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ACCESSIBILITY EVALUATION OF URBAN LOW-ALTITUDE LOGISTICS NETWORKS BASED ON MULTI-SOURCE SPATIOTEMPORAL DATA

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Abstract: With the rapid development of the low-altitude economy, urban low-altitude logistics has become a promising solution for improving delivery efficiency and expanding logistics services. Compared with conventional ground-based logistics, it shows strong potential in reducing traffic congestion, improving timeliness, and enhancing service capacity in special scenarios. However, existing studies have mainly focused on route planning, facility location, and scheduling optimization, while systematic evaluations of service capacity at the urban scale remain limited. Taking Shenzhen as a case study, this research integrates multi-source spatiotemporal data on spatial environment, logistics demand, operational constraints, and network supply to construct an urban low-altitude logistics network and assess its accessibility in terms of spatial coverage and travel-time performance. The results reveal a clear core–periphery pattern: central districts such as Nanshan, Futian, and Luohu show higher coverage and shorter travel times, while peripheral districts such as Pingshan, Dapeng, and Yantian exhibit lower accessibility. Scenario analysis further shows that peak periods and operational restrictions reduce network coverage and increase travel time, especially in peripheral areas. The study provides an accessibility evaluation framework that supports network optimization and differentiated governance.
Keywords: Urban low-altitude logistics network; Multi-source spatiotemporal data; Accessibility evaluation

1 INTRODUCTION

In recent years, with the rapid development of the low-altitude economy and the growing demand for instant delivery, smart logistics, and refined urban governance, low-altitude logistics has gradually emerged as an important component of urban transportation and logistics systems[1-2]. Logistics services enabled by unmanned aerial vehicles and other low-altitude aircraft can, to some extent, overcome the constraints of ground traffic congestion, physical barriers, and time-sensitive delivery bottlenecks, thereby offering new solutions for last-mile distribution, emergency supply transport, and high-efficiency logistics services[3-4]. Against the backdrop of increasingly complex urban spatial structures and increasingly diversified delivery demands, low-altitude logistics networks are no longer merely a technical application of aerial transport, but are evolving into a new type of infrastructure network embedded in urban space, operational environments, and service demand systems. Accordingly, evaluating the accessibility of urban low-altitude logistics networks from the perspective of urban service capacity has become an important issue for supporting network planning and operational optimization[5].

Existing studies on low-altitude logistics and drone-based delivery have produced substantial findings, mainly focusing on route planning, facility location, network optimization, scheduling coordination, and operational safety. These studies have provided important support for the engineering implementation and operational organization of low-altitude logistics systems. However, research that systematically evaluates the service capacity of low-altitude logistics networks at the urban scale remains relatively limited. In particular, current accessibility-related studies often rely on static and idealized analytical frameworks, while paying insufficient attention to the combined effects of demand distribution, built environment, airspace constraints, and temporal variation on network accessibility. Moreover, most existing studies place greater emphasis on efficiency improvement and cost optimization, while offering relatively limited discussion of the spatial disparities, temporal fluctuations, and underlying mechanisms of accessibility within urban low-altitude logistics networks. With the increasing availability of multi-source spatiotemporal data, employing more detailed and dynamic datasets to characterize the operational conditions and service capacity of urban low-altitude logistics networks has become a promising direction for further research.

Against this background, this study takes the urban low-altitude logistics network as the research object and develops an accessibility evaluation framework based on multi-source spatiotemporal data to reveal its overall spatial pattern, spatiotemporal variation, and major influencing factors within the urban context. Specifically, this study first integrates multi-source data on logistics facilities, demand points, urban spatial environment, and low-altitude operational constraints to construct an urban low-altitude logistics network. It then measures and analyzes network accessibility from two dimensions, namely spatial coverage and travel-time performance. Finally, by comparing different time periods or operational scenarios, the study identifies the differentiated characteristics of accessibility within the city and examines the impacts of node layout, demand distribution, and spatial environment on accessibility. The study aims to provide methodological support and practical implications for the planning, optimization, and refined governance of urban low-altitude logistics networks.

