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Spatial Distribution Evaluation and Optimization of Medical Resource Systems in High-Density Cities: A Case Study of Macau via GIS and Space Syntax Analysis

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Abstract

As a typical example of a high-density city, Macau's medical resource allocation system, a key component of the city's complex socio-technical system, suffers from significant spatial imbalances, which restricts the overall effectiveness of the medical service system. Based on the perspective of systems science theory, regards the allocation of medical resources as a dynamic system with multiple coupled factors. It comprehensively utilizes systems research methods such as POI data mining and space syntax analysis and employs techniques such as kernel density analysis and spatial structure coupling models to systematically evaluate the spatial structure, resource accessibility, and service balance of Macau's medical service system. It found that (1) the Macau Peninsula has concentrated core medical resources, such as the Conde de São Januário Hospital (CHCSJ) and Kiang Wu Hospital, which form a core subsystem with high service saturation. Excessive concentration of resources has led to high concentration of a certain type of facility. (2) Taipa Island and the Cotai Reclamation Area have created an extended subsystem of medical resources along with urban development. However, the northern area does not have enough facilities, and its internal structure is not balanced. (3) Coloane Island has only basic health stations remaining, forming a marginal subsystem with scarce medical resources, which has a significant hierarchical gap with the core and extended subsystems. This spatial pattern of "saturated Macau peninsula, expanded Taipa Island, and sparse Coloane Island" is essentially a concrete manifestation of the imbalance between the medical resource allocation system and the urban spatial development system. Therefore, based on system optimization theory, it proposes constructing a multi-level, networked spatial system for medical facilities to promote the coordinated operation of various regional medical subsystems and achieve overall functional optimization and a balanced layout for Macau's medical service system. This research analyzes the imbalance mechanism of high-density urban public service systems using systems science methods, providing not only a scientific basis for the precise optimization of Macau's medical resource allocation system but also a practical reference for the planning and governance of similar high-density urban public service systems under a systems thinking framework.

Keywords: healthcare resource system; high-density city; pharmacy space; healthcare services; POI analysis; GIS spatial analysis; spatial syntax; Macau

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1. Introduction

1.1. Research Background

The distribution of medical resources is not only an indicator of a country's healthcare level but also a foundation for achieving social justice [1]. The third UN Sustainable Development Goal, "Good health and well-being" explicitly requires "ensuring healthy lifestyles for all ages and promoting their well-being," with specific goal 3.8 emphasizing Universal Health Coverage (UHC), including equitable access to basic healthcare services [2,3]. As a Special Administrative Region of China, Macau is actively responding to this global commitment, and the spatial distribution of its medical resources directly impacts the achievement of UHC. A systematic review by Wang et al. shows that healthcare services are the most studied topic in the field of health sciences [4]. The balanced allocation of high-quality resources can guarantee the basic health rights of all citizens, improve the overall health level of the population, and reduce social conflicts caused by healthcare disparities [5]. As a representative of high-density cities, Macau faces unique challenges in the allocation of its medical resources [6]. In July 2024, the Macau Special Administrative Region Government, to align with the *Healthy China 2030: Blueprint for a Healthy China* [7], formulated and released the *Healthy Macau Blueprint*, comprehensively integrating health elements into all public policies [8]. Currently, Macau has formed a medical network system centered on "public hospitals, private hospitals, and primary healthcare centers" (Figure 1). However, it still faces problems such as uneven spatial distribution of medical resources and insufficient service balance [9], leading to real challenges such as "difficulty in accessing medical care" for residents. To effectively protect the health rights of the public and improve the fairness and efficiency of medical services, systematically study the spatial structure coupling and service balance of Macau's medical healthcare facilities and build a more efficient and inclusive medical and health service system through scientific planning and resource optimization.

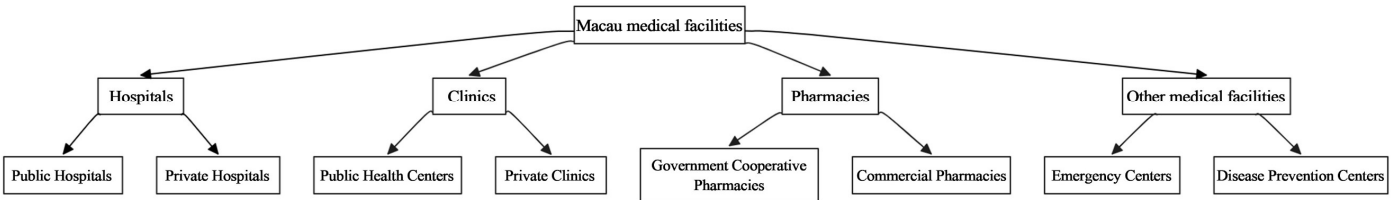


Figure 1. The Composition of Macau's Medical Institution System. (Image source: drawn by the authors).

1.2. Literature Review

Within the framework of systems science, the system for allocating urban healthcare resources, as a crucial subsystem of a complex socio-technical system, directly impacts the overall stability and sustainable development of the urban social system through the equilibrium of its spatial distribution and operational efficiency [10,11]. Therefore, it has become a research hotspot at the intersection of public administration, urban planning, and systems engineering [12,13]. With the acceleration of global urbanization, high-density cities, characterized by population concentration and space constraints, are experiencing increasingly prominent contradictions and spatial imbalances in healthcare resource supply and demand. Related research largely focuses on core issues such as spatial structure coupling assessment and allocation efficiency optimization, forming a diverse research trajectory encompassing theoretical construction, methodological innovation, and practical application.

Many scholars have discussed the distribution of medical resources or the medical system in China. For example, Guangzhou's medical resources exhibit a "strong core, weak

periphery" pattern, with high-quality tertiary hospitals highly concentrated in the central urban areas such as Yuexiu and Tianhe [14]. Wuhan's medical resources show a differentiated spatial distribution, with pharmacies exhibiting a "multi-center + multi-circle" pattern, clinics a "center + axis + point" layout [15], and Xi'an's medical resource allocation shows a gradient characteristic, with the central ring districts of Beilin and Yanta having abundant resources and high-quality services [16].

In recent years, Points of Interest (POIs) data, combined with Geographic Information System (GIS) and spatial statistics, has been widely used to explore the spatial heterogeneity, accessibility, and influencing factors of medical resources [17–21]. For instance, Zhang et al. (2023) used POI data to classify medical resources and quantified their spatial clustering via kernel density, mean nearest neighbor, and standard deviation elliptic methods [21]. Du et al. (2022) showed uneven medical distribution in Wenzhou (eastern better accessibility) and suggested cross-sector collaboration to narrow gaps [17]. Wan et al. (2021) revealed significant spatial heterogeneity in China's medical allocation (eastern areas better), with GDP strongly influencing distribution [18]; they proposed policy optimization to alleviate imbalances. Zhu et al. (2019) indicated Shenzhen's medical accessibility was generally high but uneven between communities, with the southwest best and southeast worst [19]. Liu et al. (2024) found Anhui's medical healthcare facilities and pharmacies showed a "one core, multi-level growth" pattern, with pharmacies most clustered and primary care relatively even [20]. These studies have deeply revealed spatial phenomena and problems of medical systems in major Chinese cities.

On the other hand, space syntax primarily provides objective analytical tools for healthcare facility design by quantifying spatial layout and connectivity, with a particular focus on the correlation between behavioral patterns (such as patient and staff movement and wayfinding) and psychological responses (such as stress and privacy perception). Its core is to transform building plans into computable topological networks, generating independent variables to predict the impact of the environment on health outcomes [22,23]. Haq & Luo's (2012) review indicates that initial research (circa 2000) concentrated mainly on nurse behavioral patterns (e.g., walking paths) and patient wayfinding experiences, whereas contemporary studies have evolved to incorporate interdisciplinary integration (e.g., discrete event simulation) to enhance spatial planning in emergency departments [22]. Sadek & Shepley (2016) emphasize the iterative improvement of space syntax tools, such as combining visual graph analysis and axial maps to enhance the analytical capabilities of healthcare layout spaces [23]. However, current research on space syntax mainly focuses on optimizing the internal spatial layout of hospitals. A systematic methodology for analyzing the spatial structure coupling and service balance of medical healthcare facilities at the regional scale has not yet been formed, especially in typical ultra-high-density cities like Macau.

Furthermore, existing research also indicates that Macau's medical resources and healthcare facilities currently face challenges such as uneven spatial distribution, structural systemic contradictions, and insufficient regional collaboration. However, through policy reforms, cross-regional cooperation, and the development of the traditional Chinese medicine (TCM) industry, a sustainable and high-quality medical system is gradually being built [24–26]. Cheang et al. (2024) provided pathways for Macau to build a sustainable and high-quality medical system through policy analysis, cross-regional collaboration, and innovative solutions [24]. They worked to improve medical resources and encourage regional collaboration, which led to changes in the medical system and better training for workers. They also worked to become more involved in the Guangdong-Hong Kong-Macau Greater Bay Area. The TCM industry has achieved significant growth with legislative support and industry-academia-research cooperation, balancing current needs

with long-term planning goals. Li through research on the spatial distribution of healthcare facilities in Macau, indicated that the fairness of resource allocation needs to be optimized, and medical spatial structure coupling needs to be improved in conjunction with urban development planning to support the goal of building a "Healthy Macau" [25]. Through GIS analysis, she found that the overall distribution of medical resources was discrete, with a severe shortage of medical resources in the Taipa Island, and secondary healthcare facilities facing problems of insufficient medical personnel and uneven distribution. A review by Zhang et al. (2025) pointed out that research on Macau's healthcare facilities mainly focuses on the medical system [26], salary system, and service model, suggesting that the Chinese mainland can learn from Macau's experience and promote the construction of closely integrated medical alliances through fiscal coordination, salary standardization, and strengthening of primary care capabilities.

Other studies have focused on the balance of public service facilities in Macau and the evolution of policies. For example, Liu et al. (2025) used high-resolution geospatial data to explore spatial inequalities in accessibility to primary healthcare in Macau within the framework of a "15 min city," finding significant socio-spatial disparities at a fine scale despite relatively good overall coverage [27]. Furthermore, Wu et al. (2024) traced the formation of Macau's public–private partnership healthcare model from the perspective of urban history and health governance [9]. However, existing research largely relies on measurements of Euclidean distance or road network distance (such as the 2SFCA method), resulting in a lack of exploration of the intrinsic relationship between road network topology and healthcare resource allocation from the perspective of urban spatial configuration. Especially given Macau's narrow streets and complex urban fabric, residents' visual guidance and walking habits significantly impact the efficiency of healthcare resource utilization. This study introduces spatial syntax analysis to fill this gap in topological research.

In summary, while existing research has revealed the challenges facing Macau's healthcare system, a systematic quantitative analysis of its spatial structure coupling and service balance remains lacking. More importantly, previous assessments of healthcare facilities at the regional scale have largely relied on traditional GIS buffer analyses based on Euclidean distances or simple road network distances. This approach often overlooks the constraints imposed on residents' actual travel behavior by the complex street textures and road network topologies in high-density cities.

Therefore, we innovatively propose a comprehensive analytical framework integrating POI kernel density analysis and space syntax. Space Syntax is different from traditional methods because it does not just measure physical distance. It also uses topological indicators like Integration and Choice to measure how the spatial structure of the urban road network guide's pedestrian flow. This methodological improvement is particularly crucial for densely populated cities like Macau with narrow streets and complex road networks. It can accurately simulate residents' healthcare access experiences at a micro-level "walking scale," overcoming the shortcomings of traditional macro-accessibility models in providing a micro-human perspective. By overlaying high-precision POI data, it aims to construct an assessment model that better reflects the true convenience of accessing healthcare, thereby providing a more scientific basis for the precise optimization of Macau's healthcare resource allocation.

1.3. Problem Statement and Objectives

In the process of urban development, the rationality of the spatial layout of healthcare facilities is directly related to the convenience and fairness of residents' access to medical services. To understand the spatial distribution of urban healthcare facilities more scientifically and accurately, we need to use effective data and analysis methods. Based

on the current situation of spatial allocation of medical resources, we focus on the layout characteristics and service efficiency of healthcare facilities in Macau. Through a multi-dimensional spatial analysis methodology, it systematically evaluates the distribution pattern of medical system resources in Macau and the convenience of residents' access. The following three issues are analyzed in detail: (1) the spatial distribution of healthcare facilities; (2) the service balance between healthcare facilities and residents' residences; and (3) the spatial coupling characteristics between healthcare facilities and road network structure. It aims to measure the differences in the convenience of residents' access to medical resources in different areas; assess the matching degree between the distribution of healthcare facilities and population agglomeration; and identify areas of unbalanced resource allocation and obstacles to residents' actual access to medical care, so as to provide a scientific basis for Macau's planning to build a "medical city" and optimize service coverage and resource allocation.

2. Study Area, Materials and Methods

2.1. Study Area: Macau S.A.R.

The Macau S.A.R. is located on the southeastern coast of Chinese mainland, on the western bank of the Pearl River Delta, in the lower reaches of the Xi River, adjacent to Guangdong Province. It is 60 km from Hong Kong and 145 km from Guangzhou [28]. The area studied here comprises the Macau Peninsula, Taipa Island, Coloane Island, and the Cotai Reclamation Area (without parish divisions), comprising seven parishes: Freguesia de Nossa Senhora de Fátima (花地瑪堂區), Freguesia de Santo António (聖安多尼堂區/花王堂區), Freguesia de São Lázaro (望德堂區), Freguesia de São Lourenço (風順堂區), Freguesia da Sé (大堂區), Freguesia de Nossa Senhora do Carmo (嘉模堂區), and Freguesia de São Francisco Xavier (聖方濟各堂區) (Figure 2). Although we use the concept of Freguesia to describe the distribution of healthcare system facilities and resources, some newly reclaimed areas in Macau have been incorporated into the existing Freguesia in recent years. Examples include the Macau Port Management Area of the Hong Kong-Zhuhai-Macau Bridge, five plots of land in the new urban reclamation area, and the Hengqin Campus of the University of Macau. However, as of the end of 2025, these new reclamation areas are still under construction, and healthcare buildings and facilities are not yet complete. Therefore, our discussion focuses more on the traditional seven freguesias. The disparity in healthcare resource matching between the Macau Peninsula and the outlying islands, the increased burden of chronic diseases due to population aging, and the growing demand for cross-border healthcare highlight the importance of research on spatial structure coupling and service balance.

