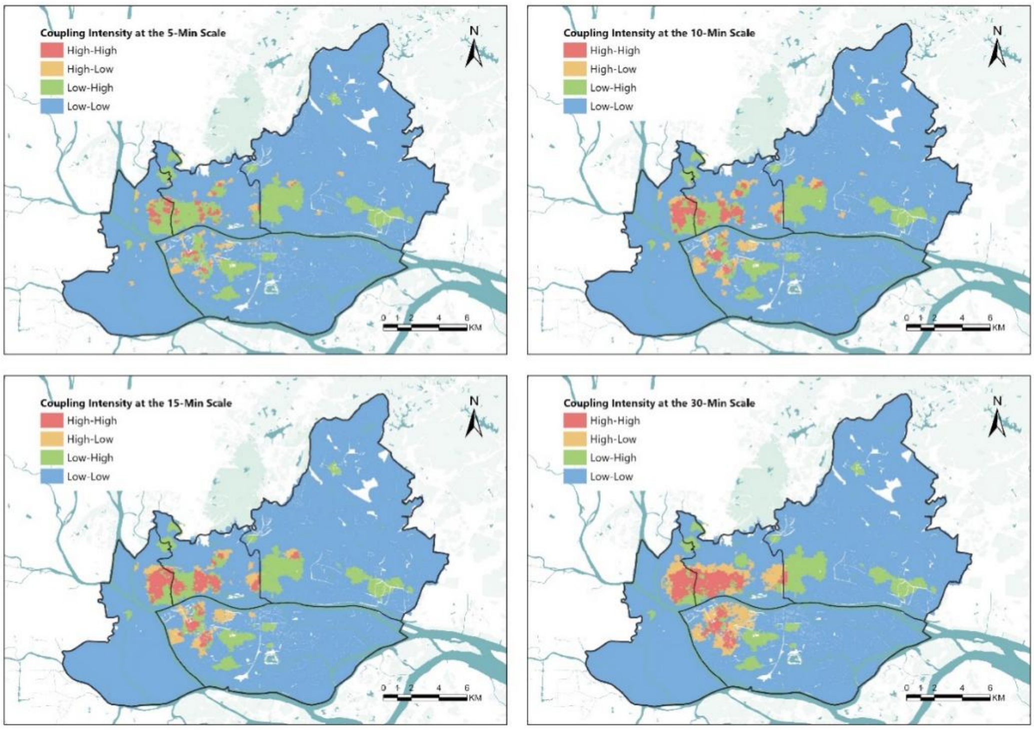


Fig 6. Multiscale Community Grid Type Distribution

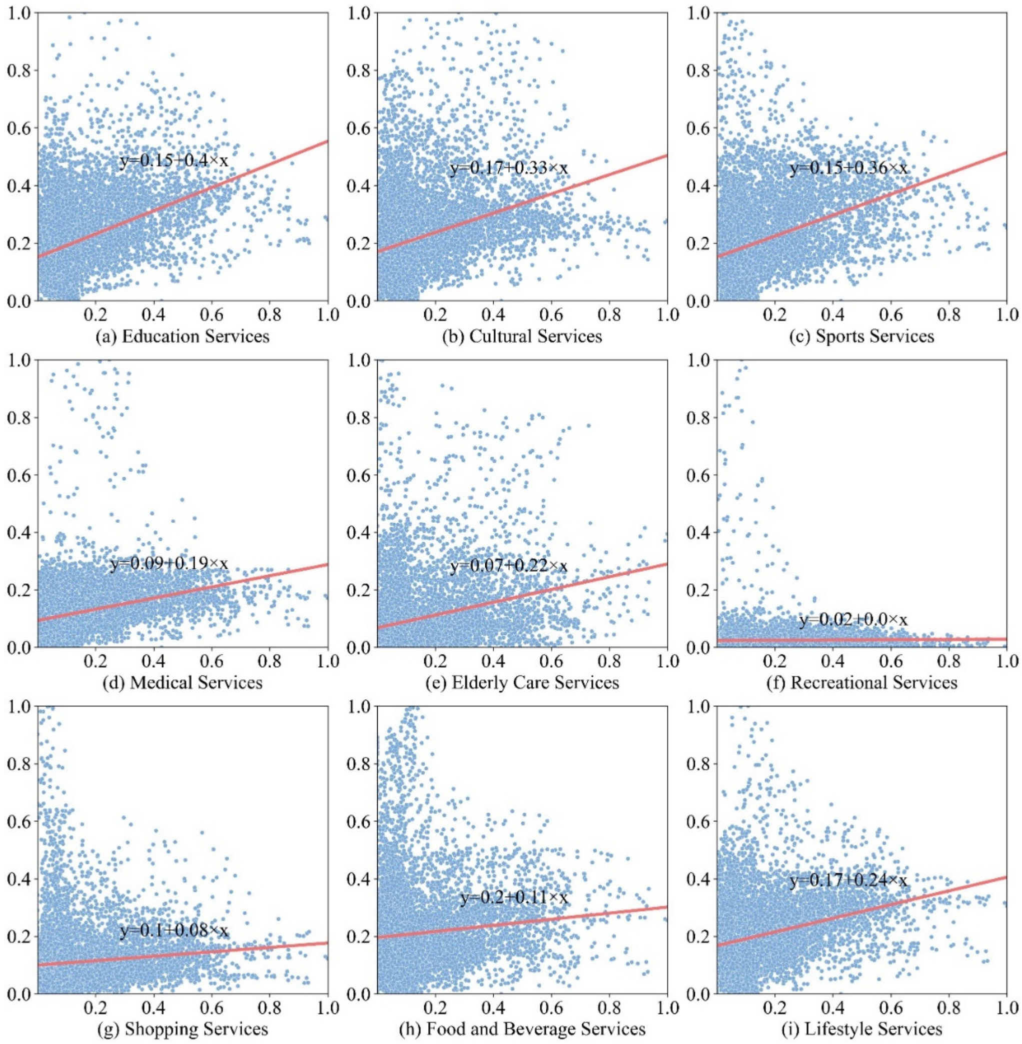


Fig 7. Coupling of Spatial Centers in 10-min Living Circles and Public Service Facilities

Since the previous results did not elucidate the relationship between spatial centers and different types of facilities at various scales, this study focuses on the ten-minute walking scale, which is most suitable for residents. We further conducted an OLS regression analysis between the z-scores from local autocorrelation analysis at the ten-minute scale and public service facilities (**Fig 7**). The study found that education, sports, and cultural facilities have a higher correlation with ten-minute living circle spatial centers, with regression best-fit line slopes of 0.4, 0.36, and 0.33, respectively. Conversely, recreational services, shopping services, and dining services showed lower correlations. Across all scales, the regression slopes for shopping, dining, and recreational services increased with scale, while other types of services exhibited a trend of decreasing and then increasing.

4. Conclusion

This study addresses the coupling issue between living circle spatial centers and the distribution of public service facilities. Supported by open-source data, the research circumvents the barrier of acquiring GPS data types, employing the crystal-growth algorithm to simulate the internal structure of community living circles at multiple scales. We defined the spatial centers of living circles using spatial autocorrelation methods and identified spaces requiring enhanced construction through coupling analysis. The study revisits the guidance of living circle theory in public service facility construction, advocating a shift from an equal distribution layout to a more concentrated layout in facility planning. It discusses the economic efficiency of spatial centers in urban construction, suggesting that living circle theory should guide actual planning in conjunction with spatial center structures.

Our findings reveal that the identified community living circle centers are located in population and road-concentrated areas, mostly centered in spaces defined by obstacle-type spatial elements, demonstrating high spatial accessibility. Spatial centers identified at multiple scales show that five-minute travel range centers are scattered bead-like, while thirty-minute travel range centers form connected clusters, mainly concentrated in Liwan, Yuexiu, and Haizhu districts. The results indicate that the crystal-growth algorithm effectively simulates hotspots in different areas at various scales. By coupling different types of facilities with the spatial center structures of multiple scales, we found that areas with high-valued spatial centers and low-valued public service facilities require special attention.

The study innovatively contributes in the following ways: It provides a new perspective of clustering for researching the coupling characteristics of facilities by focusing on the relationship between public service facility distribution and the spatial structure of residential community living circles. It extends the use of the crystal-growth algorithm with the Seventh Census data to delineate living circle boundaries, revealing support for planning decisions after uncovering the internal structure of living circles. The research also offers a method for spatiotemporal behavior analysis of public service facility supply at multiple scales.

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