Spatial Patterns, Connectivity Structure and Planning Strategies of the Logistics Network in the Wuhan Metropolitan Area: A Truck Navigation Data-Based Study

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Abstract: Based on big data from Gaode truck navigation, this study investigates the spatial characteristics and planning methodologies of the logistics network in the Wuhan Metropolitan Area. The findings reveal that the overall spatial pattern of logistics activities is hub-dominated, with geographical agglomeration driven by resource distribution. Specifically, heavy truck activities exhibit a pattern of concentration in core areas and dispersion toward peripheral industrial parks and port zones. In contrast, medium, small and micro-truck activities demonstrate a hierarchical distribution — anchored in core urban areas, showing clustered agglomeration in built-up zones of central cities, and showing fragmented dispersion in peripheral regions. Through clustering analysis, 122 functionally differentiated logistics spatial units were identified, some of which exhibit misalignment with current planning policies. Network analysis further uncovers a "Matthew effect" in logistics connectivity, identifies potential regional transport corridors in multiple directions, and measures significant disparities in internal linkage strength and cross-regional flow among secondary associated communities. To address spatial imbalances in resource allocation, lagging connectivity, and insufficient inter-cluster coordination within the freight logistics network, this paper proposes a strategic planning framework centered on hub enhancement, corridor development, and community reorganization. The framework outlines a spatial logistics structure comprising five facility types, seven corridors, and five communities, and offers three optimization pathways and actionable measures. The study provides a theoretical foundation for modern logistics development and spatial layout planning in China's metropolitan areas.

Keywords: truck navigation data; logistics network; logistics spatial layout; planning strategy; metropolitan area

The coordinated layout and integrated planning of modern logistics spaces is of great significance for enhancing regional economic efficiency, optimizing transportation structures, promoting inter-city industrial linkages, and stabilizing supply chains in metropolitan areas [1-3]. In November 2024, the General Office of the CPC Central Committee and the General Office of the State Council issued the Action Plan for Effectively Reducing Logistics Costs Across the Entire Society, proposing further improvements to the "hub-and-spoke" logistics service system, the cultivation of hub economies and corridor economies, and the construction of a modern logistics operating system integrating "corridors + hubs + networks." The Wuhan Metropolitan Area, as the core economic zone in the middle reaches of the Yangtze River and a major national comprehensive transportation hub, has seen expanding logistics scale and a growing number of logistics enterprises in recent years. Its logistics activities play an increasingly important role as an engine for regional economic growth, giving rise to policy-driven spatial configurations. The 2022 Wuhan Modern Logistics Industry Development "14th Five-Year" Plan proposed establishing logistics synergy development axes along the Wu-E-Huang-Huang, Han-Xiao, Wu-Xian, and Wu-Xian-Tian-Qian

(Wu-Xian) urban development corridors, and deepening regional linkages and cascading development among logistics nodes along these axes. However, the implementation of plans and construction projects has exposed shortcomings such as poor connectivity among logistics hub nodes, incomplete cross-city transportation networks, inadequate logistics infrastructure, and unbalanced logistics resource planning — reflecting an immaturity in understanding the developmental patterns of logistics space at the metropolitan scale.

Regional resource allocation and factor layout based on logistics activity characteristics have increasingly become a topic of high attention in planning scholarship. In terms of data, earlier studies relied primarily on Origin-Destination (OD) surveys and questionnaire collections (revealed preference, RP), as well as population censuses and travel surveys, to identify key freight nodes [4-6]. Subsequent research has largely depended on truck GPS data [7], toll station data [8], traffic flow data [9], and field survey data from Taobao shop visits [10], making it possible to map the topological structure and traffic flow distribution of regional logistics networks at large scales [11-12]. Methodologically, most studies have used provinces, cities, or districts/counties as statistical units, with empirical research focused primarily on the national level [13-14], provincial scales [8], and urban agglomerations [15]. Social network analysis methods have been widely employed, focusing on key indicators such as network density, connection strength, and coefficient of variation [16-17]. In terms of content, mapping the spatial structure of regional logistics networks remains the core work; some studies have also explored the application of hub-and-spoke theory in reducing overall costs and accelerating regional logistics node coordination [18-19]. Others have examined cross-border logistics networks in inter-city transitional zones, investigating the "distance decay–boundary effect" in network evolution [18]. Overall, existing research has accumulated valuable experience in quantitative analysis techniques; however, statistical analyses based on administrative district scales cannot accurately capture the large volume of logistics activities occurring within industrial parks and logistics parks, nor can they reflect the actual travel patterns of trucks in physical space. Therefore, there is a need to introduce higher-precision grid units to improve the reliability of analytical results and the validity of conclusions [20-21].

Given this, this study employs 2 km × 2 km grid cells to measure the spatial distribution patterns of logistics activities of different types of trucks in the Wuhan Metropolitan Area, integrates spatial clustering techniques to identify regional logistics spatial units, and utilizes social network analysis to characterize the connectivity structure and community relationships of the logistics network, thereby guiding the optimization of the regional logistics spatial structure of the Wuhan Metropolitan Area.

