Urban Low-Altitude Planning: Elements, Implementation Pathways, and Planning Responses for Ground-Air Coordination

HUANG Jianzhong, HE Jiawen, ZHANG Weicong, XIAO Zuopeng, WU Zhiqiang

Abstract: The development of the low-altitude economy has given rise to new demands for the integrated utilization of ground and airspace. In urban low-altitude planning, ground-air coordination has become essential for building effective lowaltitude service networks. However, existing research has focused primarily on technical issues and lacks analysis of the elements and implementation pathways from a spatial-organization perspective. Taking drone delivery logistics as an example, this paper, employing a literature review and case study approach, analyzes the elements, characteristics, and implementation pathways of ground-air collaboration, elaborates on the practical challenges, and proposes corresponding planning strategies. The study finds that ground-air coordination is characterized by multi-agent scenario collaboration, multi-target network collaboration, and multi-scale node collaboration. In terms of implementation, it follows a pathway that ranks demand to construct a spectrum of service scenarios, anchors ground-based elements to organize route networks, and integrates node facilities into the built environment. To this end, the study suggests that urban low-altitude planning should identify real needs, promote hierarchical planning, improve airspace control, coordinate route development, innovate management mechanisms, and integrate facilities into a network. These measures can provide the spatial safeguards to advance the coordinated development of ground and air operations.

Keywords: low-altitude economy; drone delivery; ground-air coordination; new infrastructure; new quality productive forces

Since the low-altitude economy was first incorporated into the Outline of the National Comprehensive Three-dimensional Transportation Network Planning in 2021[1], low-altitude flight activities have rapidly stimulated the development of related industries, including aircraft manufacturing[2]. Applications have emerged in various fields, such as logistics delivery, infrastructure inspection, emergency rescue, agricultural operations, and cultural tourism. Among these applications, drone delivery has achieved rapid development, particularly driven by enterprises such as China Post, JD.com, Meituan, and SF Express. Drone-based delivery services have increasingly been applied in high-density urban commercial areas, remote rural regions, scenic areas, industrial parks, islands, and disaster-response scenarios, providing rapid delivery of meals, fresh products, medical supplies, and emergency materials. Compared with conventional logistics systems, drone delivery is less dependent on ground transportation infrastructure and can overcome geographical barriers while significantly improving transportation efficiency. As an important example of how the low-altitude economy contributes to the development of new quality productive forces[2], drone delivery has become a key phenomenon requiring attention in urban low-altitude planning.

The rapid expansion of drone delivery demonstrates that low-altitude resources can effectively connect and reorganize ground-based supply and demand systems[3-5]. Although drones and low-altitude flight constitute the primary carriers and operational modes of low-altitude logistics, their operations still rely heavily on ground facilities, operators, information systems, and spatial conditions. Flight routes and takeoff-and-landing facilities are also constrained by ground-based factors. Therefore, drone delivery is not merely a process of connection and transportation within airspace; rather, it represents the extension of ground resources into low-altitude space and the spatial embedding of airspace resources into urban environments. In other words, the development of the low-altitude economy cannot be separated from ground-based spatial systems, and research on low-altitude transportation should emphasize the coordinated relationship between ground and air systems.

Existing studies on ground-air coordination in low-altitude development can generally be summarized into three categories. First, some studies examine how ground resources and management systems influence airspace capacity[6], risk assessment[7], route planning[8-9], and operational management[10-11]. Second, research focuses on coordination between drones and ground transportation modes[12], including collaboration between drones and trucks[13], electric vehicles[14-15], autonomous vehicles[16], and robots[17]. Third, some studies analyze optimization strategies for node layout[18-19], route design, and task allocation from the perspective of ground-air coordination[20-21]. However, existing research has primarily concentrated on aviation and transportation fields, emphasizing algorithm development and technological optimization. Moreover, relatively few studies have incorporated real-world cases to investigate the spatial organization of ground-air coordination, including the composition of ground and air elements, coordination mechanisms, and planning implications. Consequently, the relationship between land use, spatial development, infrastructure configuration, and low-altitude planning remains insufficiently explored.

To address this gap, this study analyzes the structural elements and technical requirements of ground-air coordination in low-altitude flight and identifies the characteristics and internal mechanisms of drone delivery coordination. Through case studies of leading enterprises, it explores the implementation pathways of drone delivery-based ground-air coordination, discusses practical challenges, and proposes planning responses. The study aims to provide methodological and policy insights for integrating ground-air coordination into urban low-altitude planning.

