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Research on a Model for Allocating Medical Resources to Lower-Level Facilities by Integrating GIS and Multi-Agent Systems

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Abstract: *The unbalanced distribution of medical resources restricts the improvement of primary medical service capabilities. Traditional strategies for allocating resources to lower-level facilities lack precise spatial analysis and intelligent decision support. This study constructs a model for allocating medical resources to lower-level facilities that integrates GIS spatial analysis technology and multi-agent simulation modeling. Taking Jinan City as the research area, kernel density analysis is adopted to identify the spatial agglomeration characteristics of medical resources, and network accessibility evaluation is applied to quantify the differences in service coverage. A multi-agent simulation system is established to simulate the process of resource allocation to lower-level facilities, and a GIS-agent coupling framework is designed to achieve in-depth integration. Experimental results show that this integrated model significantly improves the precision of allocated resources to lower-level facilities and enhances the coverage of primary medical services, providing effective technical support for the targeted allocation of medical resources.*

Keywords: *Allocating Medical Resources to Lower-Level Facilities; Geographic Information System (GIS); Multi-Agent System (MAS); Spatial Agglomeration; Resource Allocation Optimization*

1. Introduction

The unbalanced allocation of medical resources restricts the high-quality development of the medical and health industry. High-quality medical resources are excessively concentrated in large urban hospitals, while the service capacity of primary medical institutions remains weak, resulting in the structural contradiction of "difficult and expensive medical care". Geographic Information System (GIS) can accurately identify the distribution characteristics of resources and blind spots in service coverage, and multi-agent modeling technology is capable of simulating complex resource allocation processes. Existing studies are mostly confined to the application of a single technology, lacking in-depth integration of these two technologies. Constructing a model for allocating medical resources to lower-level facilities that combines GIS spatial analysis and multi-agent simulation, with Jinan City as the empirical research area, is of great significance for improving the scientificity of regional medical resource allocation.

2. Analysis of the Spatial Distribution Characteristics of Medical Resources

2.1 Evaluation of the Spatial Agglomeration Degree of Medical Resources

Medical resources in Jinan City exhibit a highly concentrated spatial layout, with varying degrees of agglomeration among medical institutions at different levels. Class III Grade A hospitals show the most prominent agglomeration, mainly concentrated in the bustling areas of Lixia District and Shizhong District [1], forming core regions with highly intensive resources. Specialized hospitals demonstrate a medium-scale agglomeration pattern. Relying on general hospitals, they form secondary agglomeration centers and are densely distributed in areas such as Huaiyin District and Tianqiao District. Although primary medical institutions are extremely large in quantity, their agglomeration degree is relatively low. Despite being distributed across all regions, there are significant differences in their density. The distribution of medical resources presents distinct hierarchical characteristics, and the concentration of high-level medical institutions in central urban areas is particularly notable. This agglomeration pattern reflects the spatial intensification characteristics and hierarchical distribution model of medical resource allocation in Jinan City, where the density of medical resources in central urban areas is

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significantly higher than that in peripheral regions.

2.2 Identification of Spatial Differences in Medical Service Accessibility

There are obvious gradient differences in the spatial distribution of medical services in Jinan City, with a significant gap in medical resource accessibility between central urban areas and peripheral regions. The core areas such as Lixia District and Shizhong District have the densest medical resources, and local residents spend relatively less time seeking medical treatment [2]. Suburban areas including Huaiyin District and Tianqiao District have convenient basic medical conditions, but residents still need a long time to access high-end medical services. Distant suburban areas like Changqing District and Zhangqiu District are relatively lacking in medical resources, and residents generally need to spend a considerable amount of time traveling to Class III Grade A hospitals. Rural areas and urban fringe zones have become weak links in medical service coverage. Restricted by factors such as traffic conditions and geographical distance, residents in these areas face great inconvenience in accessing medical services. Overall, the spatial distribution of medical services presents a typical concentric circle structure, where the accessibility of medical resources decreases as the distance from the city center increases.

2.3 Division of Regions with Imbalanced Supply and Demand of Medical Resources

There are significant disparities in the spatial allocation of medical resources in Jinan City, with an imbalance between medical resource allocation and population distribution across different regions. Medical facilities are relatively concentrated in areas such as the central part of Lixia District and the eastern part of Shizhong District, exceeding the actual medical needs of the local population. Most areas of Huaiyin District and Tianqiao District have a relatively balanced supply and demand of medical services, which can meet residents' basic medical needs. Peripheral districts and counties including Changqing District and Zhangqiu District are confronted with a shortage of medical resources, where the per capita possession of medical resources is lower than the municipal average. The contradiction between medical supply and demand in rural areas is particularly acute, characterized by a small number of medical institutions and weak service capabilities. On the whole, it presents a "core-periphery" distribution pattern, with medical resources highly concentrated in central urban areas and severely insufficient in peripheral regions. This phenomenon of medical resource mismatch is quite prominent.