1 Research Data and Methods

1.1Research Scope

The Wuhan Metropolitan Area Development Plan was officially approved by the National Development and Reform Commission in 2022. Given that its boundaries have not been officially published, the nine cities covered by the Wuhan Metropolitan Area Three-Year Action Plan (2023–2025) were selected as the research scope: Wuhan, Ezhou, Huangshi, Huanggang, Xiaogan, Xianning, Xiantao, Tianmen, and Qianjiang. The non-balanced development pattern of "strong core–weak hinterland" in the Wuhan Metropolitan Area, along with the significant disparity in economic density and infrastructure levels among member cities, provides an ideal laboratory for measuring the "siphon–spillover" effects of the regional logistics network.

1.2Data Advantages

The truck navigation data used in this study are provided by AutoNavi (Gaode) Software Co., Ltd., with three major advantages:

① More authentic and accurate reflection of actual trip origins and destinations. Unlike truck GPS data, which are subject to technical parking, signal interruptions, and coverage gaps under bridges or in remote mountainous areas (leading to OD chain disruptions and false stopover points), truck navigation data are generated by users' active navigation requests and are not affected by such interference. Moreover, Gaode navigation truck users account for approximately 40% of all truck users, ensuring data reliability. The proportion of truck trip OD pairs with relatively stable origins and destinations within a single day in the Wuhan Metropolitan Area reaches as high as 75%, which is conducive to comprehensively and continuously capturing high-frequency and short-cycle recurring patterns of truck travel.

② More detailed truck size classification information. Conventional studies often use truck travel data exceeding 12 tons (such as data from transportation departments for heavy truck monitoring) as a proxy, which cannot represent the logistics activities of medium, small and micro trucks [21]. The truck navigation data collected in this study include key parameters such as truck type, vehicle length, width, and weight, enabling a more comprehensive and balanced characterization of the operational conditions of different types of freight vehicles.

③ Considering cost constraints, data were collected from April 10 to 17, 2023. First, trips originating within the Wuhan Metropolitan Area were filtered, yielding over 1.44 million initial OD records. Second, following Jiao Hongzan et al. [20], truck trip OD pairs with both origin and destination coordinates within the metropolitan area were extracted to scientifically reflect the regional logistics network structure. Third, anomalous coordinate points were cleaned (removing data with coordinate offsets, speed distortions, and incomplete field information), and abnormal trips were cleaned (removing trips with OD path distance < 500 m). Finally, 780,229 valid truck trip OD records were extracted, of which approximately 56% were heavy truck trip records and approximately 44% came from medium, small and micro trucks. Each trip record includes 8 fields: vehicle ID, trip date, origin coordinates, destination coordinates, truck type, OD path distance, and others.

1.3Research Methods

(1) K-means Clustering Method

By calculating the similarity of comprehensive logistics activity volumes between grid cells, all grids are partitioned into K clusters, and regional logistics spatial units are identified based on inter-cluster differences in comprehensive logistics activity volume. The pseudo-F statistic is used to determine the optimal number of clusters for the Wuhan Metropolitan Area logistics spatial units. The calculation formula is:

$$F = [SSW/(N-K)] / [SSB/(K-1)]$$

where SSW is the within-cluster sum of squares, representing data similarity within the same cluster; SSB is the between-cluster sum of squares, reflecting data differences between clusters; N is the total number of samples; and K is the number of clusters. A higher pseudo-F statistic indicates a more valid measure of the degree of inter-cluster similarity and intra-cluster differentiation.

(2) Social Network Analysis (SNA)

Indicators including network density, coefficient of variation, average clustering coefficient, and connection strength are selected to characterize the connectivity structure of the regional logistics network of the Wuhan Metropolitan Area. The "nodes" in the social network are translated as "logistics spatial units" in this study. The key indicators and their measurement methods are as follows.

① Connection strength (F) reflects the interaction level between logistics spatial units. The calculation formula is:

$$F = F_{ij} + F_{ji} \tag{1}$$

where Fij represents the comprehensive logistics activity volume from logistics spatial unit i connected to logistics spatial unit j; Fji represents the comprehensive logistics activity volume from logistics spatial unit j connected to logistics spatial unit i.

② Network density (M) reflects the degree of close connection between logistics spatial units. A higher density indicates closer connections. The calculation formula is:

$$M = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} F}{n(n-1)} \tag{2}$$

where n is the number of logistics spatial units in the network.

③ Coefficient of variation (CV) measures the relative degree of dispersion of a mathematical statistic among logistics spatial units. A higher coefficient of variation indicates greater differences in truck trip volume, logistics connection volume, and logistics connection strength among units. The calculation formula is:

$$C_V = \frac{\sigma}{\mu} \times 100\% \tag{3}$$

where σ and μ are the standard deviation and mean of truck trip volume, logistics connection volume, and logistics connection strength among logistics spatial units, respectively.

④ Average clustering coefficient (C) measures the tendency of logistics spatial units to form local clusters or "small groups." The calculation formula is:

$$C = \frac{1}{n} \sum_{i=1}^{n} \frac{2E_i}{k_i(k_i - 1)} \tag{4}$$

where Ei is the number of actual connections between logistics spatial units connected to logistics spatial unit i, and ki is the degree of logistics spatial unit i (i.e., the number of logistics spatial units directly connected to it).