2 STUDY AREA AND DATA

2.1 Study Area

This study selects Shenzhen as the study area. As one of the earliest cities in China to develop the low-altitude economy and one of the leading centers of the drone industry, Shenzhen provides a strong practical foundation for research on instant delivery, urban logistics, smart transportation, and low-altitude application scenarios[6-7]. In recent years, with the growing demand for highly efficient urban delivery services and the gradual expansion of drone logistics, low-altitude distribution, and air-ground coordinated delivery, Shenzhen has become a representative city for examining the organizational structure and service capacity of urban low-altitude logistics networks. Compared with ordinary cities, Shenzhen is more representative in terms of low-altitude logistics infrastructure deployment, application demand intensity, and industrial support conditions, making it a suitable empirical case for this study.

From the perspective of urban spatial structure, Shenzhen exhibits a clear multicenter and cluster-based development pattern, with significant differences across districts in terms of functional composition, population density, industrial distribution, and transport conditions. Central districts such as Futian, Luohu, and Nanshan are highly concentrated in commercial and office functions and generate strong demand for time-sensitive delivery services. Districts such as Bao'an, Longgang, and Longhua combine residential areas, manufacturing zones, and industrial parks, forming a diverse demand structure for urban distribution. Some peripheral areas are relatively weaker in terms of the efficiency and timeliness of conventional ground logistics services, and are therefore more suitable for testing the potential of low-altitude logistics in spatial supplementation and service extension. At the same time, Shenzhen has a highly complex built environment, with dense development, high-rise buildings, mountainous and coastal terrain, sensitive facilities, and airport clearance protection requirements, all of which jointly shape the practical boundary conditions for low-altitude flight activities. As a result, the accessibility of urban low-altitude logistics networks in Shenzhen shows stronger spatial heterogeneity.

In addition, Shenzhen offers favorable conditions in terms of data availability. Its basic geographic information, building distribution data, population data, functional facility data, transport network data, and some flight-related constraint information are relatively well developed, which supports the spatial representation and accessibility analysis of the low-altitude logistics network. Overall, Shenzhen not only reflects a realistic demand for low-altitude logistics development, but also provides strong data support and sufficient spatial complexity for research. It is therefore a valuable case for evaluating the accessibility of urban low-altitude logistics networks[8].

2.2 Data Sources and Network Construction

2.2.1 Data sources

To comprehensively characterize the supply foundation, demand distribution, and operational constraints of Shenzhen's low-altitude logistics network, this study integrates multi-source spatiotemporal data to establish the research database. In line with the research objectives, the data used in this study mainly fall into four categories: spatial environment data, logistics demand data, low-altitude operational constraint data, and network supply data.

Spatial environment data are mainly used to describe the basic spatial structure and built-environment characteristics of the study area. Specifically, these data include Shenzhen's administrative boundaries, road network, land-use types, building footprints, and building height information. Road network and administrative boundary data are mainly obtained from the Amap Open Platform, land-use data are primarily based on the GlobeLand30 dataset, and building footprint and height data are compiled from urban building vector datasets. On the one hand, these data are used to characterize the distribution of urban functional spaces and the built environment; on the other hand, they provide essential support for identifying facility layout, route organization, and service coverage in the low-altitude logistics network. For urban low-altitude logistics, building density, height variation, and spatial obstruction directly affect flight feasibility, node deployment, and service coverage efficiency, making such data a crucial basis for network construction.

Logistics demand data are mainly used to represent the spatial distribution and intensity of potential service demand for low-altitude logistics within the city. Given that actual order data are often commercially sensitive and difficult to obtain, this study uses population density, residential communities, commercial service facilities, office parks, industrial parks, and hospitals as proxy variables for demand. Population density data are mainly derived from the WorldPop dataset, while POI data for commercial facilities, communities, office parks, and industrial parks are collected from Amap. Different types of demand units correspond to different potential logistics scenarios. Residential communities and commercial facilities mainly reflect demand for instant delivery and retail distribution; office and industrial parks are more closely related to business delivery and intra-park logistics; hospitals and similar public service facilities partly indicate the potential demand for emergency supplies or highly time-sensitive delivery services. By identifying, classifying, and spatially aggregating these demand units, this study captures the spatial differentiation of low-altitude logistics demand in Shenzhen.