3. Construction of the Model for Allocating Medical Resources to Lower-Level Facilities by Integrating GIS and Multi-Agent Systems

3.1 Spatial Network Evaluation Model for Medical Resource Allocation

This model converts the urban road network into standardized linear grid units and constructs a spatial analysis framework for medical resource allocation, thereby achieving refined spatial characterization of resource layout. The model adopts the following formula for calculating the network division length:

$$L_i = le \cdot f_1 \cdot f_2 \cdot ... f_j \tag{1}$$

In the formula, L_i denotes the division length of the i-th road; *le represents the initial division granularity;* f_j *is the weight of factor "j".* The weight factors include indicators such as road capacity, population density, and medical institution service capacity. The grid unit is set to 50 meters in core areas and expanded to 200 meters in peripheral areas. The model correlates service capacity parameters of medical institutions - such as the number of beds, the number of physicians, and equipment configuration - with corresponding network arcs, establishing an accurate mapping relationship between medical resources and spatial locations. The service radius of Class III Grade A hospitals is set at 2,000 meters, and the radiation range of primary medical institutions is determined to be 800 meters. By virtue of a comprehensive weight algorithm, various influencing factors are integrated into the network model, forming an evaluation network that incorporates medical resource density, service capacity, and transportation convenience. Network Voronoi diagrams are utilized to divide the service areas of each medical institution, providing spatial data support for resource allocation analysis.

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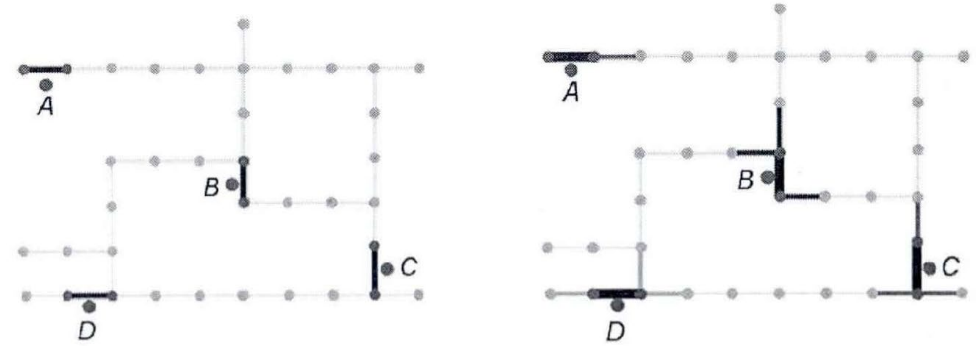
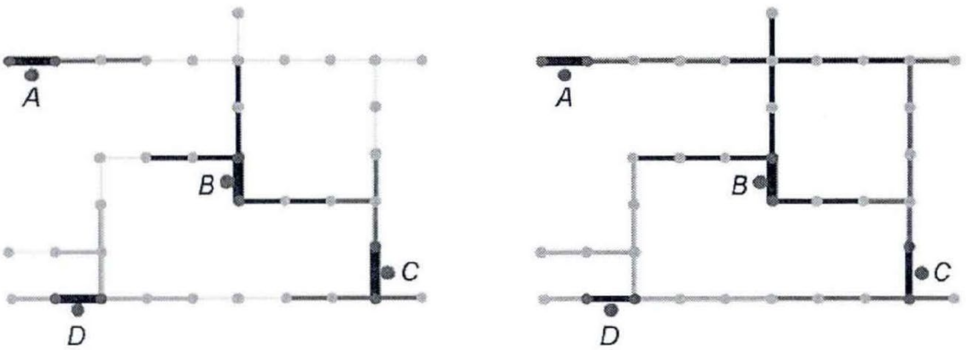
3.2 Multi-agent Simulation System for Allocating Medical Resources to Lower-level Facilities

With the multi-agent simulation system, a dynamic simulation platform for allocating medical resources to lower-level facilities is built, designed to evaluate the implementation effects of different strategies. In the system design, supply agents represent Class III Grade A hospitals, while demand agents stand for primary medical institutions, with the quantity ratio of the two types of agents roughly set at 1:8. The decision-making rules for agents are based on cost-benefit analysis. The costs of allocating medical resources to lower-level facilities include such elements as personnel assignment expenses, equipment configuration costs, and operation and maintenance costs. The simulation system sets the time step to three months and runs multiple cycles to simulate the resource sinking process. In each iteration, supply agents select the targets for resource sinking based on distance costs and the urgency of demand. Demand agents apply for corresponding resources according to service gaps. The system adopts a reinforcement learning algorithm to optimize the decision-making behaviors of agents, and generates the optimal resource allocation plan after multiple iterations. Figure 1 illustrates the generation process of the network Voronoi diagram, which includes four key steps: event point projection, outward expansion, intermediate state, and completion of expansion, providing technical support for the spatial division of the simulation system.