(3) Leiden Community Detection Algorithm

Introducing more refined termination conditions to improve the over-segmentation problem of the traditional Louvain algorithm in certain situations, this method can reveal community structures in regions with higher quality. The "community" in this method is translated as the "logistics-related community" studied in this paper. Based on "community detection" technology (essentially partitioning nodes in a network into groups), the logistics-related communities in the metropolitan area's regional logistics network are identified. The measurement indicator is the network modularity (Q); a larger modularity indicates closer connections within the logistics-related community [22]. The calculation formula is:

$$Q = \frac{1}{2p} \sum_{c} e_c - \gamma \frac{T_c^2}{2p} \tag{5}$$

where p is the total number of connections between logistics spatial units across the entire network, ec is the sum of logistics connection strengths between logistics spatial units within logistics-related community c, Tc is the total logistics connection volume of logistics-related community c, and γ is the resolution parameter of the model.

2 Spatial Pattern Characteristics of Logistics Activities in the Wuhan Metropolitan Area

2.1Spatial Pattern Characteristics of Logistics Activities

2.1.1Spatial Pattern of Heavy Truck Activities

The total number of heavy truck trips within each grid cell during the data collection period was calculated (in units of vehicles). The results show that the number of grids with non-zero values is 11,809 (58.4% of all grid cells), with a mean heavy truck trip volume of 84 and a coefficient of variation reaching 3.3, indicating that heavy truck activities have extensive geographical distribution and significant energy-level differences.

Spatial analysis reveals that heavy truck activities in the metropolitan area exhibit a pattern of "concentration in core areas for operations, with dispersion to peripheral parks and port zones." The rare 78 high-value grid cells (defined as grids with truck trip volume > 1,304, accounting for 0.7%) are located in 10 important regions, with prominent siphon effects. Among them, the Cihui–Zoumaling Modern Circulation Industrial Cluster is the regional logistics organization core for heavy trucks, undertaking high-intensity cargo collection, distribution, and transshipment functions (see ① in Fig. 1). Close to the Wuhan Third Ring Road and radiating outward via expressways, several contiguous heavy truck activity agglomeration zones have formed (see ②③④⑥⑧ in Fig. 1). The Central Macheng Stone Circular Economy Industrial Park, Yangluo Port, Daye Lake High-Tech Zone, and Gedian Development Zone also serve as major hubs for heavy truck activities (see ⑤⑦⑨⑩ in Fig. 1).

Fig.1 Spatial pattern of heavy truck activities in the Wuhan metropolitan area

2.1.2Spatial Pattern of Medium, Small and Micro-Truck Activities

Using a similar method, the total trip volume of medium, small and micro trucks within each grid cell was calculated. The results show that the number of grids with non-zero values is 12,412 (61.3% of all grid cells), with a mean trip volume of 72 and a coefficient of variation reaching 4.0, indicating that medium, small and micro trucks have a broader activity range within the metropolitan area, greater regional differences, but lower average trip volumes compared to heavy trucks.

Spatial analysis reveals that medium, small and micro-truck activities in the metropolitan area exhibit a pattern of "strong core pull, metropolitan-zone sectoral agglomeration, peripheral fragmented dispersion." There are 68 high-value grid cells (defined as grids with truck trip volume > 1,304, accounting for 0.5%, fewer than heavy trucks), concentrated primarily in the Cihui–Zoumaling Modern Circulation Industrial Cluster, Hankoubei Commercial Logistics Zone, and Baishazhou Cold Chain Logistics Zone. The Cihui–Zoumaling area, which serves as the logistics organization core for heavy trucks, has also been proven to be the quantitative center of medium, small and micro-truck activities with an even more significant polarizing effect. The high-frequency "procurement–distribution" business of small commodity trade and wholesale in Hankoubei and cold chain/frozen food distribution enterprises in Baishazhou generates multiple, small-batch transportation demands for medium, small and micro trucks. In addition, the main urban area of Wuhan, with its concentrated residential population, thriving consumer market, and dense urban road network, is almost entirely covered by medium, small and micro-truck activities (Fig. 2).

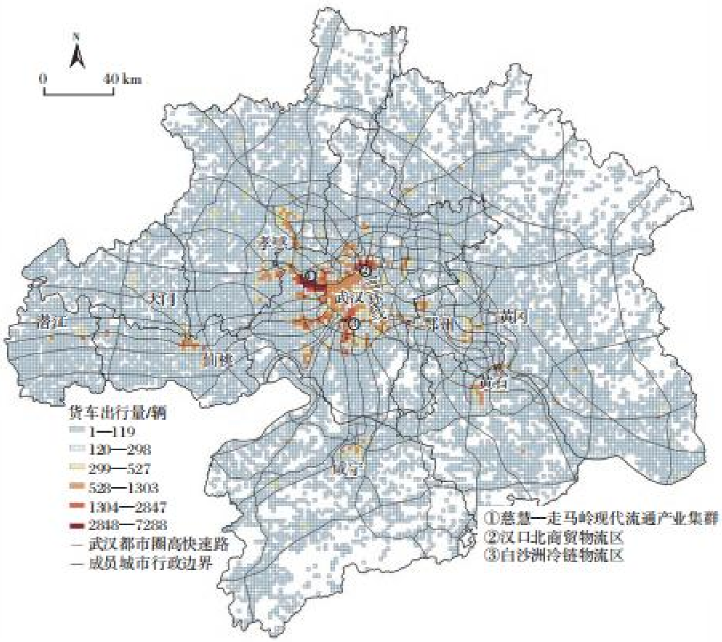


Fig.2 Spatial pattern of medium, small and micro truck activities in the Wuhan metropolitan area