1 Elements and Requirements of Ground-Air Coordination

1.1Elements and Technical Requirements of Ground-Air Coordination in Low-Altitude Flight

Conceptually, ground-air coordination can be traced back to the broader framework of the "Space-Air-Ground Integrated Network" (SAGIN)[13,17,22] (Figure 1). This framework relies on communication and information systems provided by space-based technologies, combined with ground infrastructure systems and unified data standards, to enable real-time information sharing and coordinated allocation of flight tasks in both time and space. Through the integration and utilization of different resources, it supports transportation activities involving manned aircraft, drones, and airships, thereby forming an efficient and stable collaborative operational system[24].

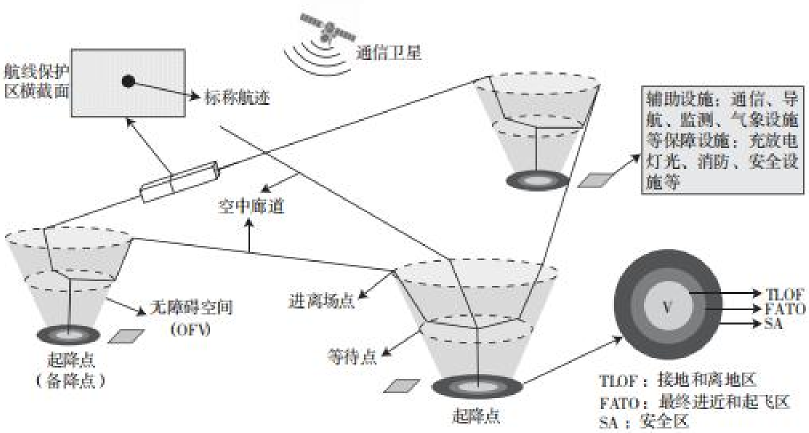


Fig.1 Ground-air coordination system and its elements for low-altitude flying

The air system mainly includes obstacle-free volumes (OFVs) required for aircraft vertical takeoff and landing operations, flight corridors connecting different takeoff and landing sites, and airspace classifications established to ensure safe flight operations. The obstacle-free volume refers to a funnel-shaped spatial area above a vertical takeoff and landing site designed to reduce interference from surrounding environments, noise, and obstacles during aircraft operations[25].

Airspace is generally divided according to different levels of operational permission, including permitted flight zones, controlled zones, and prohibited zones. Flight routes are typically located within permitted zones, where drone operations can be conducted without additional approval procedures. Controlled zones require authorization before operation, while prohibited zones restrict all drone activities. The ground system primarily refers to takeoff-and-landing facilities, which support drone operations involving cargo loading, unloading, and passenger transfer. These facilities include hub-based landing sites, delivery cabinets or lowering points for cargo transfer, and emergency landing areas reserved for unexpected conditions such as weather changes or electromagnetic interference. From a spatial perspective, takeoff-and-landing facilities consist of touchdown and liftoff areas (TLOF), final approach and takeoff areas (FATO), safety areas (SA), and associated supporting infrastructure[22]. TLOF provides the physical platform for aircraft landing and departure[26]; FATO supports hovering, landing, and takeoff procedures; and safety areas serve as protection zones to reduce risks caused by deviations from operational areas[25]. Supporting facilities include parking spaces, communication, navigation, monitoring, meteorological systems, command centers, data platforms, storage areas, charging facilities, lighting systems, and firefighting equipment. Together, these elements constitute the fundamental spatial framework for ground-air coordination in low-altitude flight.

1.2Characteristics and Internal Requirements of Ground-Air Coordination in Drone Delivery

The above framework explains the key elements of ground-air coordination systems in low-altitude flight from a vertical perspective and clarifies the technical requirements for achieving coordination among different elements. Together, these elements establish the fundamental operational model of ground-air coordination (Figure 2). However, from the perspective of actual drone delivery operations, ground-air coordination involves more complex dimensions and requirements.