2.2. Data Sources and Processing

Python (version 3.13.0) is used to call the AMap Global Open Platform API (https://mobile.amap.com/cn/, accessed on 26 October 2025). Data acquisition and use strictly comply with the *AMap Open Platform Service Terms* (https://lbs.amap.com/api/webservice/summary/, accessed on 28 October 2025) and are used solely for academic research, without involving commercial applications. After data cleaning, filtering, and matching, a total of 2327 POIs for healthcare services (Supplementary Materials Table S1) in the Macau Special Administrative Region were collected (data as of May 2025), covering types such as hospitals, clinics, and pharmacies in the healthcare system (Table 1). The healthcare facilities in each Freguesia were classified (Figure 3a and Table 2). A total of 4186 POI data for commercial and residential (Supplementary Materials Table S2) areas were also collected (Figure 3b and Table 2) to analyze the service balance between healthcare facilities and population distribution. The GIS base map and road network data were obtained from

the official digital map (https://cadastre.gis.gov.mo/MGSP_Cad/port/main.html, accessed on 26 October 2025) updated by the Cartography and Cadastre Bureau of Macau S.A.R. in 2025.

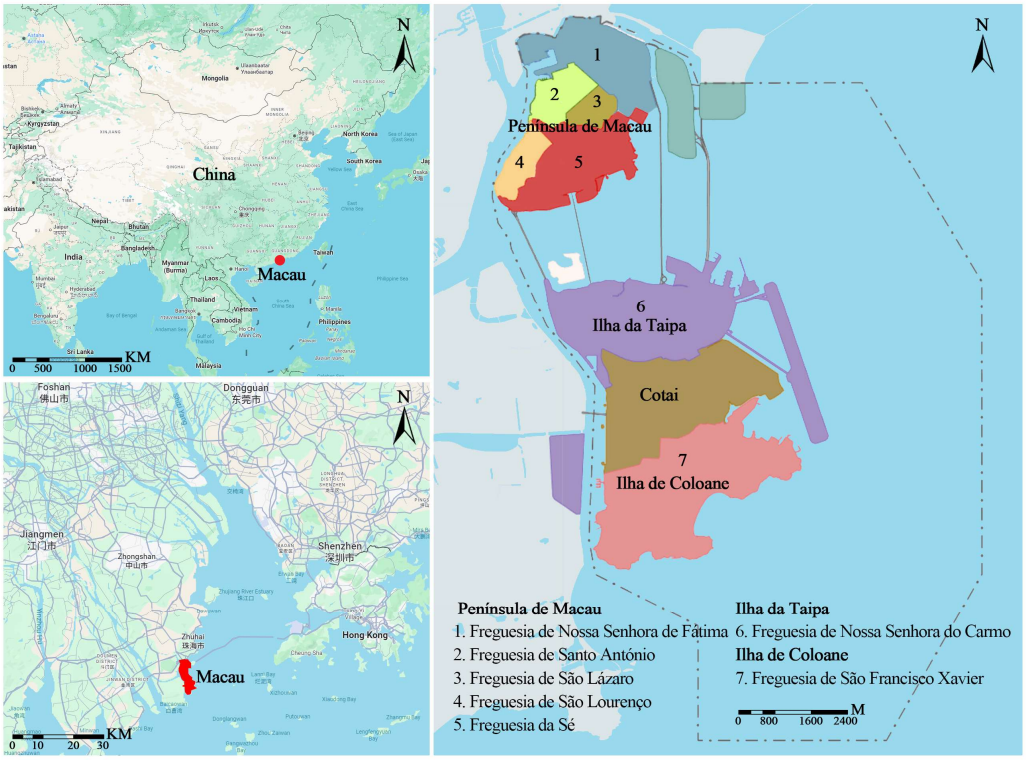


Figure 2. Location analysis of Macau and its main parishes (Freguesia). The Chinese characters are place names and have no special meaning. (Image source: drawn by the authors).

Table 1. Classification of Medical Healthcare Facilities in Macau.

Major Categories	Secondary Classification	Subcategories	Number of POIs	Proportion/(%)
Hospitals	General Hospitals	General hospitals; health centers	105	4.51
	Specialized Hospitals	Specialized hospitals; infectious disease hospitals; gynecology hospitals; psychiatric hospitals; dental hospitals; ophthalmology hospitals; plastic and cosmetic surgery hospitals.	31	1.33
Clinics	/	Private clinics; comprehensive TCM clinics	1291	55.48
	Healthcare Service Facilities	Private healthcare facilities; medical centers	149	6.40
Pharmacies	Pharmacy & Health Products Stores	Pharmacies; medical and health product sales venues; pharmaceutical and healthcare related venues	748	32.15
Other Medical Healthcare Facilities	Emergency Centers	/	1	0.04
	Disease Prevention	/	2	0.09

Source: Author statistics.

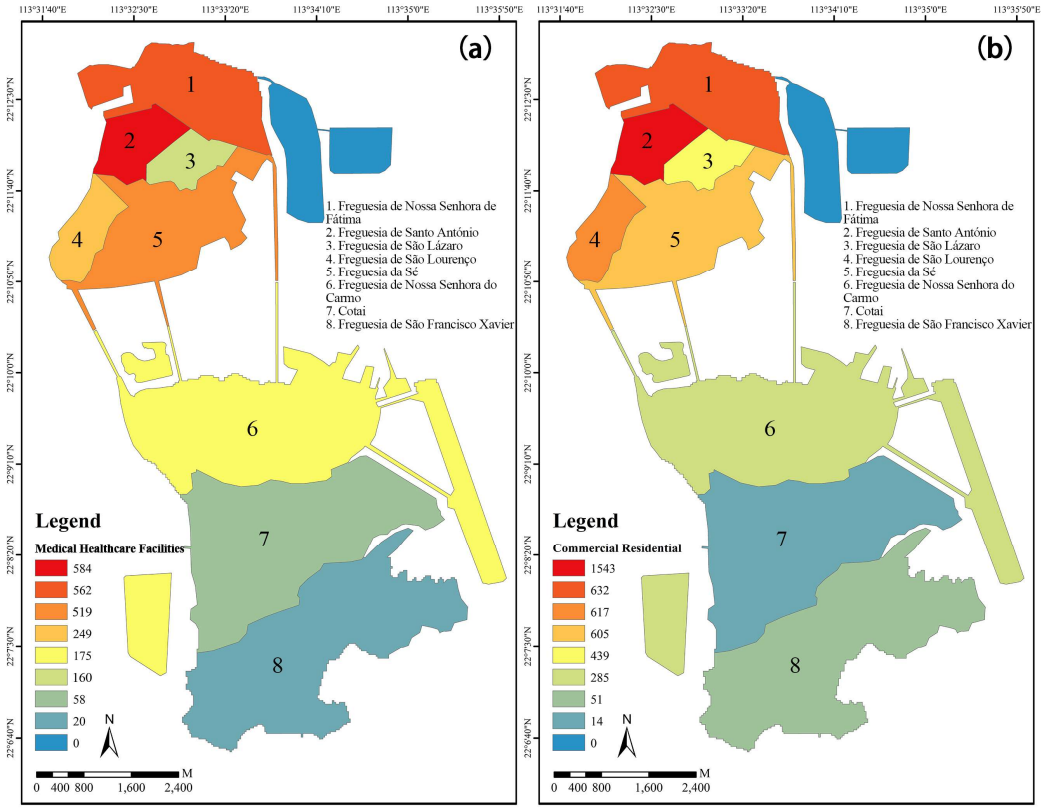


Figure 3. The map illustrates the distribution of medical facilities and residences in each Freguesia in Macau. (**a**) Medical facilities; (**b**) residences. (Image source: drawn by the authors).

Table 2. Quantity of medical facilities and commercial residences in each Freguesia in Macau.

Area	Freguesia	Residence	Hospitals	Clinics	Pharmacies	Other Medical Healthcare Facilities	Total	Proportion/(%)
Macau Peninsula	Freguesia de Nossa Senhora de Fátima	632	17	316	229	0	562	89.13
	Freguesia de Santo António	1543	23	408	153	0	584	
	Freguesia de São Lázaro	439	19	119	21	1	160	
	Freguesia de São Lourenço	617	16	173	59	1	249	
	Freguesia da Sé	605	47	272	199	1	519	
Taipa Island and Cotai Reclamation Area	Freguesia de Nossa Senhora do Carmo	285	9	116	50	0	175	10.01
	Cotai	14	2	25	31	0	58	
Coloane Island	Freguesia de São Francisco Xavier	51	3	11	6	0	20	0.86

Source: Author statistics.

2.2.1. POI Data Acquisition and Refined Cleaning

Python (version 3.13.0) is used to access data via the AMap Global Open Platform API. To ensure the comprehensiveness, accuracy, and reproducibility of the data, we implemented a rigorous query and cleaning strategy:

(1) API Query and Restriction Processing: We used category keywords such as "general hospital," "clinic," "pharmacies," and "commercial residences" for retrieval. To over-

come the limitations of API call quantity and rate, we employed a bounding box-based grid partitioning method combined with a pagination request mechanism to ensure traversal of the entire Macau S.A.R.

(2) Coordinate System and Spatial Units: The original AMap data used the Geodetic Coordinate System 2002 (GCJ-02). To perform accurate Euclidean distance calculations and spatial overlay, all POIs and official road network data were converted to WGS84 coordinates and uniformly reprojected to the WGS_1984_UTM_Zone_49N projection coordinate system (https://epsg.io/32649, accessed on 26 October 2025). Distance measurements were uniformly expressed in meters (m).

(3) Data Cleaning Rules: We strictly adhered to the basic principles of POI cleaning. First, redundant locations with names that are less than 5 m apart or have similar heights were identified and removed using geospatial computing tools. Second, we filtered out invalid locations that had status tags such as "under construction," "internal," "closed," or "relocated" using text matching. After rigorous deduplication and filtering, 2327 valid POIs for medical facilities and 4186 valid POIs for commercial and residential use were retained.

2.2.2. Spatial Model Reproducibility Parameters

To ensure the complete reproducibility of the research results, we standardized the implementation environment and core parameters for kernel density analysis and space syntax.

Kernel density analysis was performed using ArcMap 10.8 software. This study precisely categorized the collected spatial point data by type, including overall medical facilities, hospitals, clinics, pharmacies, other medical institutions, and commercial/residential properties. To minimize subjective bias caused by parameter settings, the software's built-in Silverman rule of thumb was used to automatically determine the output raster and cell size for each category based on the spatial extent and distribution characteristics of each element. A quadratic kernel was uniformly used, and no planar boundary correction was performed. Furthermore, to avoid invalid overflow of density analysis results into the sea area, all layer operations used the official land boundary of Macau as a mask to ensure that the kernel density spatial raster output was strictly limited to the actual land area.

Secondly, we use DepthmapX (version 0.8.0) space syntax software, with DXF vector data (Supplementary Materials Table S3) from the Macau road network as input, to complete line segment map construction and angle analysis. The specific operation process is as follows, ensuring the reproducibility of the analysis process:

(1) Importing DXF Files and Building the Workspace

First, launch DepthmapX 0.8.0 software. Create a blank workspace using the "File → New" command to store road data and analysis results. Then, click the "Map → Import" command. In the pop-up file selection dialog box, select the Macau road network DXF file and complete the import, ensuring that the road vector data is completely loaded into the workspace.

(2) Segment Map Construction

Considering the instability of directly converting DXF files to segment maps using software, this study employs an axis map conversion method to construct the segment map. The specific steps are as follows:

(a) Click the "Map → Convert Drawing Map" command in the top menu bar. In the pop-up conversion dialog box, select "Axial Map" for the "New Map Type" option and click "OK" to convert the imported road vector data into an axis map.

(b) Keep the axis map active and click the "Map → Convert Active Map" command. In the dialog box, select "Segment Map" for the "Create New Map" option, and check "Retain

original map" to retain the previously generated axis map. Check the bottom intersection processing option (i.e., when an axis intersects with other axes, if the extension length at the intersection is less than 25% of the total length of the axis, the extension portion is removed).

(c) Click "OK" to complete the conversion from the axis map to the segment map, generating a Macau road segment network suitable for subsequent analysis.

(3) Angular Segment Analysis

After the segment map is constructed, perform global and angular segment analysis at different radii. Specifically: Click the "Tools → Segment → Run Angular Segment Analysis" command in the top menu bar. A parameter setting dialog box will pop up. Set the core parameters as follows: Select analysis radii of 400 m, 800 m, 1200 m, and 1600 m, and the global radius (n). Keep the other parameters at their default settings. After confirming the parameters, click "OK." The software will automatically complete the angular analysis at different radii and output three core spatial syntax indicators—integration, choice, and depth—for subsequent quantitative analysis of Macau's medical facilities.

2.3. Methodology

It employs a deep fusion of POI data and space syntax to construct a multi-scale, refined, comprehensive analytical methodology aimed at achieving accurate assessment and scientific optimization of the spatial distribution of healthcare system resources. This methodology comprehensively utilizes kernel density analysis, statistical analysis of POI distribution characteristics, and core space syntax indicators (including integration, choice, and depth) for a holistic quantitative evaluation. It deeply analyzes the spatial structure coupling characteristics and service balance of Macau's healthcare system resources, providing detailed and reliable reference for the subsequent development of strategies to optimize healthcare resources. The research framework, as shown in Figure 4, includes steps such as data acquisition and processing, spatial layout analysis of Macau's healthcare system, and extraction of Macau's road network structural characteristics.

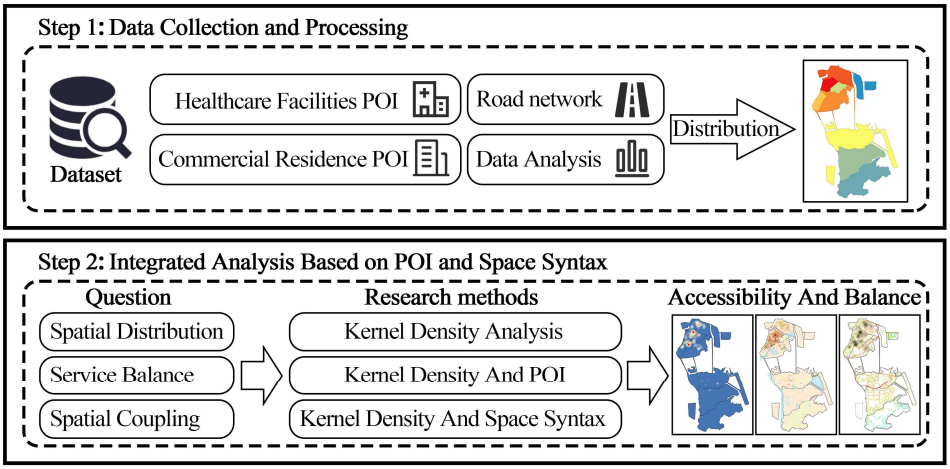


Figure 4. Research Framework. (Image source: drawn by the authors).