2.1.3Overall Spatial Pattern of Metropolitan Area Logistics Activities

Daily logistics activities in the metropolitan area are jointly carried by trucks of different capacities and operational characteristics. To more accurately reflect actual activity scale and trip intensity, this study references Liu Xinxuan et al.'s approach to the relationship between truck types and freight volumes [17-18], integrating heavy truck and medium, small and micro truck datasets, using vehicle weight as a weighting factor [17-18], and summing the comprehensive logistics activity volume for each grid cell. The results show that the total number of grids with non-zero values is 13,990 (69.1%), with a mean comprehensive logistics activity volume of 1,152, a maximum value of 119,295, and extreme high values (kurtosis = 346). Mapped onto the territorial structure, logistics activities at the metropolitan scale exhibit an overall spatial pattern of "hub-dominated, resource development-driven freight agglomeration." The formation and growth of hubs are driven by multiple factors including transportation, industry, and consumption; the relatively high logistics activity volumes in Macheng (stone materials) and Huangshi (copper ore) reflect the spatial pull of resource extraction, processing, warehousing, and trading activities on regional logistics transportation.

2.2Identification of Logistics Spatial Units

Using the K-means clustering method, the similarity of comprehensive logistics activity volume values between grids across the metropolitan area was calculated to automatically identify regions with consistent flow characteristics. The results show that when the number of clusters is 6, the pseudo-F statistic is maximized and the inter-cluster difference in comprehensive logistics activity volume is greatest (Means are 248, 1,619, 3,542, 17,212, 35,583, 87,565, respectively). Accordingly, based on ArcGIS, the six categories of grid cells were subjected to spatial patch redivision and merging, referencing the transportation system and comprehensive logistics hub content of the Wuhan Metropolitan Area Development Plan, the main functional area system of the metropolitan area spatial plan, and the national territorial spatial master plans and provincial urban and industrial cluster high-quality development series studies of each member city. Ultimately, 122 metropolitan area logistics spatial units were identified (Fig. 3), with an average unit area of approximately 20.3 km². Observing the geographical locations of the logistics spatial units, four typical functions were summarized: logistics hub service functions (6), industrial park service functions (86), logistics park service functions (17), and transshipment and distribution service functions (11). Additionally, some expressway service areas show potential to develop into logistics spatial units.

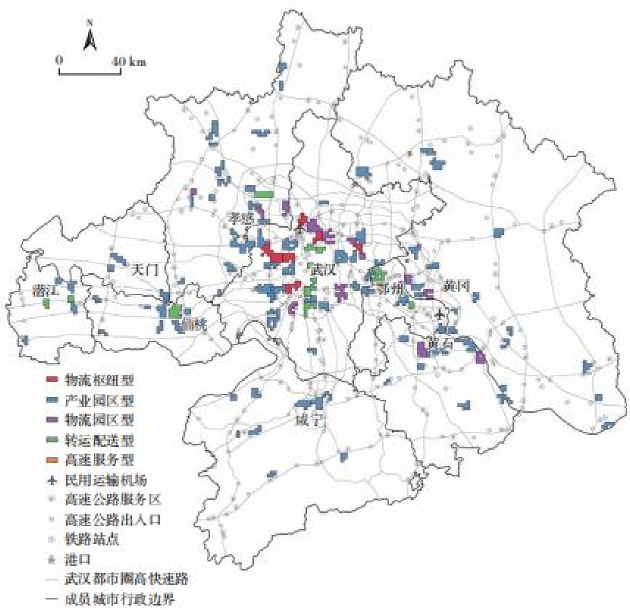


Fig.3 Spatial distribution of 122 logistics units in the Wuhan metropolitan area

Based on the Wuhan Metropolitan Area current and planned land use atlas compiled by the research team, the 122 logistics spatial units were overlaid and analyzed with industrial land, logistics and warehousing land, port land, and expressway networks to examine spatial compatibility. Five logistics spatial units were found to be highly compatible with planning intentions. The logistics spatial units formed relying on the Xiantao High-Tech Zone and the Zhuankou Automotive and Parts Industrial Zone align with the metropolitan area's planning orientation toward developing intelligent automotive manufacturing. The Cihui–Zoumaling Modern Circulation Industrial Cluster has laid the foundation for achieving the goal of building a national land-port-type logistics hub. The Hankoubei Commercial Logistics Zone supports the regional positioning of "building a modernized commercial logistics center." The logistics spatial units serving the Yangluo Heavy Industry Manufacturing Zone and the Daye Lake High-Tech Zone have exerted cargo agglomeration and radiation functions relying on the hundred-million-ton-class major port and high-volume trunk railways. However, four logistics spatial units were also found to be not fully compatible with current plans: for example, the planned land use in the Dijiao Urban Industrial Park and Baishazhou Cold Chain Logistics Zone remains primarily industrial, residential, and commercial service land, lacking spatial supply for high-frequency logistics distribution and transshipment functions; another example is that the plans for the Miaoshan Equipment Manufacturing Zone and the Huangzhou Railway Station Economic Development Zone have insufficient reservation and organization of freight roads within these units, particularly lacking heavy-duty roads and dedicated channels required for large-scale transportation.