Low-altitude operational constraint data are used to characterize the practical boundary conditions for low-altitude flight activities in urban areas. These data mainly include airport clearance protection zones, no-fly areas, the distribution of sensitive facilities, and meteorological conditions. Airport clearance zones and some restricted flight areas are spatially identified based on publicly available control boundaries and relevant planning documents. Sensitive facilities mainly include airports, government compounds, substations, major transport hubs, and other important spaces that require flight avoidance, which can be screened using POI data and public information. Meteorological data are mainly obtained from the China Meteorological Data Service Center and include variables closely related to drone operations, such as wind speed, precipitation, and visibility. Together, these constraints indicate that the low-altitude logistics network is not a completely open network, but rather a constrained service network jointly shaped by flight regulations, safety boundaries, and environmental conditions.

Network supply data are mainly used to characterize the service capacity and spatial organizational basis of low-altitude logistics. Since complete real-world data on low-altitude logistics facilities and routes are generally difficult to obtain, this study identifies a set of representative low-altitude logistics facility nodes based on public information, corporate sources, map interpretation results, and relevant literature. These nodes include takeoff and landing sites, front warehouses, and transfer nodes. Typical drone operating parameters are then used to define link connectivity conditions and travel-time costs within the network. These parameters are mainly referenced from previous studies and publicly available industry materials, including typical cruising speed, effective range, single-trip service radius, and takeoff-landing transition time. Although this approach cannot fully reproduce every detail of real-world operations, it provides a reasonable representation of the basic supply capacity and structural characteristics of the urban low-altitude logistics network under current data conditions.

2.2.2 Network construction

Supported by the multi-source spatiotemporal data described above, this study abstracts Shenzhen's low-altitude logistics system into an urban analytical network composed of logistics facility nodes, route connection relationships, and demand service units. The network construction process mainly includes three steps: node identification, edge construction, and demand mapping.

First, in the node identification stage, supply-side nodes are established according to the spatial locations and functional attributes of low-altitude logistics facilities. In this study, nodes are classified into three categories: takeoff and landing nodes, front warehouse nodes, and transfer nodes. Takeoff and landing nodes mainly serve as the basic infrastructure for drone departure, arrival, and short-term stopover. Front warehouse nodes mainly undertake cargo organization, task dispatching, and delivery coordination functions. Transfer nodes are introduced to strengthen network connectivity and improve interregional service capacity. Given the limitations in data availability, this study uses public information, map interpretation, and the distribution of urban functional zones to identify and screen low-altitude logistics facilities, thereby forming the set of supply nodes used in the analysis. The spatial distribution of these nodes determines the organizational basis of low-altitude logistics services and directly affects the spatial pattern of subsequent accessibility measurement.

Second, in the edge construction stage, route connections between nodes are established based on spatial distance, flight feasibility, and operational constraints. Unlike conventional ground transport networks, where road connections are relatively explicit, node connections in low-altitude logistics networks must satisfy multiple conditions simultaneously, including that the flight distance does not exceed the effective operating range of the drone, that the path does not cross major no-fly zones or highly sensitive spaces, and that the flight process meets basic operational safety requirements. For node pairs that satisfy these conditions, the study further calculates travel-time costs. These costs mainly consist of three components: flight time between nodes, takeoff-landing transition time, and additional detour time if necessary. Flight time is calculated based on effective flight distance and typical cruising speed, transition time reflects the basic time consumed in takeoff, landing, and loading or unloading, and detour time represents the additional cost caused by restricted airspace or environmental constraints. Through this process, the study constructs a low-altitude logistics edge structure with resistance attributes, making the network representation closer to actual operating conditions.

Finally, in the demand mapping stage, different types of urban demand units are incorporated into the service system of the network, forming an integrated analytical framework that links supply, connectivity, and demand. Specifically, this study takes residential communities, commercial facilities, office parks, industrial parks, and hospitals as demand service objects. According to their spatial relationship with low-altitude logistics nodes, potential service links are established between demand units and logistics facility nodes. On this basis, considering network connectivity, service radius, and operational constraints, the study identifies the low-altitude logistics service opportunities available to different demand units under given conditions. It should be noted that demand units are not treated merely as static points. Instead, through type identification and spatial aggregation, the study reflects the differences and spatiotemporal characteristics of demand across urban functional zones to some extent.