2.3.1. POI Kernel Density Analysis

Points of Interest (POIs), as key data units in Geographic Information Systems (GISs), are used to accurately identify specific locations [29]. They encompass various entities such as buildings, shops, bus stops, and healthcare facilities and are one of the important types of basic geospatial data [29]. Each POI data package contains basic elements such as name, category, coordinates, address, and contact information [30], and its classification system follows a structure combining primary and secondary categories. With its signif-

icant advantages of rich content, timely updates, and high accuracy, POI data has been widely used in various fields such as urban spatial analysis, commercial layout planning, and medical resource distribution research [31]. Through meticulous organization and in-depth analysis of medical institution POI data, we can use professional GIS software v10.8 to visually present the location information of healthcare facilities in the form of maps, seeing their specific distribution in various urban areas, including which areas have a high concentration of healthcare facilities and which areas have a relative scarcity.

Then, kernel density analysis [32] was employed to conduct a multi-dimensional study of POI data for healthcare facilities. Kernel density analysis is not only used to quantify the spatial distribution of POIs but is also a core analytical tool for assessing service equalization. It can transform discrete healthcare facility POI data into a continuous density surface, thereby intuitively identifying areas of excessive resource concentration and scarce resources in space. Firstly, focusing on different types of medical healthcare facilities (including hospitals, clinics, pharmacies, and others), the overall kernel density and the independent kernel density of each category were calculated to quantitatively assess the spatial distribution characteristics of various types of medical healthcare facilities. Secondly, to further explore the service balance between the distribution of medical healthcare facilities and residential areas in Macau, the kernel density of residences overlaid with the overall medical POIs and the POIs of various medical healthcare facilities for analysis, thus accurately depicting the coverage and balance of medical services in residential areas. Thirdly, within the walkable scale, to reflect the spatial permeability of medical care in residents' actual experience, key indicators such as integration, choice, and depth in space syntax were overlaid with the overall medical kernel density for analysis, comprehensively revealing the spatial coupling characteristics of the medical system and the road network structure, thereby further revealing the spatial structure coupling of healthcare facilities.

2.3.2. Space Syntax Model Construction and Multi-Scale Parameter Selection

Space syntax theory, a novel quantitative language for describing architectural and urban spatial patterns, enables scientifically quantitative research on space [33]. It quantifies urban spatial patterns by converting building plans and road networks into computable topological maps. The axis map is constructed based on official Macau road network data from 2025, following a three-tiered road network structure of main roads-secondary roads-local roads. We generated the longest axis representing continuous visual and mobility paths in urban space. To ensure the model accurately reflects the actual mobility paths of residents in Macau's high-density environment, rigorous topological cleaning was performed, merging scattered road segments and removing isolated axes not connected to the main network to maintain spatial continuity. This resulted in a complete axis map covering the entire street network of the Macau Peninsula, Taipa Island, and Coloane Island.

To bridge the gap between spatial patterns and residents' actual medical behavior, it employs a multi-scale analysis strategy. Unlike typical urban studies, the radius (R) was chosen to consider Macau's compact urban morphology and its walkable city characteristics. The scale of the radius range can be divided into the following cases:

- R = 400 m (5 min walking circle) [34]: Represents the core community scale and is crucial for assessing the spatial structure coupling of basic health stations and pharmacies for mobility-limited groups (such as the elderly).
- R = 800 m (15 min community living circle): Corresponds to a standard 10–15 min walking distance. This is the primary scale for residents to access primary care clinics and reflects the efficiency of the community healthcare network.
- R = 1200 m and R = 1600 m (cycling or public transport connection scale): Due to Macau's small geographical area, these radii reflect extended walking activities or

short-distance cycling or public transport connections and are valuable for reference regarding cross-regional access to specialized services at general hospitals.

- Global scale (Rn): Represents the integration capacity of the healthcare facility network at the macro-city level. Based on this multi-scale framework, we calculated three key morphological variables: integration, choice, and depth.

Integration is an important metric in space syntax used to measure the topological centrality of a space within a road network system, primarily reflecting the global accessibility of spatial nodes within the network structure. In the context of healthcare facility accessibility, streets with high integration indicate that the healthcare facilities located there have stronger core location attributes, allowing residents to reach them with high global convenience regardless of their origin within the city. It reflects the level of global accessibility and spatial equity in obtaining centralized healthcare resources (such as general hospitals).

Choice measures the potential of an axis to be traversed as the shortest path between any two points in a network. In healthcare behavior analysis, roads with high choice constitute urban healthcare transportation corridors. Quantifying choice helps assess the degree of path dependence among residents during cross-regional healthcare visits or emergency transport, effectively identifying potential traffic bottlenecks that may restrict the efficiency of medical rescue.

Depth reflects the average number of topological steps required to reach all other spaces. In micro-healthcare accessibility assessments, a low depth value means residents can reach community clinics or pharmacies with fewer street turns. This indicator is particularly important for Macau's highly dense and structurally complex neighborhood fabric, directly determining the actual experience and spatial permeability of vulnerable groups such as the elderly in accessing basic healthcare services on foot within the community.

These variables together provide a scientific and systematic basis for a comprehensive and in-depth quantification of the space of healthcare facilities in Macau's healthcare system.

3. Results

3.1. Spatial Layout of Medical Healthcare Facilities in Macau

3.1.1. Overall Distribution Characteristics

The density distribution of healthcare facilities in Macau exhibits a significant spatial clustering characteristic, forming a high-density area centered on the Macau Peninsula, while the density in Taipa Island and Coloane Island is lower. The spatial pattern is characterized by "dense in the north and sparse in the south," exhibiting typical features of "dispersed-multi-center-uneven" (Figure 5a). From the perspective of each Freguesia, the high-density area of healthcare facilities is mainly concentrated in the Freguesia de Santo António and the Freguesia de Nossa Senhora de Fátima in the northern part of the Macau Peninsula. Due to its dense population and mature urban development, this area may have formed a core area with a high concentration of healthcare facilities. The junction of Freguesia da Sé and Freguesia de São Lourenço on the Macau Peninsula presents an extremely high-density core, which is also the area with the most concentrated healthcare facilities, showing a strong radiation effect of medical resources. The density of Freguesia de São Lázaro is relatively lower but still higher than that of the outer areas of the peninsula. In contrast, the Freguesia de Nossa Senhora do Carmo in Taipa Island only shows scattered low-density points in certain areas, while the Cotai reclamation area and the Freguesia de São Francisco Xavier in Coloane Island are generally extremely low-density areas with sparse healthcare facilities. The historical background of the dense population and mature urban development of the Macau Peninsula closely relates to this distribution characteristic. Although the outlying islands have been developed to some extent, medical resources

are still concentrated in the core area of the Macau Peninsula, reflecting the profound impact of urban spatial structure on the layout of public service facilities.

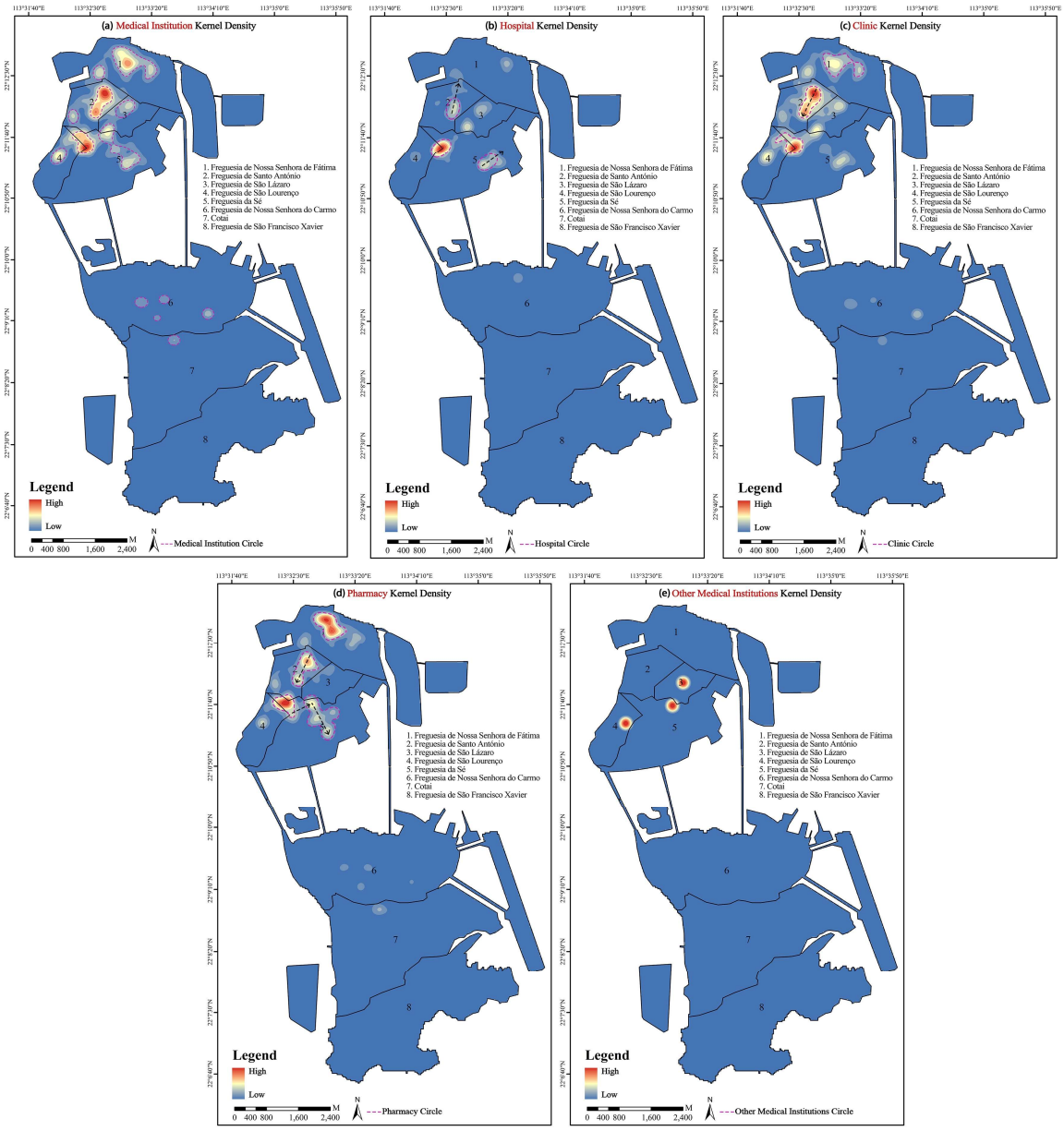


Figure 5. Kernel density analysis of medical healthcare facilities in Macau. The color gradation represents the density of healthcare facilities; warmer colors indicate a higher degree of clustering, and vice versa. (**a**) Overall kernel density of medical healthcare facilities; (**b**) Kernel density of hospitals; (**c**) Kernel density of clinics; (**d**) Kernel density of pharmacies; (**e**) Kernel density of other medical healthcare facilities. (Image source: drawn by the authors).

3.1.2. Kernel Density of Healthcare System Hierarchical Types

(1) Kernel density of hospitals

Macau's hospitals exhibit a "decentralized-single-center" layout (Figure 5b). The highest density core area is located at the intersection of Freguesia da Sé and Freguesia de São Lourenço on the Macau Peninsula, radiating outwards. This area is Macau's traditional center for government, business, and living. It has a lot of people and a lot of infrastructure, so it naturally attracts medical resources to meet its high demand. Secondary core areas are scattered across Freguesia de Santo António, Freguesia de São Lázaro, and Freguesia da Sé, reflecting the distribution logic of market-oriented medical services while also consider-

ing community needs. Among them, Freguesia de Santo António spreads northeastwards from Kiang Wu Hospital as its center point, and its main components are some private medical centers. The two centers of Freguesia de São Lázaro are mainly composed of medical centers and treatment centers; the center of Freguesia da Sé is mainly a medical center, spreading northeastwards. Freguesia da Sé also has two large general hospitals, Conde S. Januário General Hospital (仁伯爵綜合醫院) and Yin Kui Hospital (澳門銀葵醫院), but they are not clustered in the core area, possibly due to land resource constraints, government planning guidance, or historical site selection. Freguesia de Nossa Senhora de Fátima and Freguesia de Nossa Senhora do Carmo have only a small cluster, mainly composed of medical centers. Among them, Freguesia de Nossa Senhora do Carmo has the Hospital Universitário (科大醫院). Cotai and Freguesia de São Francisco Xavier have no obvious cluster. Cotai has The Islands Healthcare Complex—Macau Medical Center of Peking Union Medical College Hospital (Macau Union Hospital) (離島醫療綜合體北京協和醫院澳門醫學中心) and iRAD Hospital (卓智醫院). Freguesia de São Francisco Xavier has the Hospital de Reabilitação Ká-Hó (九澳康復醫院) (Figure 6a). Overall, the density distribution of hospitals in Macau is the result of the combined effects of urban spatial evolution, social demand stratification, and policy regulation.