3 Connectivity Structure Characteristics of the Regional Logistics Network in the Wuhan Metropolitan Area

3.1 Network Node Structure Characteristics

The regional logistics network of the Wuhan Metropolitan Area exhibits a pronounced "Matthew effect," with high-volume logistics connections strongly dominated by a small number of nodes (i.e., logistics spatial units). The cross-city multi-directional radiation and network interweaving structures are also very distinct (Fig. 4).

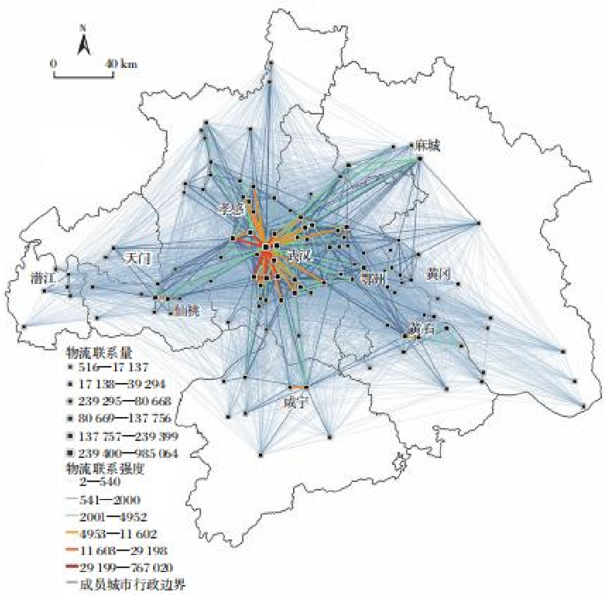


Fig.4 Structure of logistics network association in the Wuhan metropolitan area based on logistics spatial units

The measurements of network density and average clustering coefficient show that the compactness of the metropolitan area's logistics network structure reaches a medium-to-high level (density value = 0.691, clustering coefficient = 0.801), indicating that hundreds of logistics spatial units tend to form closer interrelationships.

However, the seemingly tight network relationships are not spatially balanced. Statistical analysis of the logistics connection volume of each logistics spatial unit shows that: the mean logistics connection volume of the 122 units is 39,536 with a coefficient of variation of 2.37; the top 5% of logistics spatial units in terms of connection volume number 7, and those in the 5%–10% range number 6. Among them, a small number of logistics spatial units such as the Cihui–Zoumaling Modern Circulation Industrial Cluster, Baishazhou Cold Chain Logistics Zone, and Yangluo Heavy Industry Manufacturing Zone constitute network hubs and play dominant roles. The Cihui–Zoumaling Modern Circulation Industrial Cluster is the super logistics hub dominating the entire network, while peripheral units have weak influence on network structure.

Calculating connection strengths between nodes reveals that: 4,971 connection lines are generated between the 122 units, with a mean logistics connection strength of 295 but a coefficient of variation reaching as high as 5.1, reflecting a structure characterized by strong imbalance and weak connections. Among the 115 logistics connection lines with connection strength values above 2,000, 26 cross municipal administrative boundaries, converging into four directional logistics-related corridors of the metropolitan area (Wuhan–Xiaogan direction, Wuhan–Macheng direction, Wuhan–Xianning direction, and Wuhan–Xiantao direction).

3.2 Network Community Structure Characteristics

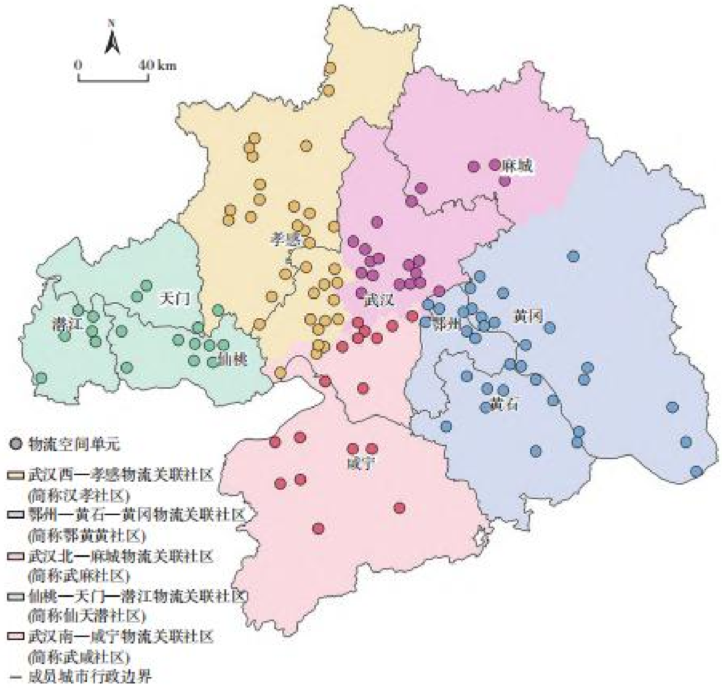
3.2.1 Spatial Distribution of Five Logistics-Related Communities

The Leiden community detection algorithm was used to reveal the community structure of the metropolitan area's logistics network. The algorithm iterated 10 times with an average modularity of 0.426, ultimately identifying five logistics-related communities: Han-Xiao, E-Huang-Huang, Wu-Ma, Xian-Tian-Qian, and Wu-Xian (Fig. 5), with a mean territorial area of 11,659 km². Among them, the Han-Xiao, Wu-Ma, and Wu-Xian communities have crossed the administrative boundaries of Wuhan, and within Wuhan have differentiated into three regions with relatively balanced logistics spheres of influence, indirectly confirming the scientific basis of the Plan's proposal to build Han-Xiao and Wu-Xian regional logistics synergy development axes.