Overall, the low-altitude logistics network constructed in this study is not simply an abstract topological structure composed of nodes and links. Rather, it is a service network embedded in the urban built environment, demand distribution, and operational boundaries of low-altitude flight. By integrating multi-source spatiotemporal data, the study places the supply capacity, connectivity, and service objects of the urban low-altitude logistics network within a unified analytical framework, thereby providing a solid data basis and spatial representation for the subsequent accessibility evaluation.

3 METHODOLOGY

3.1 Accessibility Evaluation Framework

In this study, the accessibility of an urban low-altitude logistics network refers to the ability of different urban demand units to obtain low-altitude logistics service opportunities under given spatial conditions, operational constraints, and network supply configurations. Compared with conventional accessibility studies in transportation, accessibility in low-altitude logistics is influenced not only by facility distribution and spatial distance, but also by the combined effects of flight corridor organization, airspace restrictions, built-environment complexity, drone operating performance, and spatiotemporal variation in demand. Therefore, accessibility is not simply understood here as the shortest geometric distance between nodes. Instead, it is defined as a form of network service capacity that comprehensively reflects both service coverage and travel-time efficiency.

Based on this understanding, this study develops an accessibility evaluation framework for urban low-altitude logistics networks. The framework follows a basic analytical logic of “multi-source spatiotemporal data support–network construction–accessibility measurement–difference identification and factor analysis.” First, by integrating urban spatial environment data, low-altitude operational constraint data, demand distribution data, and network supply data, the study constructs an analytical network that can reflect realistic operating conditions. Second, accessibility is measured from two dimensions, namely spatial coverage and travel-time performance, for different urban areas. Finally, by comparing accessibility differences across regions, functional zones, and time scenarios, the study reveals the spatial differentiation and underlying mechanisms of service capacity within the urban low-altitude logistics network. This framework emphasizes understanding network value from the perspective of whether service targets can be effectively served, thereby making the evaluation more relevant to practical needs in urban governance and infrastructure optimization.

More specifically, accessibility in this study is divided into two core dimensions. The first is spatial coverage, which reflects the extent to which the low-altitude logistics network can cover urban demand units under given service radius and operational constraints, that is, which areas can be served. The second is travel-time performance, which reflects the time cost required for the network to reach different demand units under a given node layout and connection structure, that is, how quickly service can be delivered. Spatial coverage emphasizes the existence of service opportunities, whereas travel-time performance emphasizes differences in service efficiency. Together, these two dimensions constitute the core of the accessibility evaluation in this study. In addition, to reflect the spatiotemporal characteristics highlighted in the paper title, the study further compares accessibility under different temporal scenarios and operating conditions so as to identify the stability and variation of the network under dynamic conditions.

Overall, the proposed framework has two main features. First, instead of focusing solely on route optimization, it approaches the low-altitude logistics network as a service system that links infrastructure supply and urban demand from the perspective of overall urban service capacity. Second, it emphasizes the role of multi-source spatiotemporal data in supporting network evaluation, so that accessibility analysis moves beyond idealized assumptions and incorporates realistic factors such as built-environment constraints, operational boundaries, and demand heterogeneity. Based on this framework, the following analysis quantitatively measures accessibility in terms of spatial coverage and travel-time performance, and further examines its spatiotemporal variation and influencing factors.

3.2 Measurement and Analysis

In terms of measurement, this study evaluates the accessibility of Shenzhen’s low-altitude logistics network from two dimensions: spatial coverage and travel-time performance. The overall analytical logic is as follows: logistics facility nodes are treated as supply origins, different demand units are treated as service targets, and, by considering network connectivity conditions and operational resistance, the study measures both the availability of service opportunities and the efficiency of access across different urban areas. In this way, a comprehensive assessment of network service capacity can be obtained.

First, with regard to spatial coverage, the study focuses on whether different demand units can be incorporated into the effective service area of the low-altitude logistics network under given conditions. Specifically, taking logistics facility nodes as service centers and considering the typical service radius of drones, network connection relationships, and low-altitude operational constraints, the study identifies whether each demand unit can obtain at least one effective service opportunity. It then calculates the number, types, and proportion of demand units effectively covered within different spatial units, so as to reflect the service coverage range and the differences in service objects across the city. Through this process, it becomes possible to distinguish areas with high service coverage from those that remain underserved or insufficiently covered. The key objective of spatial coverage measurement is not to reproduce every route detail, but to reveal the spatial boundaries of network service and the overall pattern of service distribution.