(a) Event points and corresponding grid units (b) Outward expansion by one step



(c) Intermediate expansion state (d) Completed expansion state

Figure 1 The Generation Process of the Network Voronoi Diagram

3.3 Coupling Framework of GIS Spatial Analysis and Agent Model

The coupling framework of GIS spatial analysis and agent model establishes a real-time interaction mechanism between spatial data and behavioral models, thereby realizing dynamic spatial modeling of the process of allocating medical resources to lower-level facilities. A bidirectional data interface is designed in the framework: the GIS module provides geographic information including the location of medical institutions, service scopes, and transportation networks, while the agent module outputs resource allocation decision results. Spatial constraints include factors such as geographical distance and travel time, which directly affect the decision-making of agents. The coupling mechanism adopts an event-driven approach. When agents make decisions on allocating medical resources to lower-level facilities, the GIS module is triggered to update the spatial configuration status. The framework integrates GIS functions such as network accessibility analysis and spatial overlay analysis to provide spatial decision support for agents. A synchronous update mechanism ensures consistency between changes in spatial status and agent behaviors, with the data update frequency set to once every 24 hours.

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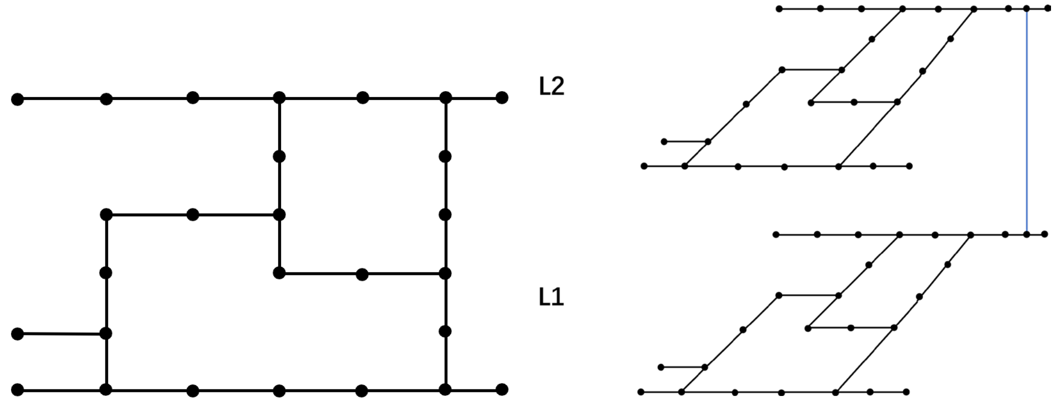
The multi-scale and multi-dimensional network division model illustrated in Figure 2 presents the spatial structure expansion from 2D plane to 3D solid, endowing the coupling framework with multi-level spatial expression capabilities and supporting refined modeling and analysis of complex medical networks.



(a) 2D Plane (b) 3D Solid

Figure 2 Schematic Diagram of the Multi-scale and Multi-dimensional Network Division Model

3.4 Performance Evaluation Index System for Allocating Medical Resources to Lower-Level Facilities

A quantitative evaluation framework for the performance evaluation index system of allocating medical resources to lower-level facilities is constructed to measure the implementation effect of resource allocation strategies. The index system covers three dimensions: spatial allocation efficiency, service capacity improvement, and cost-benefit analysis. Spatial allocation efficiency is measured by indicators such as the equilibrium coefficient of medical resource distribution and service coverage rate. Service capacity improvement includes relevant indicators such as the diagnosis and treatment capacity and technical level of primary medical institutions. The evaluation system adopts the kernel density estimation method to quantify changes in resource distribution:

$$K(x) = \frac{1}{nd} \sum \left[k\left(\frac{x - X_i}{d} \right) \right] \tag{2}$$

In the formula, K(x) denotes the kernel density value at location "x"; "n" is the total number of medical institutions; "d" represents the bandwidth parameter, set to 1,000 meters; X_i is the location of the medical institution "i"; "k" is the kernel function. By comparing and analyzing the kernel density distribution before and after the allocation of medical resources to lower-level facilities, the improvement degree of resource allocation equilibrium is quantified. The evaluation cycle is set to once every six months, and a dynamic monitoring mechanism is established to track the effect of resource allocation. The index system includes quantitative indicators such as the cost-input-output ratio and the improvement of patient satisfaction, thereby providing a scientific basis for evaluating the effect of policies related to allocating medical resources to lower-level facilities.