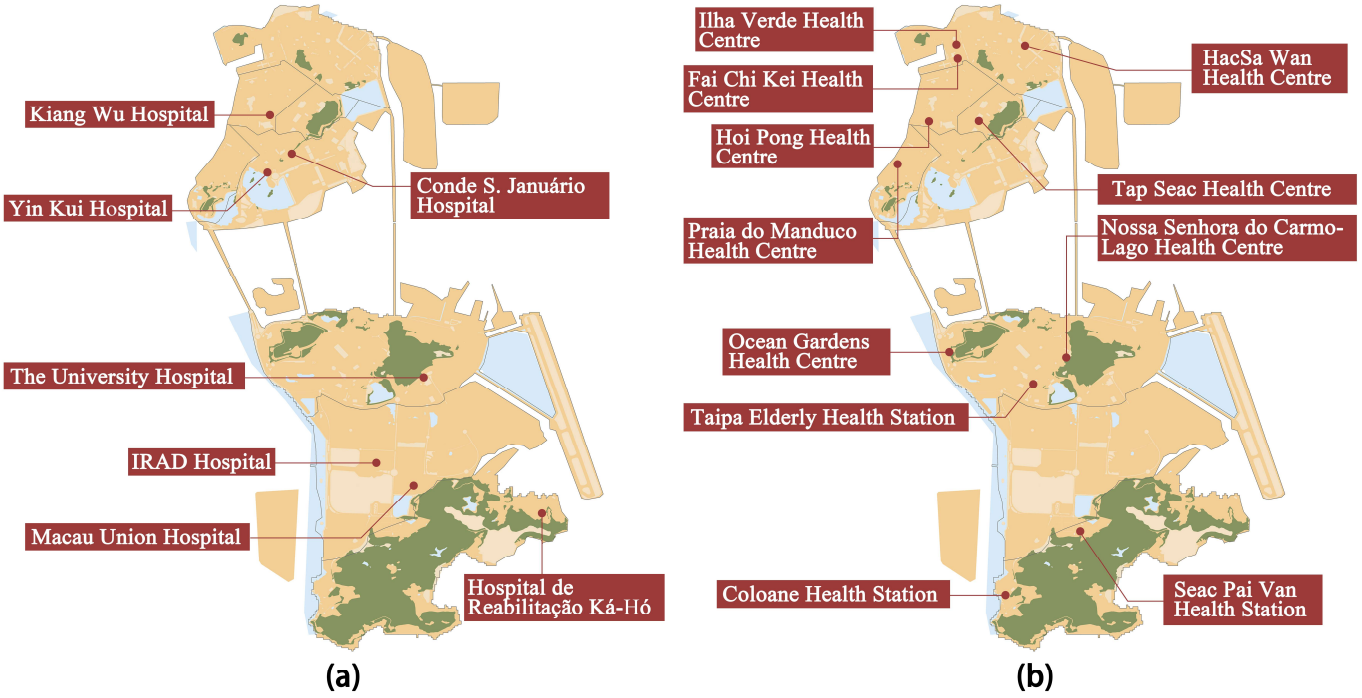


Figure 6. Distribution of general hospitals and health centers in Macau. (**a**) General hospitals; (**b**) Health centers. (Image source: drawn by the authors).

(2) Kernel density of clinics

The clinics are laid out in a "decentralized-multicenter" pattern (Figure 5c), which is similar to the spatial layout of healthcare facilities in Macau. Clinics account for the largest proportion of healthcare facilities, reaching 61.85%. On the Macau Peninsula, the highest density core area is formed at the junction of Freguesia da Sé and Freguesia de São Lourenço, while the northern end of Freguesia de Santo António also shows a high-density cluster, extending southwest to form a secondary density core, constituting a core axis. This distribution pattern makes the five freguesias on the Macau Peninsula closely connected, forming a relatively balanced medical service network. In contrast, the clinics in the outlying islands are sparsely distributed, with only a small number of clinics clustered in Freguesia de Nossa Senhora do Carmo. The Cotai reclamation area and the Freguesia

de São Francisco Xavier in Coloane show low density and decentralization, reflecting the differences in population distribution and regional development.

(3) Kernel density of pharmacies

The distribution of pharmacies also exhibits a "dispersed-multi-center" characteristic (Figure 5d). On the Macau Peninsula, the highest density core area is located northwest of Freguesia da Sé, close to popular tourist areas such as the Ruins of St. Paul's, and extends northeastward to form a secondary cluster, ultimately forming a distribution axis running northeast–southeast. Freguesia de Nossa Senhora de Fátima forms two connected pharmacy clusters centered around the Border Gate (Figure 7), mainly serving cross-border tourists and residents. Pharmacies are concentrated in the old town of Freguesia de Santo António, forming a spatial development axis extending southwestward from the old town as its core. In contrast, the distribution of pharmacies in the outlying islands is relatively sparse, with only Freguesia de Nossa Senhora do Carmo having a scattered distribution, which is basically consistent with the overall spatial pattern of local healthcare facilities, reflecting regional differences in population density, tourist flow, and commercial activity.



Figure 7. There is a cluster of pharmacies near the Border Gate. The Chinese characters in the photos are the names of the pharmacies' signs. Examples include Alpha Pharmacy (Farmácia), Royal Pharmacy, Popular Pharmacy, and Universal Pharmacy. (Image source: Photographed by the author. The core scene depicted in the photo is pharmacies lining both sides of a public street, therefore the images of people involved have been blurred).

(4) Kernel density of other medical healthcare facilities

The Macau Peninsula's core area concentrates other medical healthcare facilities in a "decentralized-three-center" pattern (Figure 5e). They are mainly concentrated in the core area of the Macau Peninsula. Among them, Freguesia da Sé houses an important institution, the Centre for Disease Control and Prevention (Macau), which undertakes public health management and emergency medical response functions. Freguesia de São Lázaro houses the Centre for Tuberculosis Prevention and Treatment (Centro de Prevenção E Tratamento de Tuberculose), focusing on the prevention and control of respiratory infectious diseases. Freguesia de São Lourenço relies on the Honour Water Safety Medic First Aid Centre (海安水上安全醫療急救中心) to ensure emergency rescue in water-related incidents. This layout reflects both the regional division of professional medical functions and the targeted coverage of resources for densely populated areas and special geographical environments (such as waterways). The lack of such healthcare facilities on the outlying islands perpetuates the overall uneven distribution of medical resources in Macau.

In summary, the facilities and resources of Macau's medical system exhibit a gradient distribution of "core-periphery." The Macau Peninsula forms a multi-tiered cluster of centers, with the highest density core located at the intersection of Freguesia da Sé and Freguesia de São Lourenço, radiating to the administrative and commercial districts. Freguesia de Santo António and Freguesia de Nossa Senhora de Fátima form secondary centers based on population density; the outlying islands exhibit a scattered, low-density distribution. The "single-center-radiating" pattern of hospital layouts contrasts with the multi-center network of clinics and pharmacies, which reflects the demand for community-based services. The core area of the peninsula concentrates specialized healthcare facilities, indicating a specialized functional division. This spatial differentiation is shaped by historical development, population distribution, policy regulation, and the tourism economy, highlighting the close connection between urban spatial structure and public service allocation.

3.2. Kernel Density Results Superimposed on Residential Buildings

3.2.1. Overall Distribution Characteristics

Residential core density in Macau exhibits a significant regional clustering characteristic, which is highly consistent with the overall spatial distribution of medical facility points of interest (POIs) in terms of service balance (Figure 8a). However, in-depth analysis reveals that, despite the similar clustering characteristics, the optimization of the layout of medical facilities still lags behind the surge in residential density at the microscale. High-density residential areas are mainly concentrated in the central part of the Macau Peninsula, including the northern edges of Freguesia de Santo António, Freguesia de São Lázaro, Freguesia de São Lourenço, and Freguesia da Sé. Secondary-density residential areas are concentrated in parts of Freguesia de Nossa Senhora de Fátima, where commercial and residential properties are densely distributed in contiguous areas, with core density gradually decreasing from the center outwards.

However, the distribution of medical facilities (hospitals, clinics, pharmacies, etc.) is centered on the Macau Peninsula, particularly in the northern edge of Freguesia de Santo António, Freguesia de São Lourenço, Freguesia da Sé, and the central part of Freguesia de Nossa Senhora de Fátima, forming a dense cluster. Hospitals, clinics, and pharmacies are numerous and spatially compact, highly overlapping with the surrounding high-density business and residential areas. Therefore, service balance is relatively good—for example, Freguesia de Santo António, as a dual core of residential and medical resources, has a high degree of matching between the density of medical facilities and residential density, making medical care convenient for residents.

In contrast, the residential core density in the southern area of the Freguesia de São Francisco Xavier on Taipa and Coloane islands is generally low and more dispersed, with only a small number of low-to-medium-density clusters in the central part of Taipa and the Cotai Reclamation Area. Although there are a few medical points in the central part of Taipa and the Cotai Reclamation Area, their overall number is far less than that on the Macau Peninsula, and their distribution is not well matched with the low-density residential distribution. Medical health facilities on Coloane Island are even sparser, with only a few pharmacies or clinics, forming a "double low" pattern with the extremely low residential density in this area, resulting in poor service balance, and residents' access to medical care is significantly weaker than in the core area of the Macau Peninsula. In addition, the sub-core-density residential area on the northern edge of the Freguesia de Nossa Senhora de Fátima, although adjacent to some medical points, has a slightly lower density of medical resources than the Freguesia de Santo António, and its service balance is between that of the core area and the Coloane Island and Cotai Reclamation Area. Overall, the central parts of the Macau Peninsula (Freguesia de Santo António, Freguesia de São Lázaro, the

northern edge of Freguesia da Sé, and the central part of Freguesia de São Lourenço) have achieved a satisfactory balance between high residential density and high concentration of medical resources, resulting in the best service equilibrium. The northern part of the Macau Peninsula, as well as the central parts of Taipa Island and the Cotai Reclamation Area, has a moderate level of equilibrium. Most areas of Coloane Island and Taipa Island have the worst service equilibrium due to a lack of both residential and medical resources.

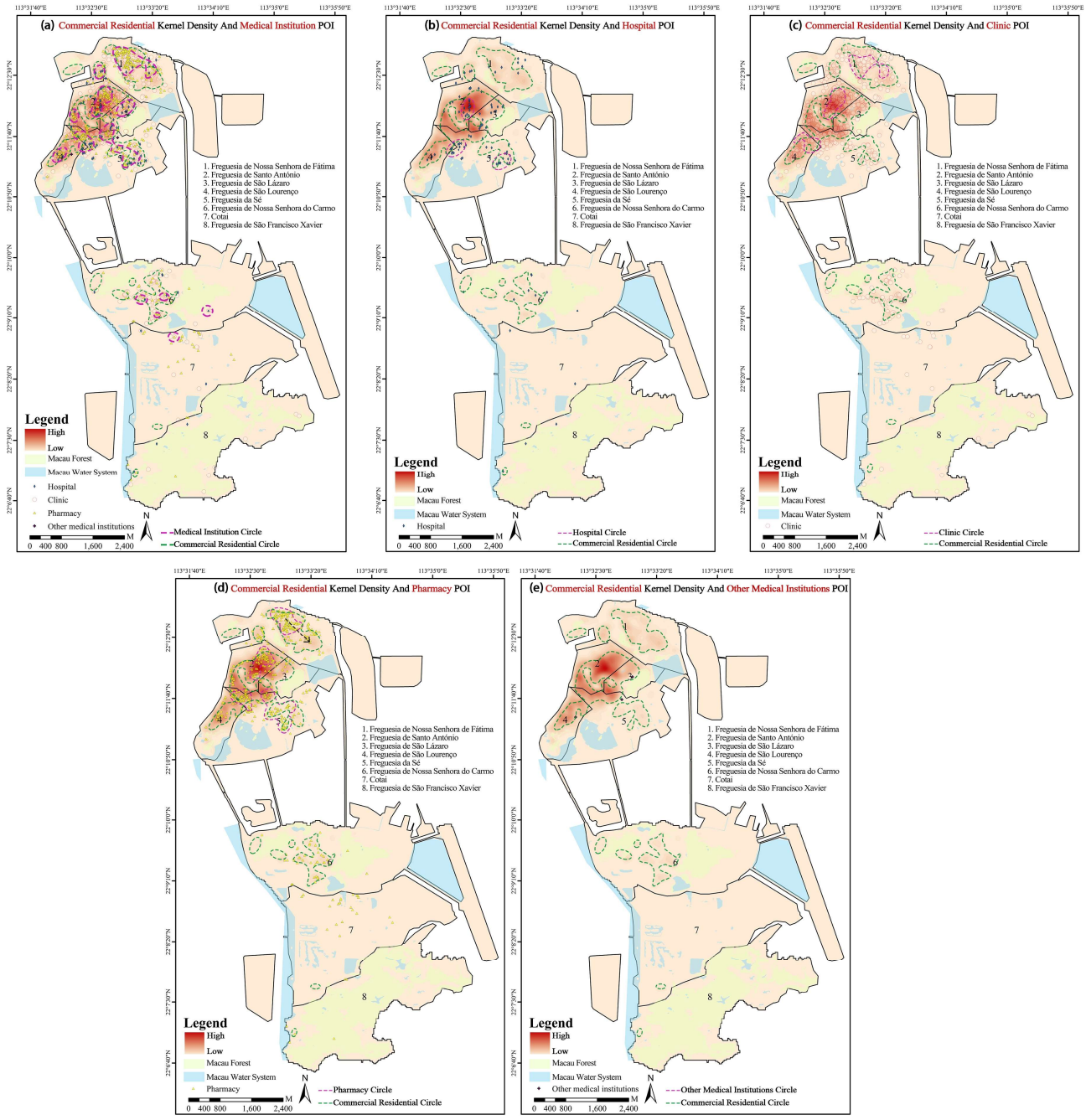


Figure 8. The results of the superimposed distribution of residential core density and medical healthcare facilities POI in Macau: (**a**) Overall POI distribution of medical healthcare facilities; (**b**) POI distribution of hospitals; (**c**) POI distribution of clinics; (**d**) POI distribution of pharmacies; (**e**) POI distribution of other medical healthcare facilities. The color gradation represents the density of residential buildings, the darker the color, the higher the degree of concentration, and vice versa. Please note that in Macau, many shops are located on the ground floor of residential buildings, while the upper floors are for residents. (Image source: drawn by the authors).