Second, with regard to travel-time performance, the study further focuses on differences in service efficiency across urban areas. For each demand unit, the shortest time cost from accessible logistics facility nodes is calculated based on the connectivity structure of nodes and edges in the low-altitude logistics network. The total time cost mainly consists of flight time, takeoff-landing transition time, and additional detour time. Flight time is determined by the effective flight distance between nodes and the typical cruising speed of drones. Transition time is used to represent the basic time consumed in takeoff, landing, loading, and unloading operations. Additional detour time is introduced to reflect the time penalty caused by restricted airspace, sensitive facilities, or complex built-environment constraints that require route adjustment. On this basis, the study further calculates indicators such as average travel time, minimum travel time, and the proportion of demand units reachable within specified time thresholds in different areas, thereby capturing spatial differences in time efficiency. Compared with simple straight-line distance indicators, this approach provides a more realistic representation of service efficiency under actual urban operating conditions.

To capture the spatiotemporal dynamics of low-altitude logistics network accessibility, this study further introduces comparative scenario analysis. Considering that urban logistics activities and low-altitude flight conditions vary over time, at least two dimensions of scenario setting are incorporated. The first is the demand-period scenario, which distinguishes peak periods from off-peak periods so as to reflect changes in demand intensity and service pressure over time. The second is the operational-constraint scenario, which distinguishes normal operating conditions from constrained operating conditions so as to capture the effects of weather changes, local no-fly restrictions, or avoidance requirements around sensitive areas on network service capacity. Under different scenarios, the study repeats the measurement of spatial coverage and travel-time performance and compares the resulting differences, thereby revealing the variation of network accessibility under dynamic conditions. This treatment helps move beyond the limitations of conventional static evaluations and makes the analysis more consistent with real-world operational contexts.

At the analytical stage, the study proceeds in three directions. First, it analyzes the overall accessibility pattern of Shenzhen, identifying general differences in service coverage and time efficiency across different urban areas. Second, it compares accessibility changes across different functional zones, time periods, and operating scenarios in order to reveal spatiotemporal differentiation. Third, it examines the major causes of accessibility differences by considering factors such as node distribution, demand patterns, built-environment complexity, and operational constraints. To this end, the study combines spatial statistics, zonal comparison, and correlation-based analysis to interpret the spatial structure and driving mechanisms of accessibility. Through the above measurement and analytical process, the study aims to develop a systematic understanding of the service capacity of urban low-altitude logistics networks from two perspectives: whether service is accessible and how quickly service can be delivered.

4 RESULTS AND ANALYSIS

4.1 Overall Accessibility Pattern

Figure 1 presents the spatial variation in the composite accessibility index of the low-altitude logistics network across Shenzhen. The overall results reveal a clear core–periphery gradient in the accessibility of Shenzhen's low-altitude logistics network. Nanshan, Futian, and Luohu exhibit the highest levels of accessibility, with Nanshan reaching an accessibility index of 85.1, indicating the strongest service capacity in the city. In contrast, Pingshan, Dapeng, and Yantian show relatively low accessibility levels, with Dapeng recording the lowest value of 45.8. These findings suggest that the service capacity of the current low-altitude logistics network is not evenly distributed across urban space, but is instead closely associated with the degree of functional agglomeration, the density of facility deployment, and the overall spatial structure of the city.