4. Implementation Strategies for Allocating Medical Resources to Lower-Level Facilities

4.1 Construction of a Precision-Oriented Path for Allocating Medical Resources to Lower-Level Facilities

The precision-oriented path for allocating medical resources to lower-level facilities shall adopt differentiated resource allocation plans based on spatial analysis results, and formulate special resource allocation measures in accordance with the characteristics of medical needs in various regions. For regions with insufficient resource supply, a focused support strategy shall be implemented. High-quality medical resources shall be prioritized for introduction into peripheral districts and counties such as Changqing District and Zhangqiu District. Local medical capabilities shall be enhanced through approaches including the establishment of medical alliance branches and the formation of expert diagnosis and treatment teams [3]. For regions with relatively balanced supply and demand, an appropriate strengthening strategy shall be adopted, focusing on reinforcing the

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development of underdeveloped specialized departments and the training of professional and technical personnel. Service gaps shall be addressed by means of regular on-site expert assignments, remote collaborative diagnosis and treatment, and other related methods. For regions with relatively surplus resources, their radiating and leading role shall be fully exerted. These regions shall undertake paired assistance tasks to dispatch medical forces to surrounding areas. Path planning must adhere to the principle of geographical proximity, prioritizing the establishment of cooperative relationships within the 30-minute medical service circle to reduce implementation costs and improve operational efficiency.

4.2 Multi-Level Collaborative Allocation Mechanism for Medical Resources

Establishing an interconnection system among medical institutions at the provincial, municipal, and county levels, and forming a gradient-ordered network for allocating medical resources to lower-level facilities, are crucial to optimizing the multi-level collaborative allocation of medical resources. Provincial-level medical institutions mainly focus on technology transfer and talent training, promoting advanced technologies to municipal-level hospitals through approaches such as specialized medical alliances and technical cooperation [4]. Municipal-level hospitals should fully play their hub role: not only introducing high-quality provincial resources to district and county-level hospitals, but also providing professional guidance to primary medical institutions. County-level hospitals need to deepen intensive medical alliance cooperation with township health centers, and improve the level of primary medical services through measures such as personnel mobility and equipment sharing. Relying on a unified resource allocation platform, this collaborative mechanism dynamically optimizes resource allocation plans based on the service capabilities and actual needs of medical institutions at all levels. Meanwhile, the effectiveness of allocating medical resources to lower-level facilities is incorporated into the hospital assessment system. Incentive measures such as financial subsidies and performance rewards are supplemented to guide the orderly flow of medical resources.

4.3 Dynamic Monitoring System for Allocating Medical Resources to Lower-Level Facilities

The dynamic monitoring system for allocating medical resources to lower-level facilities establishes a full-cycle tracking and evaluation mechanism to comprehensively grasp the deployment and actual effectiveness of the resources allocated to grassroots units. Covering three core indicators - spatial layout, service efficiency, and operational costs - the system realizes data collection and intelligent analysis through an information platform [5]. The spatial monitoring module dynamically presents the distribution map of medical resources by means of GIS technology, tracking the spatial flow of allocated resources and changes in covered areas. Service efficiency monitoring measures the effectiveness of resource allocation by analyzing dimensions such as the patient volume, professional capabilities, and patient feedback of primary medical institutions. Cost-benefit monitoring evaluates the rationality between input and output to determine the economic applicability of relevant policies. The monitoring cycle adopts a combined model of monthly data collection, quarterly effectiveness evaluation, and annual comprehensive assessment. An early warning system is also established to quickly identify problems and optimize plans. Monitoring results are regularly submitted to decision-making departments, providing reliable support for the iterative improvement of policies related to allocating medical resources to lower-level facilities.

5. Conclusion

The allocation of medical resources to lower-level facilities involves a complex process encompassing spatial allocation, behavioral decision-making, and system optimization, which requires the application of advanced technical means to enhance the scientificity of decision-making. The integrated application of GIS spatial analysis technology and multi-agent simulation modeling has opened up a new technical path for the research on the model of allocating medical resources to lower-level facilities. By evaluating spatial agglomeration degree to identify weak links in resource allocation, using accessibility analysis to quantify differences in service coverage, and combining multi-agent simulation to assess the implementation effects of resource allocation strategies, this study provides technical support for the precise allocation of medical resources. The integrated model constructed in this research offers a decision-making basis for medical and health administrative departments to formulate scientific policies regarding the allocation of medical resources to lower-level facilities.

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