3.2.2. Kernel Density of Healthcare System Hierarchical Types

(1) Residential and Hospital POIs

Macau exhibits a significant service space mismatch between residential and hospital POIs (Figure 8b). Residential buildings are mainly concentrated in the old city area in the central part of the Macau Peninsula, forming a high-density cluster at the northern border of Freguesia de Santo António and Freguesia da Sé. However, there are almost no hospitals in the surrounding area, resulting in a severe lack of medical services. Residents need to travel across districts to seek medical treatment, leading to a low service matching degree. In contrast, the four Freguesia border areas of Freguesia de Santo António, Freguesia de São Lázaro, Freguesia de São Lourenço, and Freguesia da Sé have relatively concentrated hospital POIs, which are better coupled with the residential distribution and have better service balance. Although Freguesia de Nossa Senhora de Fátima and Freguesia de Nossa Senhora do Carmo show a cluster of secondary business and residential buildings, the surrounding medical facilities are scattered, and it is difficult to form an effective coverage within a 500 m service radius, limiting the convenience of medical treatment for residents. The Cotai Reclamation Area and the Freguesia de São Francisco Xavier lack significant residential clusters, and hospital points of interest (POIs) are extremely sparse. Although the Cotai Reclamation Area has the Macau Union Hospital, its spatial structure coupling is low due to insufficient public transportation, posing significant obstacles for residents seeking medical care, resulting in the worst overall service balance. Overall, Macau faces a prominent spatial mismatch between hospitals and residential functions, urgently requiring planning guidance and transportation optimization to improve the fairness and accessibility of public services.

(2) Residential and Clinics POIs

The service matching between clinics and residences is generally excellent (Figure 8c). In the Macau Peninsula, a concentrated distribution of clinics typically accompanies business and residential clusters, establishing a robust service support system. The types of clinics mainly include private clinics, integrated Chinese medicine clinics, private health care service venues, and health centers (Figure 6b mentioned above). However, although there is a significant cluster of residences in the western part of Freguesia de Nossa Senhora de Fátima, there is a lack of surrounding clinics, resulting in relatively insufficient convenience for residents to seek medical treatment. In contrast, Freguesia de Nossa Senhora do Carmo has better coordination in the distribution of the two types of facilities, achieving a more ideal service coverage. In contrast, the Cotai Reclamation Area and Freguesia de São Francisco Xavier have not formed a significant cluster of residences, and clinics are also scattered. The distribution of public service resources remains uneven, necessitating an improvement in service efficiency.

(3) Residential and Pharmacies POIs

Pharmacies are relatively evenly distributed but fewer in number than clinics, with differences between clustered areas and clinics (Figure 8d). Pharmacies primarily serve residents and are mainly concentrated in the northwestern edge of Freguesia da Sé (near the Ruins of St. Paul's) as well as in the Avenida de Horta e Costa and Avenida do Ouvidor Arriaga areas of Freguesia de Santo António. Freguesia de Nossa Senhora de Fátima also has significant pharmacy clusters near the border gate and to its southeast, serving both tourists and residents. While there is a clear residential cluster in the western area, there is a lack of pharmacies, making it difficult for residents to purchase medicines. The distribution pattern of pharmacies in Cotai and Freguesia de São Francisco Xavier is similar to that of clinics, but the number of pharmacies in Cotai exceeds that of clinics, which may be related to the large commercial clusters in the area attracting a large number of tourists. In contrast, pharmacies in the Freguesia de São Francisco Xavier are even scarcer, exist-

ing only sporadically. In particular, the northeastern region lacks any pharmacies, forcing residents to travel to other areas to purchase medicine, which is extremely inconvenient.

(4) Residential and Other Medical Healthcare Facilities POIs

Other medical healthcare facilities are highly concentrated and provide unevenly distributed services (Figure 8e). Kernel density calculations indicate that there is one other medical institution each in Freguesia da Sé, Freguesia de São Lázaro, and Freguesia de São Lourenço, while the rest of the freguesias are completely absent. This highly concentrated distribution pattern may be related to the special functional positioning of specialized medical services.

4. Analysis Results Overlaid with Road Network

4.1. Integration Analysis

Overlaying the POIs of medical system facilities with the road network, the integration analysis in Macau (Figure 9 and Table 3) reveals the following characteristics: (a) In the overall integration (Figure 9(1)), roads with high integration mainly run through tourist areas of the Macau Peninsula (such as around Nam Van Lake Square) and entertainment hubs of Cotai (such as around the Venetian). The three cross-sea bridges are all connected to each other, but the Amizade Bridge is the most connected. The roads in the medical institution clusters of the Macau Peninsula, Freguesia de Nossa Senhora do Carmo, and Cotai have good integration and high spatial structure coupling, facilitating timely medical services. However, Freguesia de São Francisco Xavier has weak spatial structure coupling due to the lack of medical institution clusters and low road integration, requiring patients to seek medical treatment in other areas. (b) In the local integration within a radius of 400 m (Figure 9(2)), the integration of all areas was generally low, with only Freguesia da Sé near Nam Van Lake, Freguesia de Santo António center, and Freguesia de Nossa Senhora de Fátima near the Border Gate being slightly higher, but the correlation between road accessibility and accessibility to healthcare facilities could not be effectively determined. (c) In the local integration within a radius of 800 m (Figure 9(3)), the integration of Freguesia on the Macau Peninsula was significantly improved except for Freguesia de São Lourenço. Road accessibility extended to residential areas, and the integration of medical institution clusters was good, which was beneficial for residents seeking medical treatment. The integration of Freguesia de Nossa Senhora do Carmo and Cotai improved, while Freguesia de São Francisco Xavier remained poor. (d) In the local integration of 1200 m and 1600 m radii (Figure 9(4,5)), there is no significant difference in integration between the two. Compared with the 400 m range, the integration of Freguesia de Santo António and Freguesia de São Lázaro (mainly concentrated in the Avenida de Horta e Costa area) is significantly improved. Other areas have also generally improved, but the integration of the three bridges is relatively low. In addition, there are few healthcare facilities on the outlying islands, so residents need to cross islands for medical treatment, and the efficiency is limited.

Table 3. Mean, minimum, and maximum values of integration results.

Integration	Mean	Minimum	Maximum
Global Integration	1591.24	5.45161	2273.79
R = 400	65.4374	4.57654	1600
R = 800	147.403	4.57654	594.581
R = 1200	243.197	5.45161	724.051
R = 1600	342.744	5.45161	1000.17

Source: Statistical analysis results compiled by the author based on space syntax analysis.

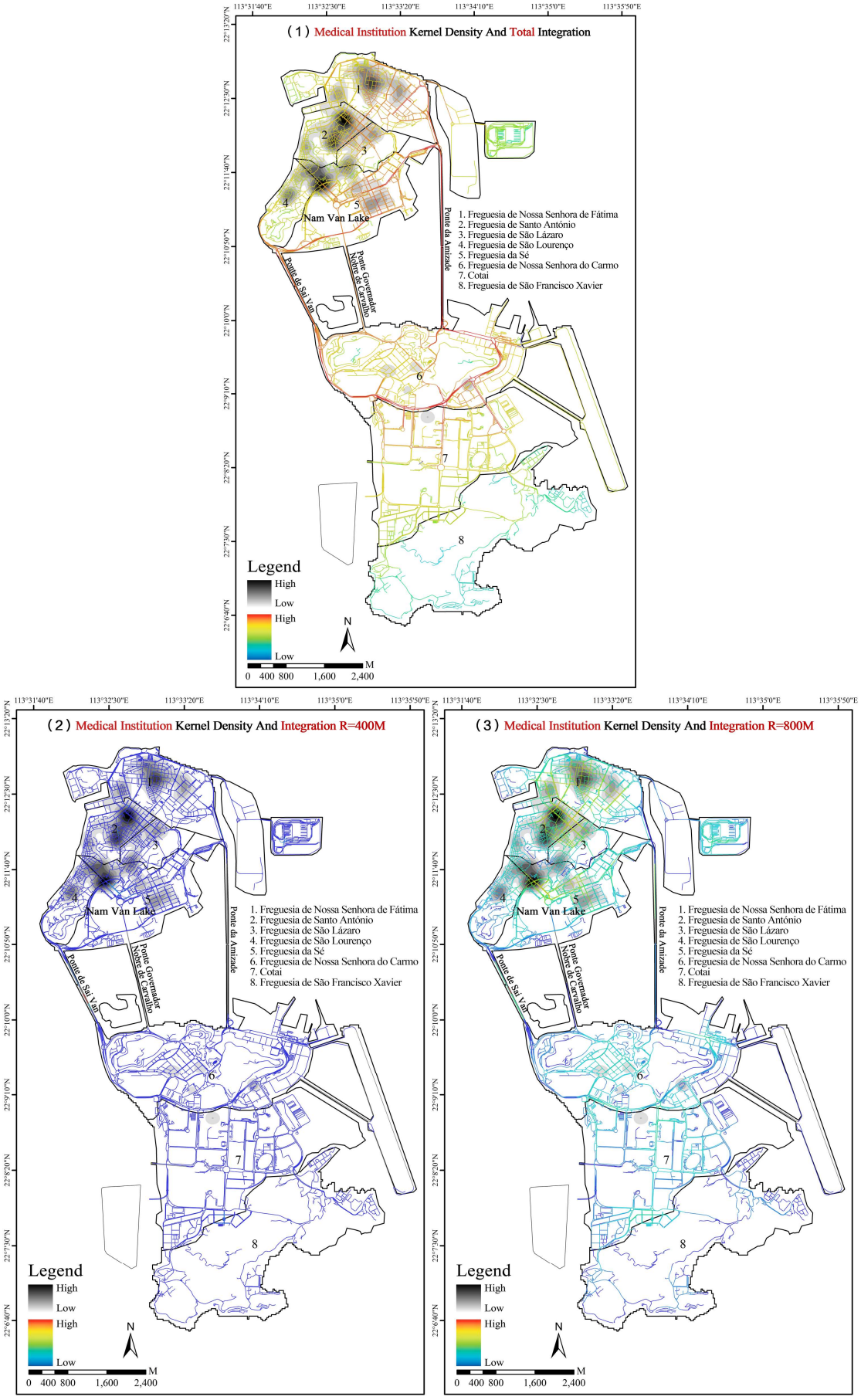


Figure 9. *Cont.*

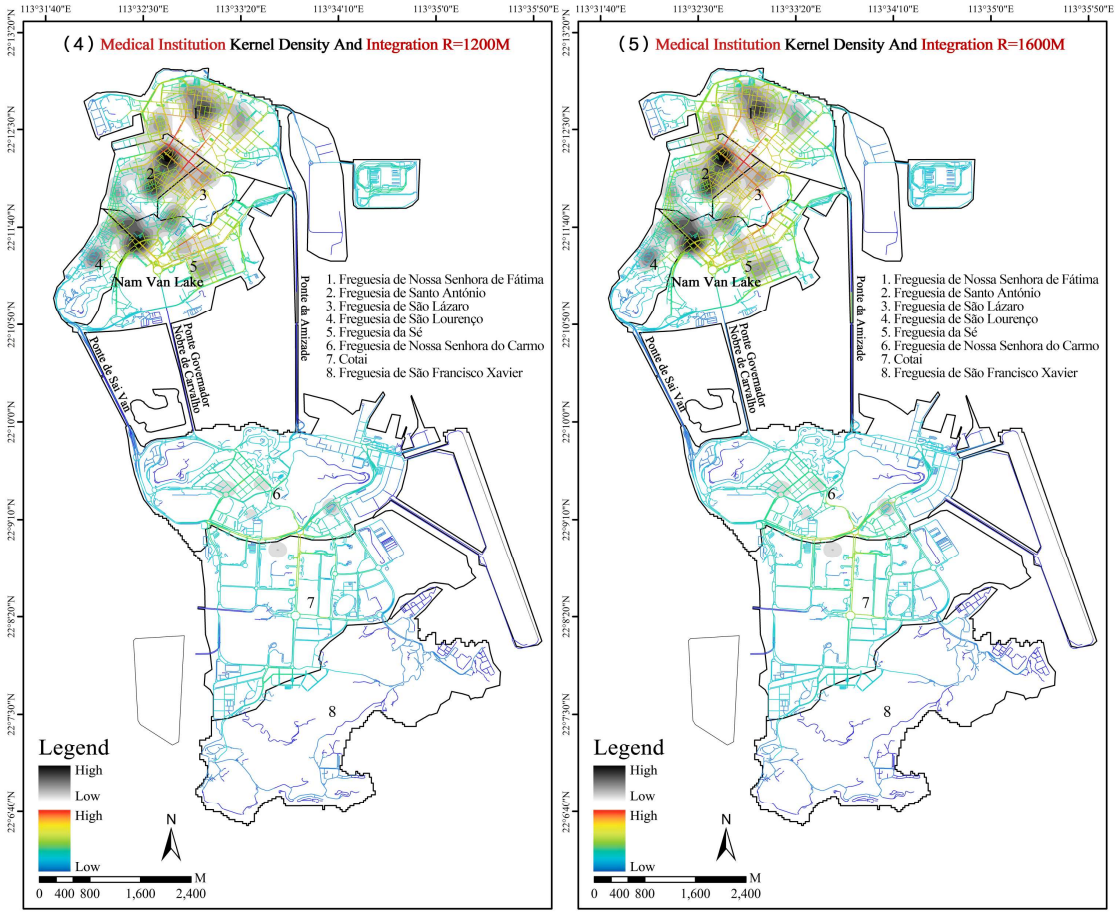


Figure 9. Analysis of the integration of kernel density and space syntax of healthcare facilities in Macau. In the legend, the black and white scale represents the density of healthcare facilities, with darker colors indicating a higher degree of aggregation; the rainbow scale represents space syntax values, with warm colors representing high values and cool colors representing low values. (**1**) Global integration; (**2**) R = 400; (**3**) R = 800; (**4**) R = 1200; (**5**) R = 1600. (Image source: drawn by the authors).

4.2. Choice Analysis

The choice analysis in Macau (Figure 10 and Table 4) reveals the following characteristics by overlaying the POIs of medical system facilities with the road network: (a) In the overall choice (Figure 10(1)), Ponte da Amizade has the highest choice, followed by Ponte de Sai Van and entertainment hubs in Cotai (such as the area around the Venetian). The remaining roads generally have fewer choices and limited throughput, making it less likely to cause traffic congestion in areas with a high concentration of medical facilities. (b) In the local choice within a 400 m radius (Figure 10(2)), the area with the highest choice is concentrated on the roads near Nam Van Lake in Freguesia da Sé. Only a few other Freguesia roads have higher choices, indicating weaker traversability in areas with a high concentration of medical facilities. (c) In the local choice with a radius of 800 m (Figure 10(3)), the choice of Freguesia da Sé spreads to the surrounding roads. The choice of some urban secondary arterial roads is significantly improved, becoming the main traffic arteries, while the choice of urban branch roads is generally low. Urban secondary arterial roads primarily guide the patients to the branch roads. (d) In the local choice with a radius of 1200 m and 1600 m (Figure 10(4,5)), there is no significant difference between the two. Both show that the choice of urban secondary arterial roads is further improved. The change in Avenida do Infante D. Henrique (near Nam Van Lake) is the most significant. It passes through the medical institution cluster center and disperses the traffic through urban branch roads.