Fig.5 Spatial distribution of five logistics-related communities in the Wuhan metropolitan area

3.2.2Connections Between Logistics Spatial Units Within Communities

Although the number of logistics spatial units among the five communities is relatively equal, the logistics connection volumes vary significantly (Table 1). Statistical data and spatial analysis show that the Han-Xiao community presents a unipolar radiation pattern in logistics network structure (coefficient of variation of logistics connection volume reaching 1.595). The Cihui–Zoumaling Modern Circulation Industrial Cluster exerts extremely strong control



over this community, forming three community logistics corridors radiating to the Hanchuan Economic Development Zone, the Hannan General Aviation and Satellite Industrial Park, and the Xiaogan National High-Tech Zone as auxiliary nodes. The Wu-Ma community has the highest network density (0.968) and lowest coefficient of variation (0.735), forming a multi-centered, balanced distribution of logistics activities. Two community logistics corridors connect Yangluo Port and the Hong'an Economic Development Zone, and the Central Macheng Stone Circular Economy Industrial Park respectively. The corridor connecting Luotian Economic Development Zone and Tuanfeng Port-adjacent Industrial Park has begun to emerge. The internal logistics association structure of the Wu-Xian community is characterized by long-distance, single-corridor, and dual-end features (Optics Valley South Health Industry Park — Xianning High-Tech Zone), which may be related to the chain division of labor in the health industry with R&D in Wuhan and manufacturing in Xianning. The E-Huang-Huang community exhibits low network density and high coefficient of variation characteristics, with high dependence on certain individual logistics spatial units such as the Huangshi Development Zone, giving rise to a vertical-river logistics corridor and a riverside logistics corridor with Huangshi New Port and Gedian Development Zone as endpoints. The Xian-Tian-Qian community presents a triangular logistics-related structure "led by Xiantao High-Tech Zone, supplemented by Tianmen High-Tech Zone and Qianjiang High-Tech Zone," with prominent network introversion characteristics.

Tab.1 Comparison of the total number of logistics links and network structure indicators of five logistics-related communities

衡量指标	汉孝社区	武麻社区	鄂黄黄社区	武咸社区	仙天潜社区
单元间物流联系量的平均值	31 731	11 655	6844	8895	4846
单元内物流联系量的极大值	283 810	31 356	30 286	26 547	16 259
单元间物流联系量的极小值	2371	2830	191	1100	956
网络密度	0.934	0.968	0.795	0.926	0.941
网络变异系数	1.595	0.735	0.971	0.877	0.852
网络平均聚类系数	0.946	0.969	0.890	0.938	0.944

3.2.3 Strength of Cross-Community Freight Logistics Connections

The logistics freight connection volume between any two communities was calculated, and the proportion of cross-community freight logistics to the community's total freight connection volume was tabulated. The results show that the Wu-Ma community's cross-community freight proportion (35.4%) is significantly higher than other communities, demonstrating distinctive outward-oriented logistics activity characteristics. The E-Huang-Huang community's cross-community freight proportion (29.8%) is slightly lower than that of the Wu-Ma community, partly because ports and railways divert dependence on road freight. The Han-Xiao and Wu-Xian communities both demonstrate strong internal logistics activity stickiness, with outbound truck trip proportions as low as 27.4% and 26.7%, respectively. The Xian-Tian-Qian community has the lowest cross-community freight flow proportion (less than 20%), with the highest degree of closed-loop internal supply chains.

4 "Hub Enhancement, Corridor Development, and Community Reorganization" — Optimization Strategies for the Logistics Network of the Wuhan Metropolitan Area

4.1 Problems and Policy Objectives in the Development and Planning of the Logistics Network

First, logistics spatial units are scattered and fragmented, with hub function layout being deficient and imbalanced, and the systematic construction of metropolitan area logistics nodes remains unsound. Second, the polycentricity and multi-directional connectivity of the logistics network are insufficient; the diffusion effect of core cities has not been fully realized, and the participation and influence of peripheral and outer-lying districts/counties are very low. The network level of logistics connection corridors urgently needs improvement: the Wu-E-Huang-Huang direction has a mid-section break in logistics connections, the Wu-Xian-Tian-Qian direction has yet to form a continuous regional corridor, and land-based logistics corridor blind spots have been exposed in northern Han-Xiao, riverside Xianning, central-northern Hong'an, the Dabie Mountain Revolutionary Base Area, and other regions. Eastward riverside and cross-river logistics corridors need to be supplemented, and a metropolitan circular corridor linking all member cities should be coordinated. Third, the local clustering and near-domain synergy capacity of the logistics network is imperfect; the logistics connection volume gap among the five logistics-related communities needs to be narrowed, infrastructure allocation balanced between communities, and introverted island-like logistics connection barriers such as those in the Xian-Tian-Qian community broken down. Fourth, the planning compatibility of some logistics spatial units needs strengthening.