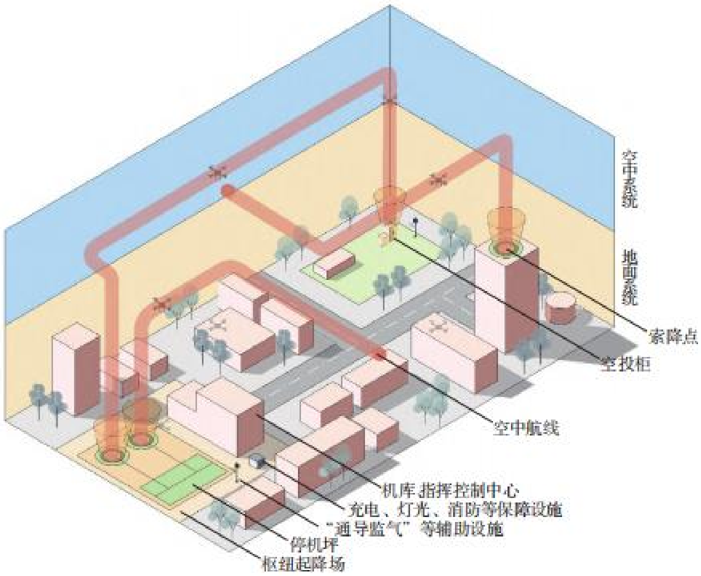


Fig.2 Diagram of ground-air coordinated low-altitude flight systems

1.2.1Multi-agent Scenario Coordination

Drone delivery is essentially a third-party logistics service that connects goods suppliers and demand-side users (Figure 3). Therefore, the primary meaning of ground-air coordination lies in coordinating products, supply-demand actors, and spatial scenarios within drone delivery processes.

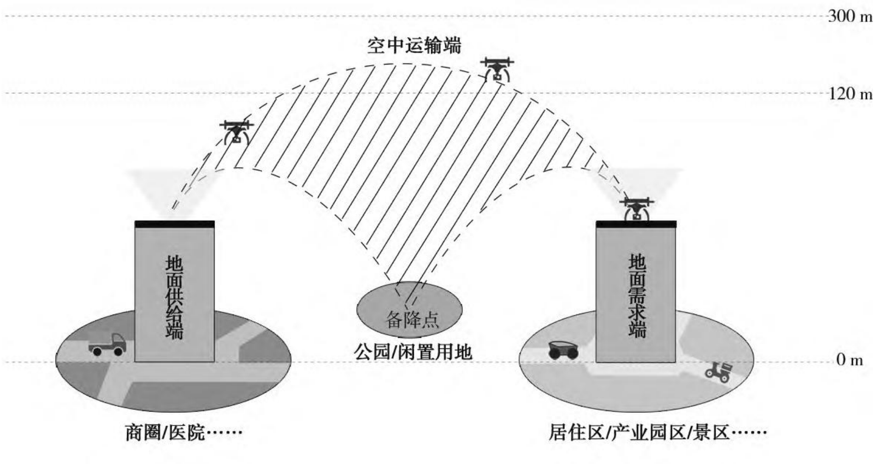


Fig.3 Ground-air coordination of drone delivery

For example, delivering food and beverages from commercial areas to customers represents an urban drone instant-delivery scenario; transporting medical samples from township collection points to urban testing centers represents low-altitude medical logistics; delivering daily necessities from coastal bases to island communities represents cross-sea low-altitude transportation; transporting emergency supplies from storage facilities to disaster areas represents emergency drone delivery; transferring construction equipment from service stations to construction sites represents engineering logistics; and transporting agricultural products from farmland to collection stations represents agricultural logistics.

The characteristics of goods, supply-demand actors, and spatial contexts jointly determine delivery frequency, origin-destination distribution, flight distance, response time, and the operational structure of "trunk–branch–terminal" networks (Figure 4). These factors provide the foundation for designing route networks and establishing ground-air coordination systems.