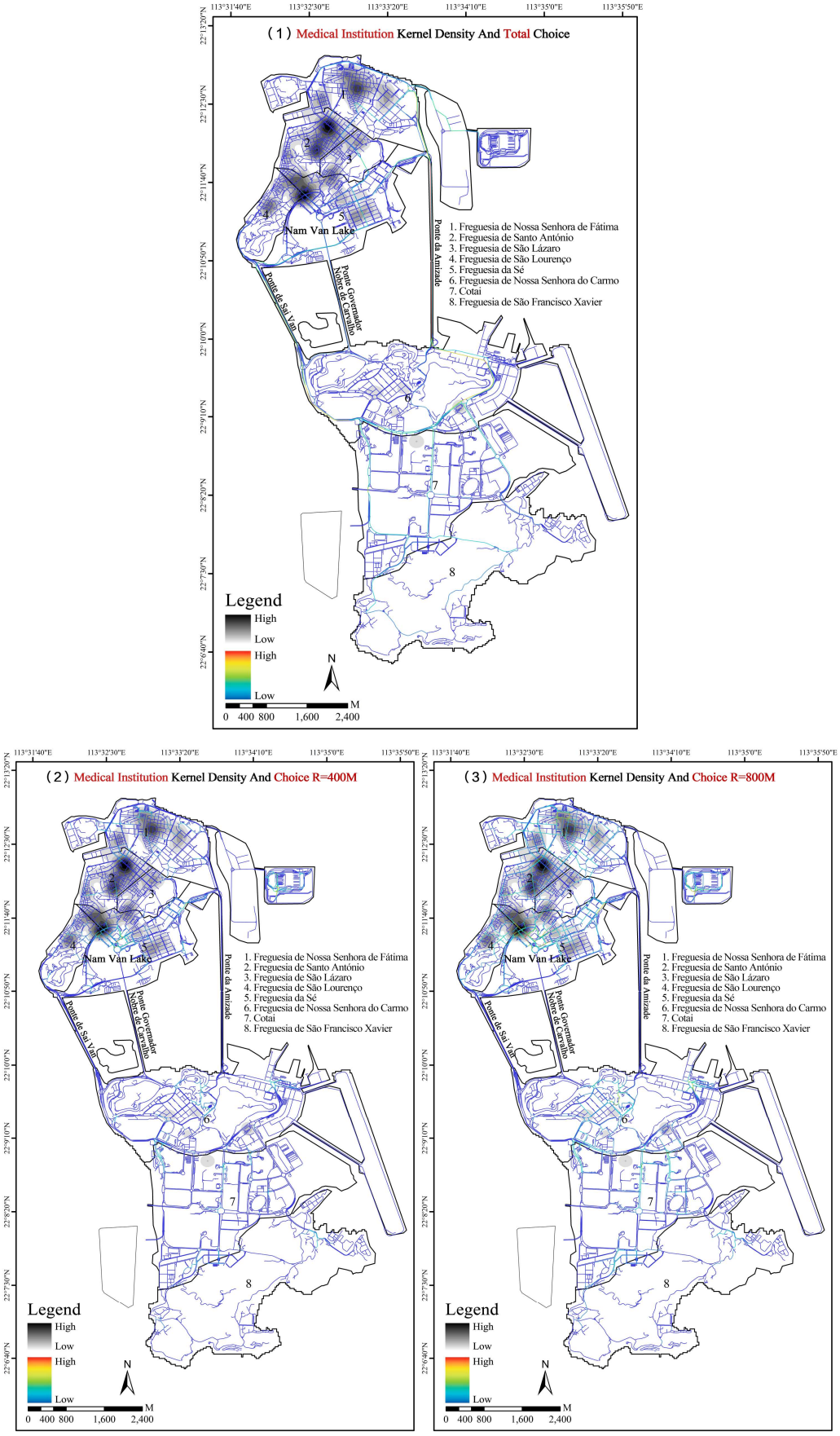


Figure 10. *Cont.*

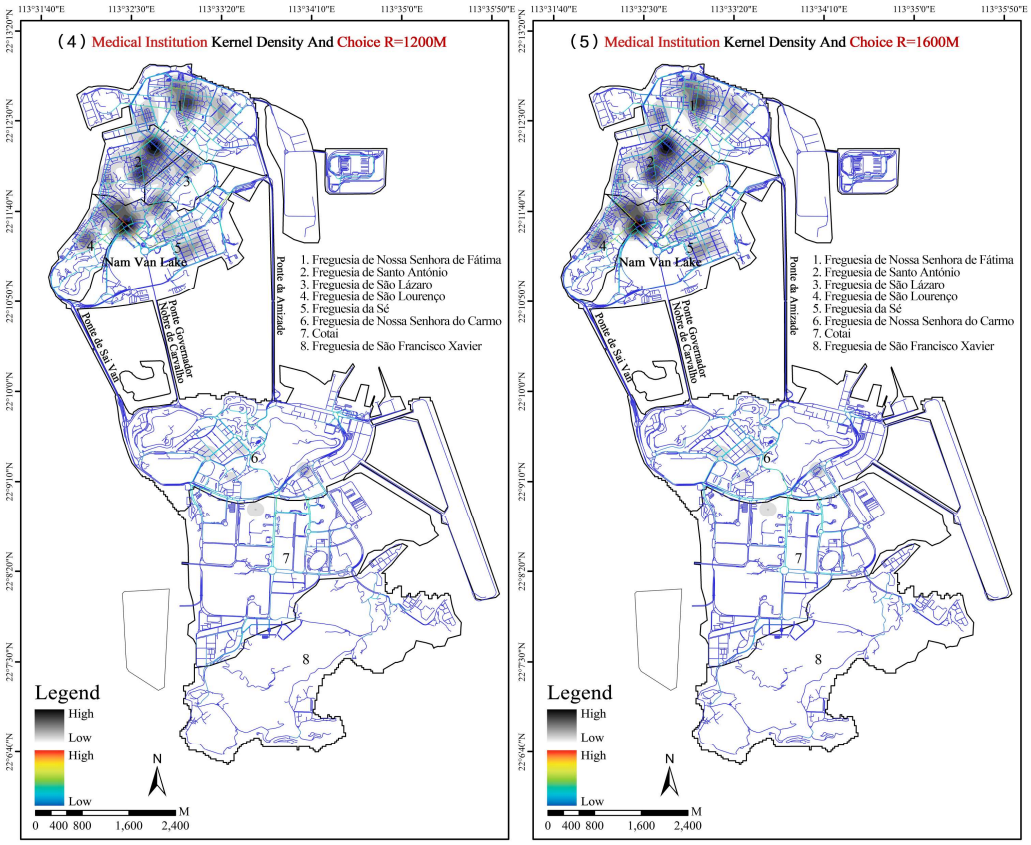


Figure 10. Analysis of the choice of kernel density and space syntax of medical healthcare facilities in Macau. In the legend, the black and white scale represents the density of medical healthcare facilities, with darker colors indicating a higher degree of aggregation; the rainbow scale represents space syntax values, with warm colors representing high values and cool colors representing low values. (**1**) Global choice; (**2**) R = 400; (**3**) R = 800; (**4**) R = 1200; (**5**) R = 1600. (Image source: drawn by the authors).

Table 4. Mean and maximum values of choice results.

Choice	Mean	Maximum
Global Choice	3,245,260	117,902,000
R = 400	3127.45	57,187
R = 800	15,602.2	213,305
R = 1200	40,889.4	636,666
R = 1600	80,044.5	1,483,880

Source: Statistical analysis results compiled by the author based on space syntax analysis.

4.3. Depth Analysis

The depth analysis in Macau (Figure 11 and Table 5) reveals the following characteristics by overlaying the POIs of medical system facilities with the road network: (a) In the global depth (Figure 11(1)), the road depth distribution is relatively uniform, with only the Freguesia de São Francisco Xavier having a higher depth value, indicating that Macau has strong overall connectivity, but the Coloane Island area has inconvenient transportation, which is not conducive to travel and medical treatment. (b) In the local depth within a radius of 400 m (Figure 11(2)), the road depth near Nam Van Lake in Freguesia da Sé is relatively large, and the depth of some urban branch roads in other areas is also relatively high, while the depth in other areas is generally low. (c) In the local depths with radii of 800 m, 1200 m, and 1600 m (Figure 11(3–5)), the local depth distribution tends to be

balanced, similar to the global depth results, and there is no significant difference in road depth throughout the entire area.

Table 5. Mean, minimum, and maximum values of depth results.

Depth	Mean	Minimum	Maximum
Global depth	673,471	0.332031	2,092,610
R = 400	1043.35	0	5460.6
R = 800	4725.03	0	16,455.8
R = 1200	11,670.7	0	41,864.2
R = 1600	21,891.1	0.0507813	67,165.6

Source: Statistical analysis results compiled by the author based on space syntax analysis.

4.4. Hierarchical Statistical Verification Based on Dual-Scale Space Syntax Index and Medical Facility Kernel Density

To rigorously verify the spatial coupling relationships revealed by the visualization overlay analysis, we further extracted road network space syntax indicators and medical facility kernel density analysis values and conducted dual-scale hierarchical quantitative statistics (see Table 6). However, in reality, due to the highly heterogeneous urban space and highly polarized spatial structure of Macau, traditional global linear models struggle to effectively capture its micro-spatial aggregation characteristics.

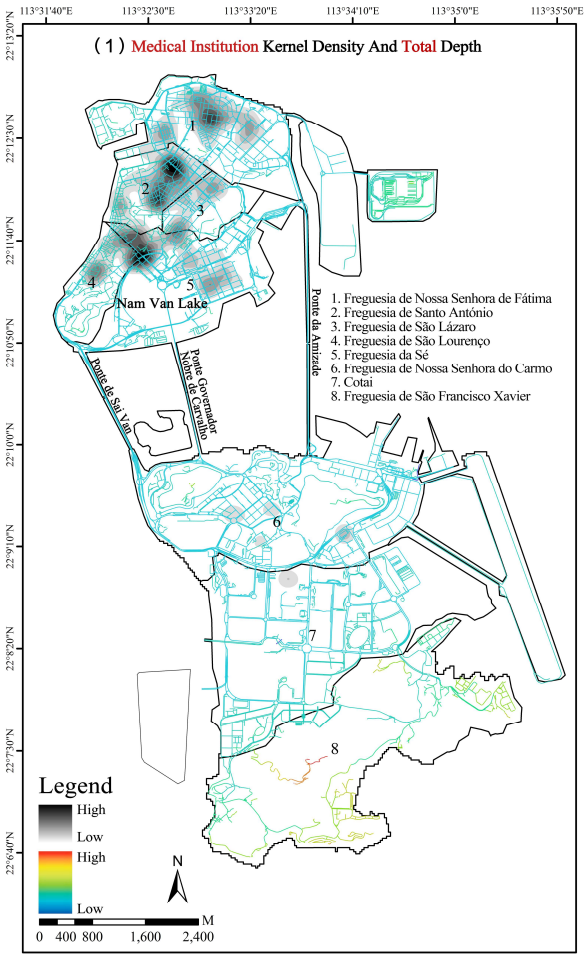


Figure 11. *Cont.*

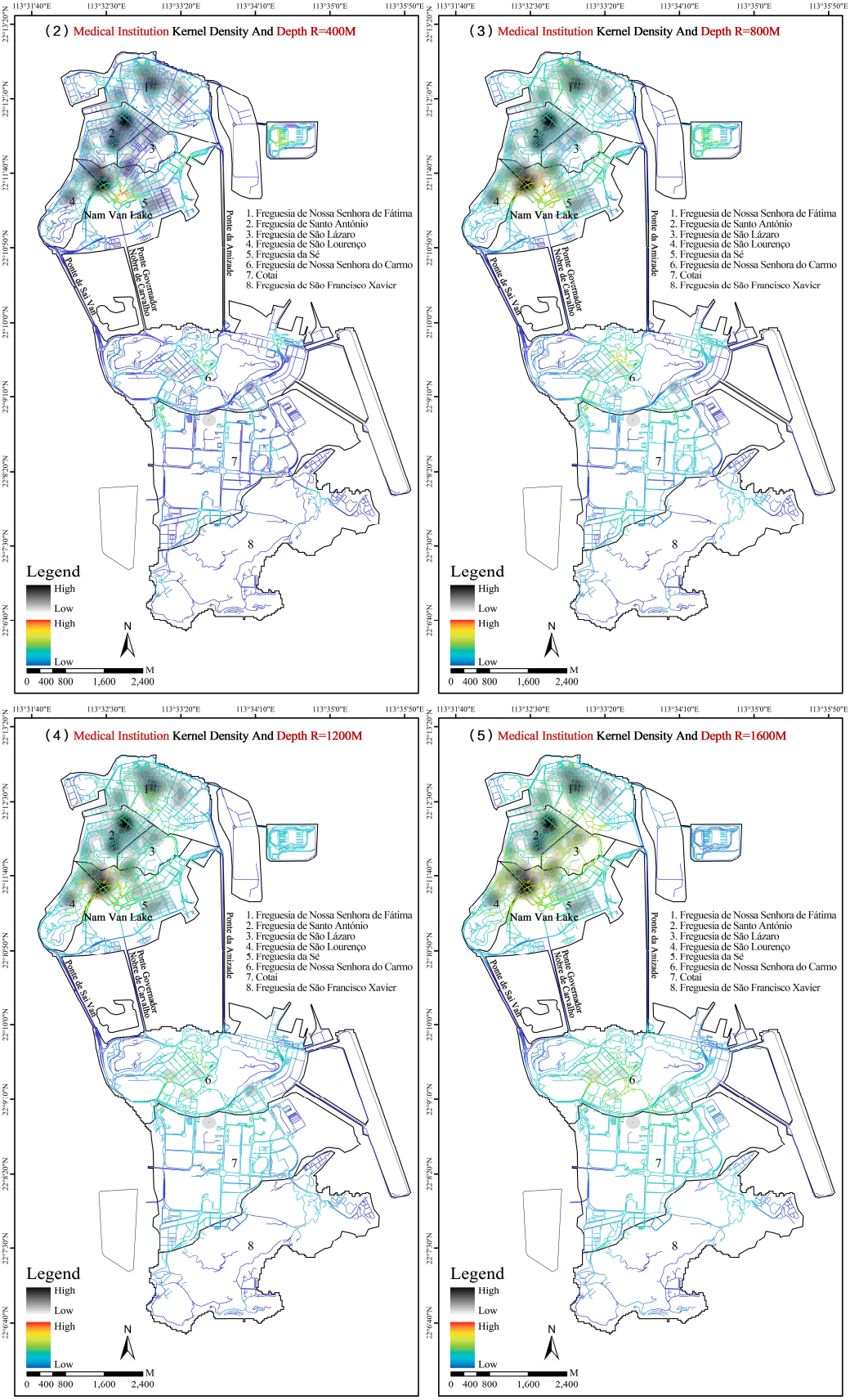


Figure 11. Analysis of the depth of kernel density and space syntax of medical healthcare facilities in Macau. In the legend, the black and white scale represents the density of medical healthcare facilities,

with darker colors indicating a higher degree of aggregation; the rainbow scale represents space syntax values, with warm colors representing high values and cool colors representing low values. (**1**) Global depth; (**2**) R = 400; (**3**) R = 800; (**4**) R = 1200; (**5**) R = 1600. (Image source: drawn by the authors).