To address the aforementioned issues, by drawing on and learning from the excellent practices of metropolitan areas in the Central region in building modernized logistics systems, and recognizing that scientific hub hierarchies, efficient logistics corridors, and deep synergy mechanisms are effective levers for improving regional logistics efficiency, this study — combining the strategic orientation of the Plan guiding same-cityization construction, along with the transportation and modern logistics spatial layout considerations of the nine member cities — proposes the logistics network optimization strategy of "hub enhancement, corridor development, and community reorganization" (Fig. 6).Based on the empirical findings of this study, the strategy consolidates and possesses the polarizing effects of the Cihui–Zoumaling Modern Circulation Industrial Cluster, Hankoubei Commercial Logistics Zone, and other comprehensive freight hubs, establishes 7 metropolitan-area-level logistics hubs including Wujiashan Land Port and Huahu Airport, promotes multimodal transport integrating road, rail, water, and air; builds community-level logistics hubs relying on Gedian Economic Development Zone, Macheng Economic Development Zone, and others, establishing 5 important community-level resource collection and distribution bases; expands industrial park-type logistics nodes within large industrial agglomerations such as the National Memory Base and Xianning High-Tech Zone to supplement production-service logistics facilities; strengthens logistics park-type nodes, such as integrating logistics enterprise resources within Huangpi Airport-adjacent Logistics Park and Xiaogan Airport-adjacent New City, to reasonably plan urban distribution zones and cross-border logistics operation zones; embeds transshipment and distribution-type logistics nodes in Baishazhou Cold Chain Logistics Base and Xiaogan National High-Tech Zone, focusing on finished goods and raw materials collection, distribution, and allocation, deploying intelligent and customized sorting facilities; and values the support capacity of expressway service areas for regional transport vehicle parking, unloading, and personnel services.

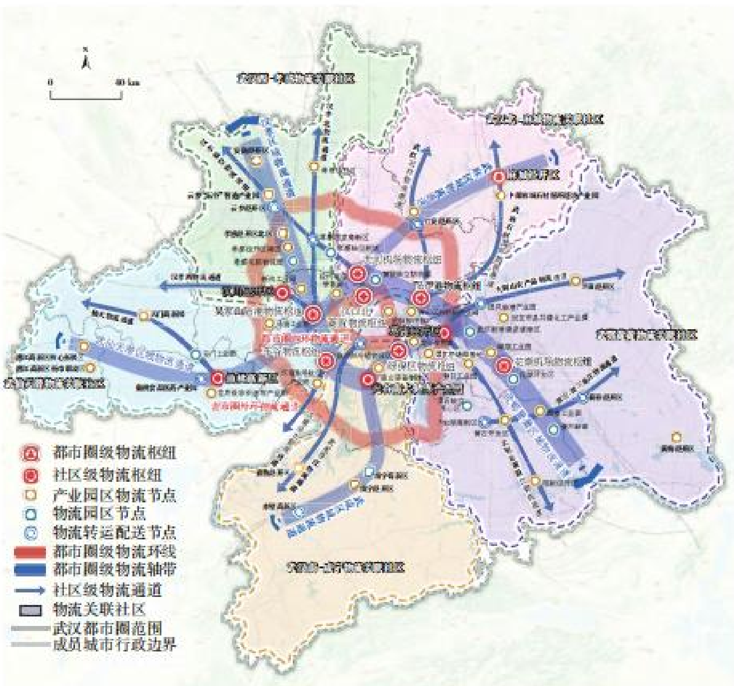


Fig.6 Proposed optimization plan for the logistics spatial structure of the Wuhan Metropolitan Area

4.2 Strengthening Two-Tier Regional Logistics Hubs and Refining Functional Node Construction

Consolidating the 6 hub-type logistics spatial units in Fig. 3, and responding to the requirements of the 2025 national logistics hub layout optimization plan, establishing principles of promoting territorial balance and conforming to local policy drivers, the metropolitan area's "two-tier hubs + three types of nodes" logistics facility system is constructed: strengthening 7 metropolitan-area-level logistics hubs including Wujiashan Land Port and Huahu Airport, promoting the integration of road freight and multimodal transport of "rail-water-air"; building 5 community-level important resource collection and distribution bases; expanding industrial park-type logistics nodes within large industrial agglomerations such as the National Memory Base and Xianning High-Tech Zone to supplement production-service logistics facilities; strengthening logistics park-type nodes, such as integrating logistics enterprise resources within Huangpi Airport-adjacent Logistics Park and Xiaogan Airport-adjacent New City, to reasonably plan urban distribution zones and cross-border logistics operation zones; embedding transshipment and distribution-type logistics nodes in Baishazhou Cold Chain Logistics Base and Xiaogan National High-Tech Zone, focusing on finished goods and raw materials collection, distribution, and allocation, deploying intelligent and customized sorting facilities; and prioritizing the support capacity of expressway service areas for regional transport vehicle parking, unloading, and personnel services.

4.3Upgrading the Metropolitan Area Logistics Corridor Network and Extending Community Flow Channels

Based on the analysis and understanding of empirical results, demonstrating the absorbing and pulling effects of the Wuhan Third Ring Road and radial expressways, conforming to the linear trends formed by several logistics spatial units in Fig. 3, and solidifying the logistics network structure, the identified Han-Xiao, Wu-Ma, Wu-Xian, and Wu-Xian corridor forms are improved. Following the principles of interpenetration, interweaving, network solidification, enhanced radiation effects, assistance to peripheral integration into the metropolitan circle, and promotion of cross-community integration, the metropolitan area's "double ring + grid axis + multi-radial" road freight corridor system is established.