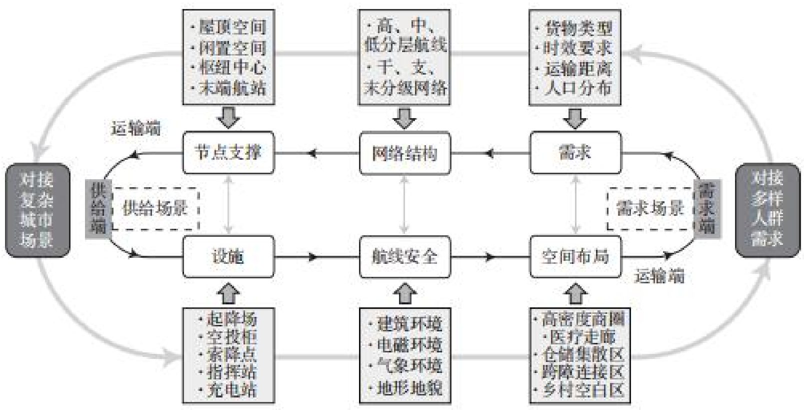


Fig.4 The logic of ground-air coordination pathway for drone delivery

1.2.2Multi-objective Network Coordination

Existing technology-oriented research on ground-air coordination mainly focuses on ensuring flight safety and route reliability from the perspective of air transportation systems.

Compared with conventional aviation transportation, drone delivery operates at lower altitudes, meaning that flight safety must consider a wider range of ground-related factors, including terrain, land use, built environments, surface activities, and population distribution (Figure 4). Beyond safety considerations, these factors also influence multiple objectives. For example, determining routes based on ground activities can improve economic efficiency; considering spatial differences in urban supply and demand can enhance accessibility of drone delivery services in high-demand and underserved areas; integrating drones with trucks, buses, and rail transit can improve operational efficiency and affordability by utilizing the advantages of different transportation modes; and such integration can strengthen network resilience. Therefore, drone delivery routes are not independent airspace systems but are deeply interconnected with ground-based socioeconomic and spatial networks.

1.2.3Multi-scale Node Coordination

Drone delivery organizes operational networks through the integration of ground spatial scenarios, generating different types of nodes. These nodes include both macro-scale service deployment locations and micro-scale facilities embedded within buildings or urban spaces, such as takeoff-and-landing facilities (Figure 4). These embedded nodes function as spatial anchors for drone delivery activities. They serve as physical carriers supporting operational organization and act as transfer hubs connecting drone delivery with other transportation modes. Consequently, they directly influence operational efficiency and service responsiveness within ground-air coordination networks.

2 Research Cases and Methods

2.1Research Cases

This study adopts a case study approach. Considering the current development status of drone delivery in China, representative enterprises engaged in instant delivery, logistics transportation, and medical transfer scenarios were selected as research cases, including enterprises referred to as M, S, and Y (Table 1).

Tab.1 Basic information on company cases

案例企业	主导业务	起降点/个	航线数量/条	平均航线距离/km	飞行高度/m
M	商圈的即时配送	61	49	2.0	120
S	网点间快递物流	222	549	6.3	120—300
Y	医院间物资转运	100	2550	7.2	120

注：M数据截至2025年8月，起降点包括起降场和空投柜；S数据截至2025年5月底；Y数据截至2025年4月，起降点包括起降场和索降点。

As one of China’s largest instant retail platforms, M Company began exploring lightweight, short-distance drone delivery services (less than 3 km) in 2017. In early 2021, it successfully completed its first drone delivery order involving real users. In February 2023, the company obtained the Specific Category Unmanned Aircraft Trial Operation Approval Letter and the General Aviation Enterprise Operation License, and began pilot drone delivery operations in Shenzhen. By the end of 2024, M Company had established 53 drone delivery routes in China.

Most routes were concentrated in Shenzhen, with additional routes deployed in Beijing, Shanghai, Guangzhou, and other cities. Its service scenarios covered offices, communities, scenic areas, municipal parks, campuses, libraries, and other urban spaces.

As one of China's largest comprehensive logistics service providers, S Company provides services including express delivery, freight transportation, cold-chain logistics, medical logistics, and intra-city delivery. The company began developing cargo drones in 2015 and became the first pilot enterprise approved by the Civil Aviation Administration of China in 2017. In March 2018, it obtained China's first Unmanned Aircraft Aviation Operation (Pilot) License issued by the Civil Aviation Administration. By the end of 2024, S Company had established 549 drone routes nationwide, completing more than 1.1 million flights, transporting over 6.2 million packages, and achieving a cumulative flight distance exceeding 5.7 million kilometers.