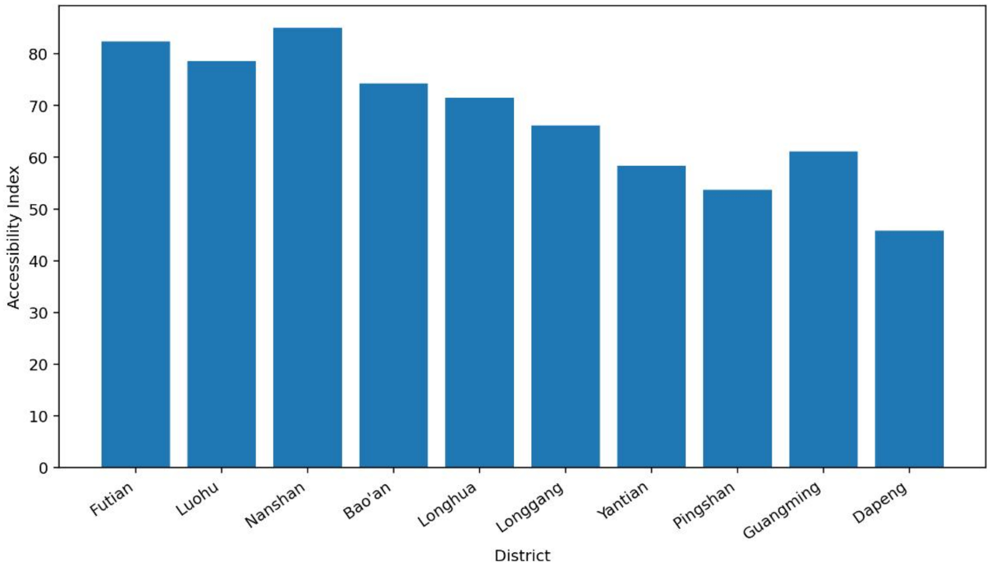

Figure 1 Overall Accessibility Pattern

As further shown in Table 1, areas with high accessibility tend to combine higher node density, stronger demand concentration, and shorter average travel times. For example, Nanshan reaches a coverage rate of 0.88 and an average travel time of only 13.5 min, indicating that it not only covers a larger number of service targets but also delivers services more efficiently. Futian and Luohu exhibit similar characteristics. By contrast, Pingshan, Yantian, and Dapeng, although still incorporated into the service system, show lower coverage rates and longer travel times, indicating an evident peripheral disadvantage. This pattern suggests that, at the current stage, the low-altitude logistics network tends to prioritize highly populated and commercially intensive urban cores where supporting facilities are already relatively well developed.

Table 1 Accessibility Evaluation Results of Shenzhen's Low-Altitude Logistics Network

District	Coverage Rate	Avg. Travel Time (min)	Peak Coverage Rate	Restricted Coverage Rate	Accessibility Index
Futian	0.86	14.2	0.81	0.73	82.4
Luohu	0.82	15.1	0.77	0.70	78.6
Nanshan	0.88	13.5	0.84	0.76	85.1
Bao'an	0.79	16.4	0.74	0.68	74.3
Longhua	0.76	17.2	0.71	0.65	71.5
Longgang	0.71	19.8	0.66	0.59	66.2
Yantian	0.63	21.1	0.58	0.50	58.4
Pingshan	0.58	23.4	0.53	0.46	53.7
Guangming	0.66	20.3	0.61	0.54	61.1
Dapeng	0.49	26.7	0.44	0.38	45.8

From a spatial-structural perspective, the above pattern reflects both similarities to and differences from conventional ground-based logistics networks. On the one hand, central districts remain the primary focus of network deployment because of denser facility configurations and more concentrated demand. On the other hand, some non-central areas with specific functional demand also demonstrate the potential to benefit from low-altitude logistics in terms of service extension and efficiency improvement. In other words, the low-altitude logistics network does not simply replicate the existing ground logistics structure, but instead forms a service pattern characterized by both "core reinforcement" and "peripheral extension."

4.2 Spatiotemporal Differences in Accessibility

Figure 2 compares the changes in coverage rates across Shenzhen under normal operating conditions, peak-period conditions, and restricted-operation conditions.