Building a metropolitan-area-level internal and external logistics double ring road: Upgrading the Wuhan Third Ring Road, adding intelligent logistics dedicated lanes to form a road freight inner ring road. Accelerating the completion of the metropolitan area ring expressway, pre-controlling smart logistics service areas, and assembling a freight outer ring road.

Linking metropolitan-area-level grid-shaped logistics axis corridors: Bundling national transportation trunk lines passing through the area and metropolitan backbone expressways, crossing and supporting all logistics hubs, connecting as many logistics nodes as possible, and focusing on building five cross-city corridors: Wu-E-Huang-Huang, Han-Xiao, Wu-Ma, Wu-Xian, and Wu-Xian-Tian-Qian.

Balanced radial community-level logistics corridors: Using hubs and nodes as origins, supplementing vertical-river port-connected and mountainous agricultural area routes within each logistics-related community. Examples include the Wu-Hong and Wu-Ma corridors for stone material transport, the Dabie Mountain and northern Han-Xiao corridors for agricultural and forestry product circulation, the Xian-Tian corridor and western Han-Xiao corridor for garment/textile and equipment manufacturing, and others.

4.4 Cross-Boundary Reconstruction of Logistics-Related Communities and Enhancement of

Cluster Structural Resilience

Using the five community structures revealed in Fig. 5 as a cognitive foundation, adapting to the radiation reach of planned logistics hub nodes and the bilateral service potential range of backbone logistics corridors, following the "core + axis belt" industrial spatial layout model of growing metropolitan areas [23], a cross-regional logistics-related community organizational pattern is constructed.

Accelerating integration of the Wuhan West–Xiaogan logistics-related community: Coordinating the dual hub radiation sources of "Wujiashan Land Port + Hanchuan Economic Development Zone," expanding to form a mountain-connecting, port-adjacent, water-land-air intermodal "8"-shaped corridor structure, highlighting the industrial park-type and transshipment-distribution composite logistics service functions of the Hong'an Economic Development Zone.

Accelerating the Wuhan North–Macheng logistics-related community: Uniting the four hub radiation sources of "Yangluo Port + Tianhe Airport + Hankoubei + Macheng Economic Development Zone," extending to form a mountain-connecting, port-adjacent, water-land-air intermodal "8"-shaped corridor structure, highlighting the industrial park-type and transshipment-distribution composite logistics service functions of the Hong'an Economic Development Zone.

Improving and upgrading the Wuhan South–Xianning logistics-related community: Relying on the dual hub radiation sources of "Comprehensive Bonded Zone + Optics Valley South Health Industry Park," stabilizing the regional H-shaped transportation framework, supplementing transshipment and distribution resources to the Chibi High-Tech Zone, and strengthening logistics park-type functional construction in Xianning High-Tech Zone and other areas.

Expanding and building the Wu-E-Huang-Huang logistics-related community: Strengthening the dual hub radiation sources of "Huahu Airport + Gedian Economic Development Zone," ensuring smooth "riverside + cross-river" grid-shaped main corridors, and extraordinarily expanding full-type logistics functions surrounding Huahu Airport in a circular, layered manner.

Jointly cultivating the Wu-Xian-Tian-Qian logistics-related community: Assisting the dual hub radiation sources of "Auto Valley + Xiantao High-Tech Zone," building a "human-shaped" transport corridor structure, and supplementing logistics park-type services.

5 Conclusions

Based on big data from Gaode truck navigation, this study analyzes the logistics network of the Wuhan Metropolitan Area, with key conclusions as follows: ① The regional spatial pattern of logistics activities often exhibits model characteristics such as hub dominance, agglomerated operations, hierarchical distribution, and peripheral dispersion, but the activity regions of heavy trucks and medium, small and micro trucks show significant differentiation; ② The Wuhan Metropolitan Area has formed 122 logistics spatial units, whose functions are primarily park service-oriented, supplemented by transshipment-distribution and hub-type functions, with some units showing planning compatibility deviations; ③ The "Matthew effect" in logistics connections is prominent, with the overall network dominated by a small number of high-volume nodes such as Cihui–Zoumaling, and several secondary logistics communities with markedly different internal and external connectivity structures emerging; ④ The development of the Wuhan Metropolitan Area logistics network exposes problems such as fragmented and imbalanced nodes, loose and lagging connectivity, and insufficient cluster coordination. Planning should follow the approach of 'hub enhancement, corridor development, and community reorganization,' establishing a logistics spatial structure of 'five types of facilities — seven major corridors — five communities,' optimizing the 'two-tier hubs, three types of nodes' logistics facility system and the 'double ring, grid axis, multi-radial' road freight corridor system, and improving and strengthening the service functions and structural resilience of related communities.

This study provides a new methodological chain of "data mining — pattern measurement — unit identification — network analysis — planning response" for modern logistics spatial planning in contemporary Chinese metropolitan areas, with theoretical value and application demonstration significance for breaking the barriers of "administrative district economies" and promoting regional logistics integration. Future research should extend data cycles and integrate multimodal transport of "road-rail-water-air" to deepen the study.

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