Y Company was established in 2015. In October 2019, it obtained the world's first Specific Category Unmanned Aircraft Trial Operation Approval Letter and Unmanned Aircraft Logistics Delivery Operation License issued by the Civil Aviation Administration of China. The company mainly provides drone delivery solutions in medical emergency response, intra-city logistics, fresh food delivery, postal express services, and industrial park logistics. As of August 14, 2025, it had completed more than 310,000 flights, with a total flight duration of nearly 59,000 hours and cumulative flight distance exceeding 2 million kilometers. Medical applications accounted for approximately 85% of its urban drone delivery operations, covering more than 50 cities and serving over one hundred medical alliances and hospitals above the municipal level.

2.2Research Methods

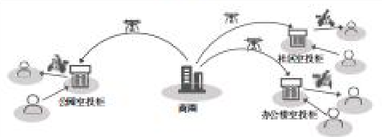
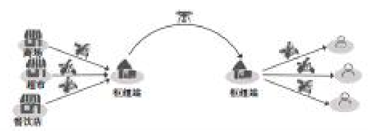
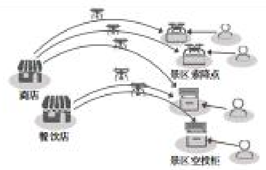
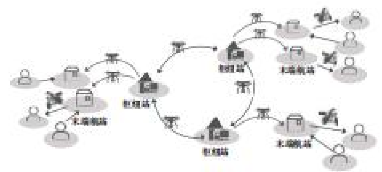
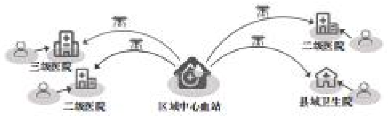
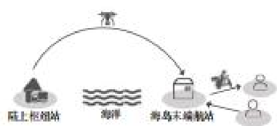
This study conducted continuous tracking research on the above three enterprises and related companies from March 2024 to June 2025. First, information regarding enterprise development, operational scale, spatial deployment, and operating costs was collected through company websites, news platforms, annual reports, and financial reports. Second, field investigations were conducted through site visits and interviews with enterprise managers and relevant personnel. These investigations focused on enterprise development processes, major business areas, operational equipment, flight routes, service models, operational conditions, safety requirements, and other related information. Data including route planning documents, operation manuals, and future development plans were obtained. Field surveys were also conducted on landing sites, command platforms, data centers, storage facilities, and maintenance facilities to understand land requirements and spatial demands. Third, based on enterprise websites, visualization platforms, and mobile applications, additional information on routes, landing facilities, and service providers was collected through operational testing methods. ArcGIS and other spatial analysis tools were then applied to conduct three-dimensional visualization simulations.

3 Implementation Pathways of Ground-Air Coordination in Drone Delivery

3.1Differentiating Demand Characteristics and Constructing a Spectrum of Ground-Air Coordination Scenarios

The primary task of achieving ground-air coordination in drone delivery is to identify the demand characteristics of specific spatial contexts and establish corresponding service models. According to the cases of the three enterprises, current ground-air coordination models are mainly oriented toward enterprise-specific operational needs, with drones being used to enhance existing service systems (Table 2).

Tab.2 Low-altitude logistics demand profile and ground-air coordination model

场景需求	地空协同模式	示意图
商圈即时配送	商圈无人机配送+末端空投柜骑手接驳配送/用户自取	
商圈集合配送	商圈骑手配送+枢纽站间无人机运输+末端骑手配送	
景区即时配送	商场无人机配送+景区索降点/自动枢纽站用户自取	
快递物流配送	枢纽站间无人机转运/配送+末端航站骑手接驳配送/用户自取	
医疗物资转运	区域中心血站无人机配送+各级医疗机构专员自取	
海洋海岛运输	枢纽站无人机运输+末端航站骑手配送/用户自取	

For example, M Company mainly focuses on food delivery services. Therefore, its ground-air coordination system is primarily organized around commercial areas. Landing facilities are established in shopping centers with high concentrations of stores, while drone delivery cabinets are deployed in high-demand areas such as residential communities, office districts, and scenic areas within a radius of approximately 0.5–2 km. This model forms a hub-and-spoke service network, where drones undertake one-way delivery from commercial centers to terminal delivery cabinets. Residents can choose whether to use this service according to their needs and may either collect goods from the delivery cabinets or arrange further delivery through couriers. In contrast, S Company mainly provides high-value parcel delivery and urgent logistics services. Its ground-air coordination model relies on existing logistics stations to establish takeoff-and-landing facilities and construct interconnected station networks. Rapid low-altitude transportation between stations (within approximately 7 km) is developed as a service product that users can select according to demand. Its major service targets include high-value commodities such as gold and jewelry, as well as time-sensitive products such as seafood and fresh fruits. Y Company focuses on medical transportation scenarios, particularly the transfer demands of biological samples, vaccines, and medical supplies within medical networks. Therefore, it establishes landing facilities in medical institutions and forms a multi-level, bidirectional ground-air coordination service network.