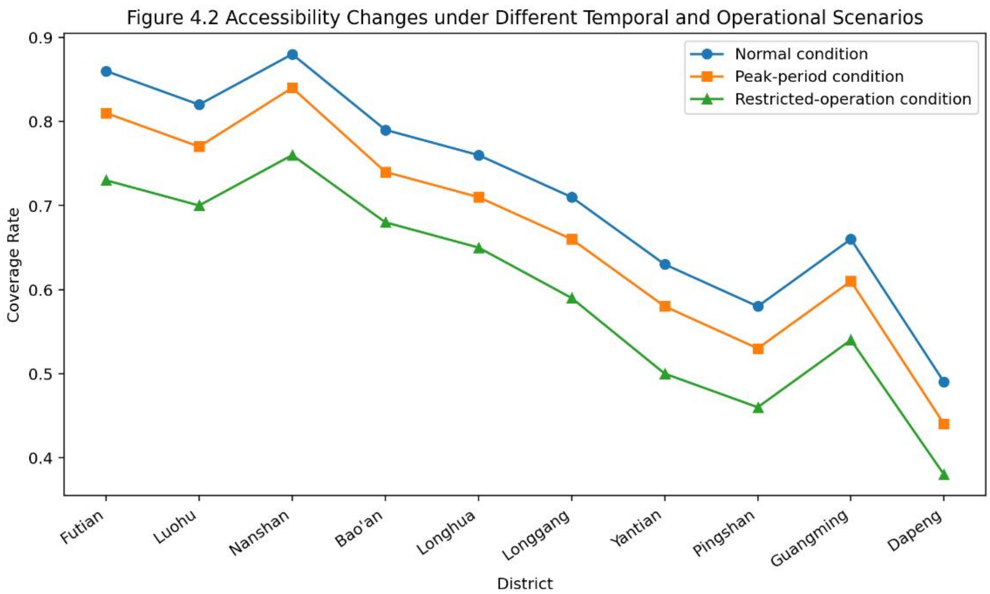

Figure 2 Scenario Comparison

In general, accessibility declines under all non-normal scenarios, but the magnitude of decline varies across districts. According to Table 2, the mean citywide coverage rate decreases from 0.718 under normal conditions to 0.668 during peak periods and further to 0.599 under restricted operations. At the same time, the mean travel time increases from 18.8 min to 20.1 min and 22.2 min, respectively. These results indicate that although the low-altitude logistics network has considerable service potential, its operational performance is jointly affected by temporal demand pressure and intensified operating constraints.

Table 2 Overall Accessibility Characteristics under Different Operational Scenarios

Scenario	Mean Coverage Rate	Highest-accessibility District	Lowest-accessibility District	Mean Travel Time (min)
Normal operation	0.718	Nanshan	Dapeng	18.8
Peak-period operation	0.668	Nanshan	Dapeng	20.1
Restricted operation	0.599	Nanshan	Dapeng	22.2

At the district level, the central districts remain relatively resilient despite the reduction in coverage rates across scenarios. For example, the coverage rate of Nanshan declines from 0.88 under normal conditions to 0.84 in the peak-period scenario and 0.76 in the restricted scenario, yet it still remains the highest in the city. Futian and Luohu exhibit similar trends. This suggests that dense node deployment and stronger network connectivity can buffer, to some extent, the negative effects of peak demand and operational disturbances. By contrast, areas that are already relatively weak in accessibility, such as Pingshan, Dapeng, and Yantian, experience more pronounced declines under constrained conditions. For instance, Dapeng's coverage rate falls from 0.49 to 0.38, indicating that peripheral areas are more sensitive to changes in operating conditions and are more likely to experience service deterioration when the network is disturbed.

From the perspective of spatiotemporal dynamics, the change in accessibility is not limited to an overall decline in performance; it also involves a further widening of spatial disparities. While central districts and peripheral areas already differ significantly under normal conditions, this disparity becomes even more pronounced under peak and restricted scenarios. This finding indicates that the low-altitude logistics network does not operate uniformly across the urban space, but is instead characterized by marked spatial heterogeneity and scenario dependence. From a planning perspective, this implies that low-altitude logistics facilities should not be allocated solely based on average static demand. Instead, greater attention should be paid to areas that are more likely to fall into a "low-accessibility trap" under temporal fluctuations and operational restrictions.

4.3 Factors Affecting Accessibility

Figure 3 shows the directional correlations between the main influencing factors and the composite accessibility level.