Table 6. Statistics on the dual-scale integration range of Macau's road network and the average kernel density of medical facilities.

Analytical Scale	Topological Integration Range	Corresponding Road Segment Proportion	Average Kernel Density of Medical Facilities	Explanation of Spatial Coupling Patterns and Site Selection Characteristics
Local scale (r = 800 m)	Low integration blind zone (<100.66)	20%	487,741	Stepped Positive Agglomeration: At the end of transportation routes, medical accessibility is extremely poor on foot.
	Medium integration transition zone (100.66–251.61)	60%	1,866,864	Regular community connectivity networks and medical services are distributed in a secondary distribution zone.
	High integration core zone (>251.66)	20%	4,510,183	The core pedestrian framework of the community living circle shows extremely high polarization in medical resources.
Global scale (overall connectivity)	Low integration blind zone (<1501.79)	20%	977,962	Inverted U-shaped Secondary Network Agglomeration: On the city's edge or in dead ends, resources are scarce.
	Optimal cluster area (1501.84–1858.82)	60%	2,654,118	Urban secondary road networks, highly compatible with medical facilities, accommodate both vehicular and pedestrian access.
	Highly integrated main road (>1858.83)	20%	1,658,421	Urban main arteries, constrained by fast traffic and high rents, show decreased density.

Source: Statistical analysis results compiled by the author.

The hierarchical interval statistical results objectively reveal two distinct deep spatial coupling mechanisms: at the local scale (r = 800 m), medical facilities exhibit significant step-like positive coupling characteristics (Supplementary Materials Table S4). The top 20% of highly accessible road networks with the highest local integration have a mean medical facility kernel density of 4,510,183, which is 9.2 times that of the bottom 20% of low-integration road networks, directly confirming the high dependence of medical service site selection on high walkability. At a global macro scale, the coupling relationship between the two exhibits a non-linear inverted U-shaped characteristic (Supplementary Materials Table S5). Medical facilities actively avoid the top 20% of urban arterial roads with the highest global accessibility, precisely clustering in the central 60% of the secondary road network area, corresponding to a peak kernel density of 2,654,118.

These dual-scale quantitative analysis results provide objective and sufficient empirical evidence for the close coupling relationship between Macau's medical facility network and spatial topology, effectively compensating for the limitations of purely visual qualitative analysis.

5. Discussion

5.1. Characteristics of the Distribution of Facilities in Macau's Medical System

From a developmental perspective, Macau's medical facilities and resource allocation system are not an isolated combination of public service nodes but a key subsystem of the city's complex social system. Its operation and evolution are deeply embedded in the core

dimensions of urban economic, spatial, and population development. In terms of system composition, this system encompasses different levels of medical facilities (general hospitals and community health centers), resource elements (medical personnel, equipment, and funding), service recipients (residents of all ages and the floating population), and management mechanisms (health policies and resource allocation rules). These elements are interconnected and mutually restrictive, forming an organic whole with a complete closed loop of "supply-transmission-consumption-feedback." From a system function perspective, this medical subsystem bears the core function of protecting residents' health rights and maintaining social stability. The balance of its spatial distribution directly affects the fairness and sustainability of the urban social system. For example, the over-saturation of medical resources on the Macau Peninsula and the scarcity of resources on Coloane Island are essentially manifestations of an imbalance within the medical subsystem. This imbalance, in turn, affects other aspects of the social system, such as urban population flow and regional development disparities. From a systemic perspective, Macau's medical resource system combines the complexity and dynamism of a social system: it adjusts with urban spatial expansion (such as the development of the Cotai reclamation area), optimizes changes in population structure (such as aging and tourist growth), and is restructured with policy guidance (such as equalization of public services). It is a typical subsystem that coexists and prospers with the urban social system.

The spatial differentiation of medical resources in Macau is essentially a result of historical path dependence and the dynamic evolution of the social system (Figure 12). As the core development area under Portuguese rule for over four centuries, the Macau Peninsula has accumulated a mature urban fabric and a high-density population, accounting for approximately 80.6% of the total population [35]. In particular, the old town areas such as Freguesia de Santo António and Freguesia da Sé have long served administrative, commercial, and residential functions, triggering a magnetic effect on medical resources and forming a self-reinforcing cycle of resource accumulation. The outlying islands (Taipa and Coloane), on the other hand, have only been developed through land reclamation in the last thirty years. This means that medical facilities are not keeping up with the growth of cities. This situation has led to a cycle of historical inertia, where the Macau Peninsula continuously absorbs new resources through self-reinforcement, while the outlying islands, due to differences in development timing, remain at a low density in terms of healthcare facilities.

5.2. Imbalance in the Hierarchical Service Structure of the Medical System

The hierarchical "core-periphery" characteristic of the spatial layout of healthcare facilities in Macau constrains their service balance. (1) Resource density gradient: There are about 8.2 times as many medical facilities per square mile on the Macau Peninsula as there are on the outlying islands. However, the service pressure is not directly related to population density [25], and some older urban areas, like Freguesia de Nossa Senhora de Fátima, are overcrowded. (2) Lack of functional division: The Macau Peninsula is dominated by comprehensive hospitals (such as Centro Hospitalar Conde de São Januário), while the outlying islands rely on primary health centers. The lack of specialized services forces residents to seek medical treatment across districts, exacerbating the vulnerability of the system. (3) Lack of feedback mechanism: The current medical planning fails to dynamically respond to the population growth of new towns on the outlying islands (such as Cotai), and the system's self-regulation capacity is insufficient.

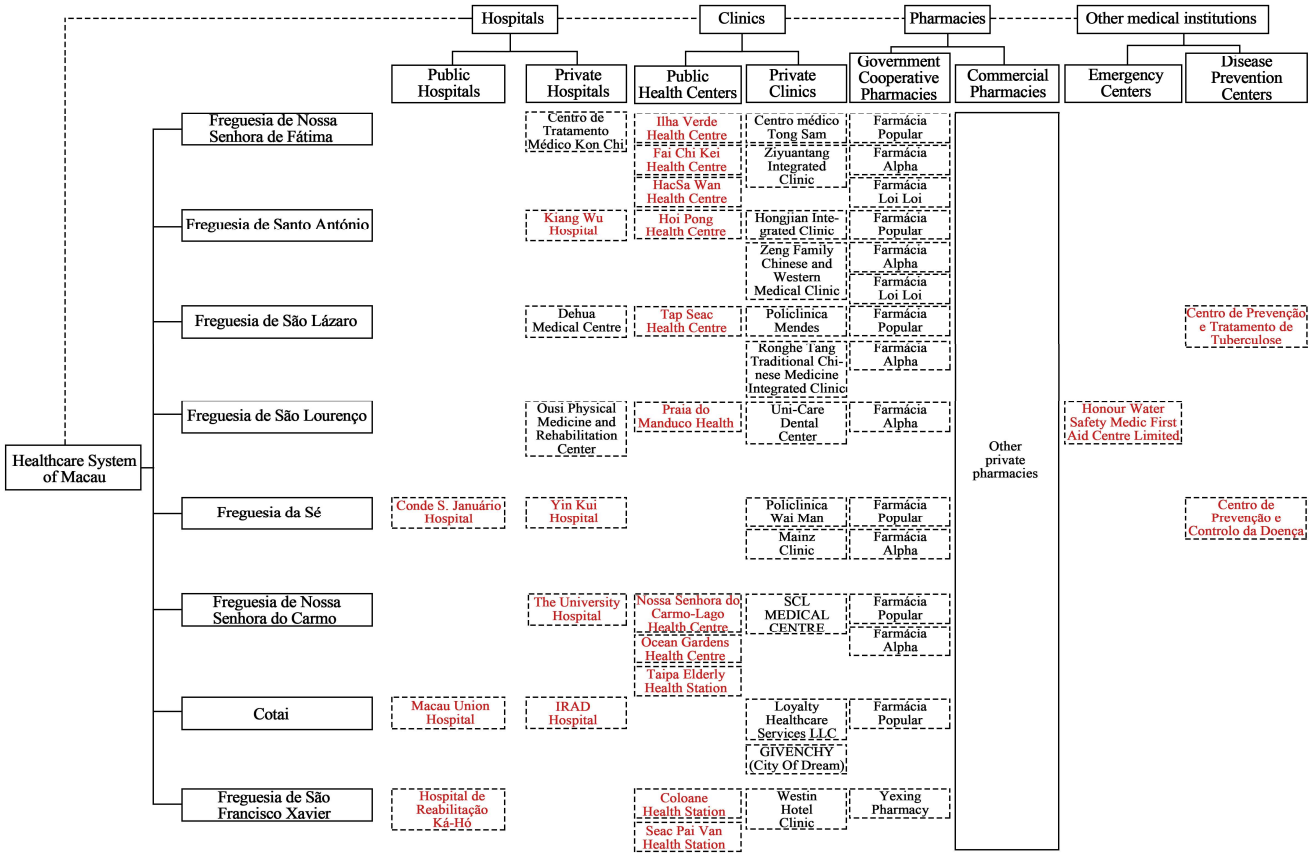


Figure 12. Macau's medical institution system. (Image source: drawn by the authors).

5.3. Spatial Coupling Characteristics of Healthcare Facilities and Road Network Structure

Spatial coupling analysis of facilities and road network structure in Macau's healthcare system reveals significant spatial differentiation and hierarchical characteristics. Highly integrated roads (such as Ponte da Amizade and the area around Nam Van Lake) highly overlap with areas with concentrated medical resources (Freguesia da Sé and Freguesia de Nossa Senhora do Carmo), forming efficient medical corridors. Conversely, low-integration areas (such as Freguesia de São Francisco Xavier) suffer from both isolated road networks and lack of medical facilities, forcing residents to seek medical care across districts. Further analysis of local integration shows that medical spatial structure coupling is highly sensitive to spatial scale; for example, road network connectivity in the core area of the Macau Peninsula improves significantly within an 800 m radius. However, the outlying islands, relying on a single, highly selective bridge (Ponte da Amizade) for cross-sea transportation, still exhibit structural vulnerabilities. Furthermore, the hierarchical differentiation of the road network leads to insufficient capillary function of branch roads, especially in areas with higher local depth such as Nam Van Lake, limiting the efficiency of short-distance medical care. Behind this phenomenon lies the dual influence of historical planning and functional orientation: the Macau Peninsula, relying on its grid-like road network and high-density development, has formed a coordinated medical and transportation system. In contrast, the outlying islands, due to later land reclamation and development, have sparse road networks that are disconnected from medical facilities. Coupled with topographical limitations (such as Coloane Island), their overall spatial structure coupling varies significantly, exacerbating the spatial imbalance.

5.4. Spatial Optimization Strategies and Regional Coordinated Development

5.4.1. Precise Supplementation of Community Healthcare Facilities Based on Syntactic Parameters

For the service blind spots in healthcare resources identified in the analysis, a minimally invasive implantation strategy is recommended. Space syntax analysis in this study shows that while residential areas in the northern part of the Freguesia de Nossa Senhora de Fátima in Macau Peninsula and Coloane Island have a certain population density, the integration and choice of healthcare facilities are both low. It is recommended to add 3–5 community health centers or private clinics to these low-integration areas, utilizing vacant commercial podiums or reserved spaces in government-owned housing. Specific site selection should prioritize street nodes with high overall integration but low local depth. For example, adding a station on Rua da Ilha Verde (青洲上街) could effectively fill the healthcare gap within a 15 min walk, alleviate the outpatient pressure on large general hospitals, and achieve the spatial foundation for "minor illnesses treated within the community."

5.4.2. Traffic Organization and Tiered Guidance Matching Medical Service Levels

Traffic optimization should not be limited to alleviating single congestion points but should establish a traffic guidance system commensurate with the level of the hospital.

- For general hospitals (such as Conde de São Januário Hospital): These facilities serve the entire Macau area, and the focus should be on optimizing their connection efficiency with high-selectivity routes along main urban roads. It is recommended to establish dedicated express lanes for medical treatment, for example, implementing dynamic traffic control on Avenida do Dr. Rodrigo Rodrigues (羅理基博士大馬路), and strengthening connections with public transport hubs will guide patients seeking medical care across districts to use public transport.
- For community clinics: These facilities rely on pedestrian accessibility. It is recommended to improve the surrounding pedestrian and cycling infrastructure, connect dead-end roads, and enhance the topological connectivity of the street network to ensure residents can reach them through a highly integrated pedestrian network.