A comparative analysis of these three cases indicates that the fundamental purpose of drone-based ground-air coordination is to replace conventional ground-based manual delivery through low-altitude transportation. This substitution is mainly driven by product characteristics and service requirements. From the perspective of products, drone delivery is primarily suitable for goods with strong requirements for timeliness or high economic value. From the perspective of service demand, drone delivery is introduced when conventional ground transportation cannot effectively satisfy operational requirements. These situations include:(1) Complex and highly dense urban road networks that reduce ground transportation efficiency; (2) Geographical barriers such as mountains, rivers, and seas that reduce delivery speed; (3) High-rise buildings where vertical transportation inefficiencies, such as waiting for elevators, affect delivery efficiency; (4) Specific areas such as tourism destinations, cultural and sports venues, and campuses where local supply cannot adequately match demand; (5) Spatial accessibility problems in areas such as scenic spots, universities, and parks where “finding entrances” or “entering spaces” creates delivery difficulties; (6) Situations where extreme weather or disasters interrupt ground transportation. Facing these scenarios, enterprises adopt different strategies, including independently constructing or collaboratively developing drone delivery service systems according to their operational characteristics and resource advantages.

3.2Anchoring Ground Elements and Organizing Ground-Air Coordinated Route Networks

Route networks constitute the core component of ground-air coordination. Based on the practices of S, M, and Y companies, drone route planning involves flight paths under different operational states, including takeoff, landing, cruising, and hovering. These routes need to consider multiple ground-related factors, including natural landscapes, land use, built environments, and human activities (Table 3).

Tab.3 Influencing factors and positive-negative impacts on the establishment of low-altitude logistics routes from ground-air coordination perspective

要素		安全性	可靠性	公共接受度
自然地貌	山体/绿地	★★★★	☆☆☆	★★★★★
	水体	★★★★	★★★★	★★★★★
土地利用	道路	★★★★	★★★	★★★★
	铁路、高速铁路	☆☆☆☆☆	☆☆	
	机场	☆☆☆☆☆	☆☆☆	
	核电站、油库	☆☆☆☆☆	☆☆☆☆☆	
	高等级居住区	☆☆☆☆	★★★	☆☆☆☆
	学校、政府机关	☆☆☆☆		☆☆☆☆
	工业、物流仓储区	★★★	☆☆☆	★★★★★
	空地荒地、未利用地	★★★	★★★★★	★★★★★
建成环境	高层建筑	☆☆		☆☆☆☆
	建筑物风口	☆☆☆	☆☆☆	
	铁塔、高压线、电力线	☆☆☆	☆☆☆	
	通信基站	☆☆☆	☆☆☆☆	
地面活动	建筑工地(塔吊)	☆	☆☆☆	
	市民活动(风筝、人群活动)	☆☆☆☆	☆☆☆	☆☆☆☆☆

注：★为正向效应，☆为负向效应

These factors may positively or negatively influence route safety, reliability, and public acceptance. Specifically: Safety refers to the protection of people and facilities on the ground, including potential damage caused by aircraft accidents, secondary disaster risks, and the difficulty of locating drones or transported goods. Reliability refers to the ability to maintain stable operations under changing weather conditions, electromagnetic environments, and obstacle conditions. Public acceptance refers to the impacts of drone operations on residents, particularly in terms of noise disturbance and privacy concerns.

(1) Natural Landscape Factors

Natural landscapes, including mountains, green spaces, and water bodies, can reduce potential harm to ground users in the event of aircraft failure and therefore serve as positive factors for route planning. However, mountainous areas may also experience unstable weather conditions, affecting operational reliability. Mountain areas, green spaces, and water bodies also influence the difficulty of searching for failed aircraft and require careful evaluation regarding possible secondary risks.

(2) Land Use Factors

Road spaces beneath drone routes can provide relatively open environments, improving route safety, reliability, and public acceptance. Therefore, drone routes operated by M, S, and Y companies are generally aligned with major transportation corridors (Figure 5).