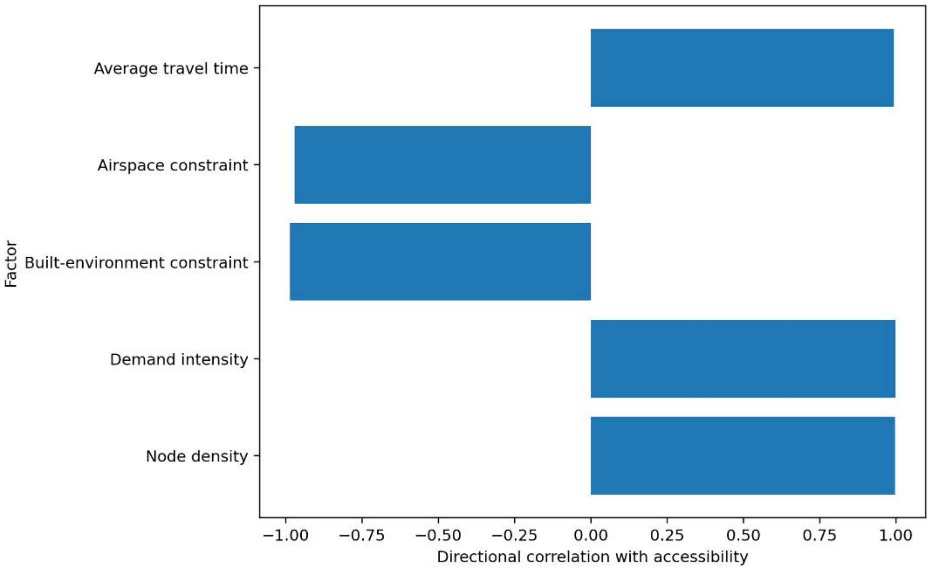

Figure 3 Factors Affecting Accessibility

The results indicate that node density and demand intensity are positively associated with the accessibility of the low-altitude logistics network, whereas built-environment constraints, airspace constraints, and average travel time are negatively associated with accessibility. Among these factors, node density exerts the strongest effect, suggesting that the spatial configuration of low-altitude logistics facilities is the key determinant of network service capacity. The denser the node layout, the higher the probability that demand units can obtain service opportunities, and the easier it becomes to shorten internal connection paths within the network, thereby improving both service coverage and delivery efficiency. This is consistent with the previous results, where high-accessibility districts such as Nanshan and Futian also exhibit denser facility deployment.

Demand intensity also shows a strong promoting effect. This indicates that the current development of the low-altitude logistics network is highly demand-oriented: areas with stronger demand concentration are more likely to receive facility investment and to form efficient service linkages. While this helps generate high service efficiency in the urban core, it may also leave peripheral low-demand areas in a persistently weak service position, thereby reinforcing spatial inequality. In other words, if network deployment relies excessively on spontaneous market demand concentration, it may strengthen pre-existing central advantages while failing to effectively address service deficiencies in outer urban areas.

In addition, built-environment constraints and airspace constraints both exert a clear inhibitory effect on accessibility. Areas with dense high-rise buildings, strong spatial obstruction, or a concentrated distribution of sensitive facilities typically require more complex route detours and stricter safety avoidance measures, thereby increasing network resistance and reducing service efficiency. These effects become even more pronounced under restricted operational conditions. This finding suggests that accessibility is determined not only by whether logistics nodes are present, but also by whether the surrounding environment is suitable for low-altitude operations. Therefore, future optimization of low-altitude logistics networks should proceed simultaneously from three perspectives: facility layout optimization, demand-service matching, and improvement of the low-altitude operating environment, rather than relying solely on an increase in node numbers.

5 CONCLUSION

This study develops an accessibility evaluation framework for urban low-altitude logistics networks by integrating multi-source spatiotemporal data, including the spatial environment, logistics demand, operational constraints, and network supply, with Shenzhen as the case study. The results show that network accessibility is unevenly distributed and exhibits a clear core–periphery pattern: central districts such as Nanshan, Futian, and Luohu have higher coverage and shorter travel times, while peripheral areas such as Pingshan, Dapeng, and Yantian remain less accessible. This suggests that the service capacity of low-altitude logistics is closely linked to urban functional agglomeration, facility layout, and broader spatial structure.

Scenario analysis further reveals strong spatiotemporal dynamics. Under peak-period and restricted-operation conditions, coverage declines and travel times increase, with peripheral and initially less accessible areas being more vulnerable to service deterioration. This highlights that evaluations based only on static average conditions cannot fully reflect actual network performance, and that a realistic assessment must incorporate demand fluctuations, operational restrictions, and spatial-environment constraints.

The results also indicate that node density and demand intensity enhance accessibility, whereas built-environment constraints, airspace restrictions, and time resistance limit service capacity. Therefore, improving accessibility requires not only more facilities, but also better facility placement, stronger demand–supply matching, and improved operating conditions. Overall, this study provides a useful framework for evaluating and optimizing urban low-altitude logistics networks, although future research should further incorporate real order data, dynamic routing, and real-time operational states.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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