5.4.3. Integrating into the Greater Bay Area's Cross-Regional Medical Resource Sharing

As a crucial node in the Guangdong-Hong Kong-Macau Greater Bay Area, it is also recommended that Macau actively expand its medical cooperation with Hengqin, Zhuhai. It is suggested that the Guangdong-Macau In-Depth Cooperation Zone in Hengqin (横琴粵澳深度合作區) serve as its hinterland and that policies be implemented to encourage Macau residents to seek medical treatment in areas with well-developed medical facilities, such as Hengqin and Zhuhai. Hengqin's vast spatial resources should be utilized to construct health and wellness bases or specialized medical centers, alleviating space congestion on Macau Island and promoting mutual recognition of electronic medical records and interconnection of emergency medical channels between the two places. It is further recommended to establish a cross-border medical green channel between the Lotus Port and the Hengqin Port, enabling rapid transfer of critically ill patients from Macau's densely populated urban areas to high-level healthcare facilities in Hengqin, thus constructing a new regional medical service pattern of "Macau initial diagnosis + Hengqin health and wellness" or "two-way referral between the two places" (Figures 13 and 14).

5.5. Limitations and Future Prospects

While this study, combining kernel density analysis and space syntax, revealed the distribution patterns of medical resources in Macau, certain limitations remain and require further refinement in future research.

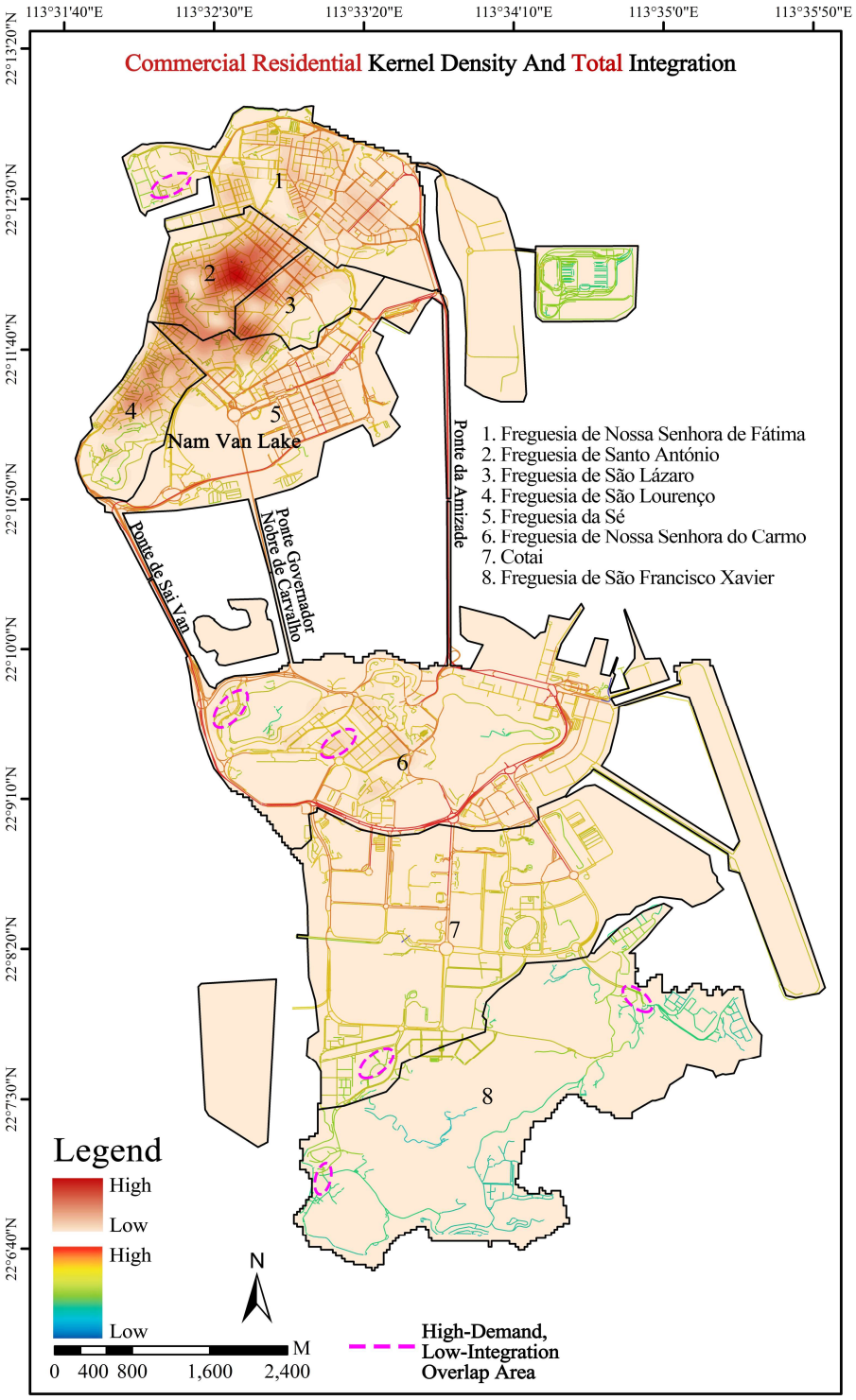


Figure 13. Analysis of the "high demand-low integration" pattern of medical resources in Macau. The red color gradation represents the density of commercial and residential areas; darker colors indicate higher concentration, and vice versa. Rainbow color gradation represents spatial syntax values; warm colors represent high values, and cool colors represent low values. (Image source: drawn by the authors).

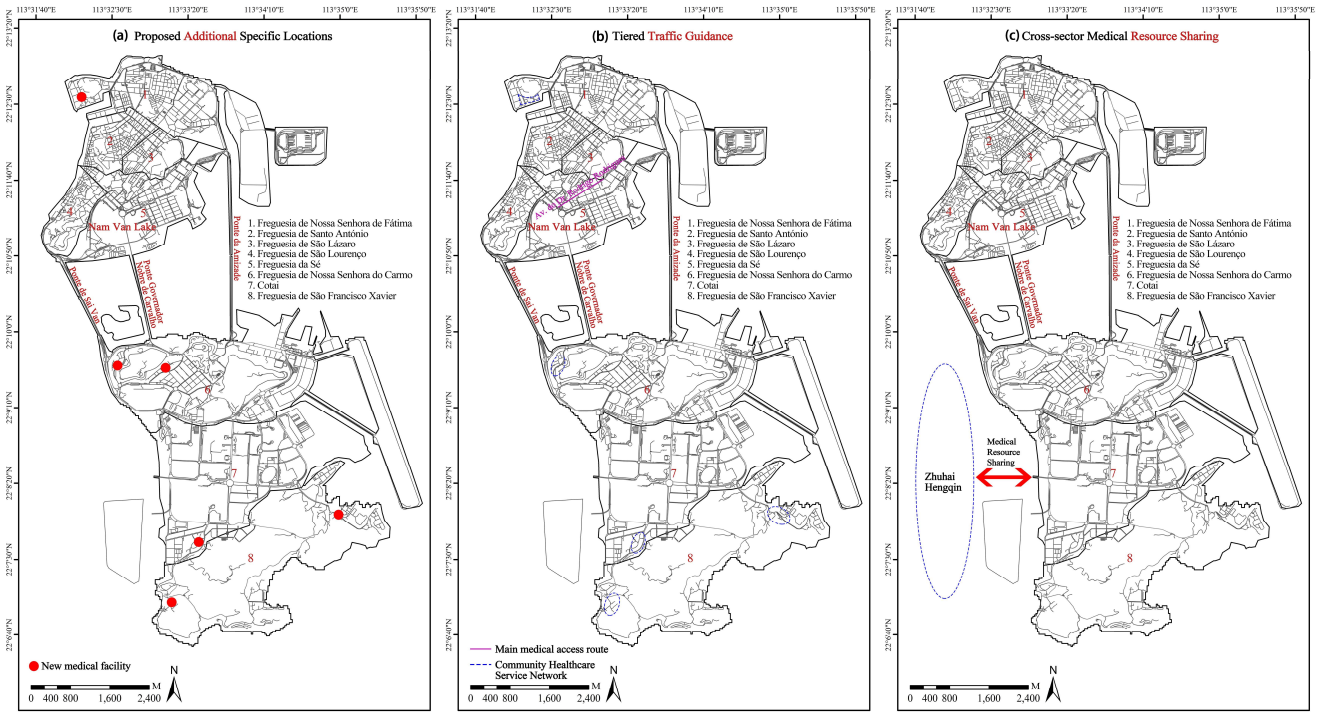


Figure 14. Space optimization and medical facility layout strategies. (**a**) Specific locations of new community medical facilities; (**b**) Tiered traffic guidance; (**c**) Cross-border medical resource sharing. (Image source: drawn by the authors).

First, it still has room for improvement in refining the measurement of supply and demand matching. While GIS kernel density analysis can visually present the spatial clustering characteristics of medical facilities, it is essentially a static descriptive analysis. Current POI statistics treat all spatial points equally, failing to reflect key differences in actual service capacity (e.g., hospital beds, number of doctors, opening hours) or real dynamic demand (e.g., morbidity rate, tourist influx). Therefore, simply having high-density POI represents spatial clustering, not absolute service saturation or efficiency loss. Similarly, sparse areas indicate spatial dispersion, not absolute scarcity of medical resources. Furthermore, due to data limitations, it has not fully considered the heterogeneity of population age structure (e.g., aging rate) and specialist medical demand, and the residential POIs used are not perfect population proxies, failing to reflect the true total resident population. Macau's unique geographical structure makes cross-sea transportation a key variable affecting accessibility; it failed to comprehensively simulate the dynamic constraints of cross-sea bridge congestion at different times (e.g., morning and evening rush hours) on the medical treatment behavior of island residents.

Secondly, there is a logical gap between spatial configuration analysis and complex real-world behavior. Spatial syntax mainly derives the spatial potential energy of human movement based on the topological logic of road networks. However, in real-world scenarios, residents' choices of medical treatment routes are influenced by multiple factors such as real-time traffic flow, vehicle driving patterns, and public transportation coverage. Static spatial skeleton analysis alone cannot fully recreate the complex real-world medical decision-making process.

Therefore, future research will expand in the following three aspects:

(1) Introducing big multi-source data to construct a dynamic accessibility model. For example, it is proposed to integrate mobile signaling data, LBS (Location-Based Services) big data, and real-time traffic heat maps to verify existing spatial syntax models. By combining the spatial potential of street networks with the actual load of population

movement, a dynamic accessibility assessment system covering peak and off-peak periods will be constructed, providing more timely data support for the accurate allocation of medical resources.

(2) Deepening algorithm models and fairness evaluation. Due to the current lack of detailed scale and business data for a large number of private clinics and pharmacies in Macau, it has not yet implemented a weighted scheme. To overcome this limitation, future research needs to establish an evaluation system weighted by service capacity, including weighting by bed capacity and hospital level, weighting by specialty classification for clinics, and ranking and weighting by size and operating hours for pharmacies. Based on the established weighted database, an improved two-step floating coverage method (2SFCA) should be introduced, combined with the Gini coefficient or Theil index, to deeply assess the social equity of medical resource allocation from the perspective of the true supply-demand ratio. Such an approach will help identify hidden service blind spots that, while having spatial facility coverage, are at a disadvantage in per capita service availability.

(3) Exploring regional collaboration and multidimensional influencing factors. Given Macau's compact urban characteristics and its status as a core node in the Greater Bay Area, future research needs to further explore the impact of socioeconomic factors such as cross-border medical treatment behavior, residents' education level, and income level on the efficiency of medical resource utilization. This cross-regional, multidimensional research perspective will provide a scientific basis for Macau to build a more resilient and inclusive urban medical planning system.

6. Conclusions

The spatial distribution of medical healthcare facilities in Macau is uneven, showing a significant "dense in the north and sparse in the south" pattern, and it is characterized by "dispersed-multi-center-uneven" features. (1) Overall, medical resources are highly concentrated in the Macau Peninsula, especially in the dense core area formed at the junction of Freguesia de Santo António, Freguesia de Nossa Senhora de Fátima, and Freguesia da Sé—Freguesia de São Lourenço. The area at the intersection of Freguesia da Sé and Freguesia de São Lourenço forms the highest density core, radiating outwards to administrative and commercial centers. The islands of Freguesia de Nossa Senhora do Carmo, Cotai, and Freguesia de São Francisco Xavier in Coloane are scattered and have a low density. (2) In terms of type, hospitals exhibit a "single-center-spreading" pattern, with the core located in the Freguesia da Sé—Freguesia de São Lourenço area. However, large facilities such as the Conde de São Januário Hospital are not clustered due to land constraints. Clinics (accounting for 61.85% of the total) and pharmacies form a multi-axis network, such as the high-density axis of clinics in the Freguesia da Sé—Freguesia de Santo António area and the pharmacy cluster in the "Ruins of St. Paul's—Border Gate" area. The Macau Peninsula's core area completely concentrates on special healthcare facilities like disease control centers and emergency centers.

Furthermore, it found that the balance of service facilities in Macau's medical system exhibits a three-tiered gradient. (1) The high-balance area is concentrated in the central part of the Macau Peninsula (Freguesia de Santo António, Freguesia de São Lázaro, northern Freguesia da Sé, and central Freguesia de São Lourenço), where high-density commercial and residential areas highly overlap with medical points such as clinics and pharmacies, forming an integrated "residence-medical" network. For example, Freguesia de Santo António has the best matching degree between medical resources and residential density. (2) The medium-balance area includes the northern part of the Macau Peninsula (Freguesia de Nossa Senhora de Fátima) and the central part of the Cotai reclamation area. The former has a slightly lower medical density than the residential demand, while the latter

has scattered medical points, but the service radius of 500 m is insufficient. (3) The low-balance area covers most of the outlying islands (the outer areas of Coloane and Taipa), presenting a "double low pattern": a double shortage of residential and medical resources. For example, Coloane relies solely on Hospital de Reabilitação Ká-Hó, resulting in a lack of pharmacies like Freguesia de São Francisco Xavier, forcing residents to travel to other districts to purchase medications. There is also a spatial mismatch. For example, there are no large hospitals in the densely populated northern residential area of Freguesia de Santo António, and the Macau Union Hospital in the Cotai reclamation area is difficult to reach due to insufficient transportation facilities.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijgi15030126/s1, Supplementary Materials Table S1 is healthcare services POIs data; Supplementary Materials Table S2 is commercial and residential POIs data; Supplementary Materials Table S3 is Macau Road Network DXF Vector Data; Supplementary Materials Table S4 is r = 800 result; Supplementary Materials Table S5 is r = n result.

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