Fig.5 Diagram of low-altitude drone delivery routes in 3D environments in Nanshan District, Shenzhen

However, visual disturbances caused by drone takeoff and landing may influence traffic safety and public acceptance. Facilities with strategic importance or high security requirements, such as civil and military airports, nuclear power plants, oil storage facilities, and high-speed railways, become prohibited areas for drone delivery routes (Figure 6).

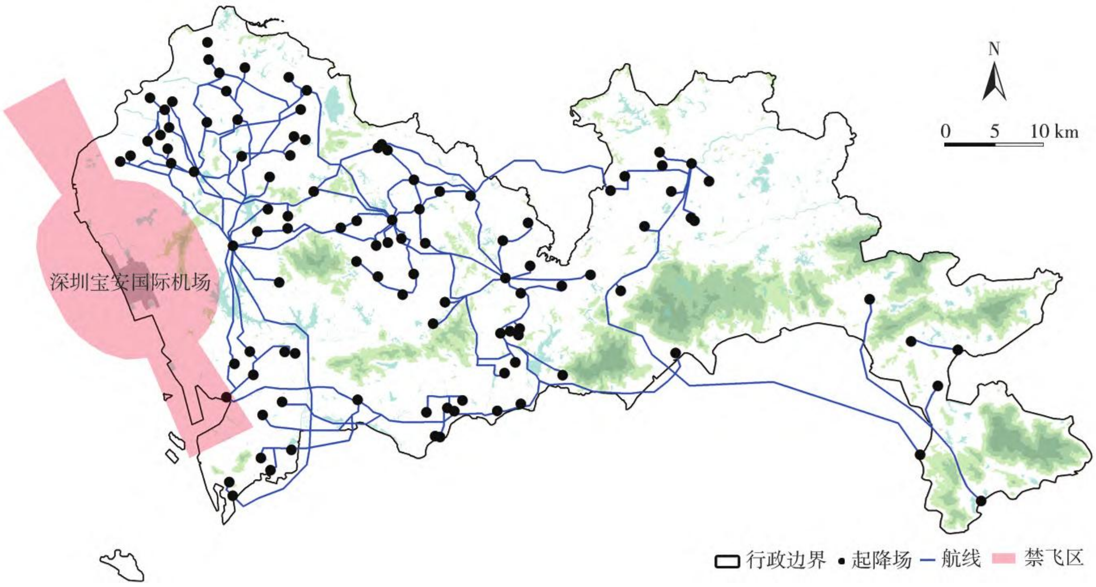


Fig.6 Current status of S company's drone delivery network in Shenzhen

Government facilities and high-end residential areas may negatively influence route planning due to privacy concerns and public acceptance. Sensitive areas such as kindergartens, schools, nursing homes, and residential communities are also considered restrictive factors due to noise impacts. In contrast, industrial parks, logistics warehouses, vacant land, and unused spaces may serve as favorable locations due to higher tolerance for noise and greater availability of emergency landing areas.

(3) Built Environment Factors

High-rise buildings and other physical obstacles influence flight safety by creating potential collision risks. Building layouts may generate wind shear zones that affect local meteorological conditions. Communication towers, high-voltage lines, and power facilities not only constitute physical obstacles but also alter electromagnetic environments, thereby influencing route safety.

(4) Ground Activity Factors

Dynamic obstacles, including birds, kites, balloons, and tower cranes at construction sites, may negatively affect low-altitude flight safety and therefore need to be considered as constraints in route planning.

3.3Embedding into the Built Environment and Expanding Ground-Air Coordination Nodes

Compared with flight routes that primarily utilize low-altitude public space, takeoff-and-landing facilities occupy more diverse spatial types (Table 4).

Tab.4 Types and spatial distribution of landing field

空间类型	M		S	Y
	起降场/个	空投柜/个	起降场/个	起降场/个
建筑楼顶	10	0	91	0
院落空间	0	4	2	16
街道空间	0	21	0	2
公园空间	0	20	0	6
总计	10	45	93	24

注：报告的数据是M公司、S公司在深圳，Y公司在合肥的统计数据

Currently, drone delivery facilities mainly include landing fields, delivery cabinets, and lowering points. Different facility types have different functions and supporting infrastructure. Landing fields provide multiple functions, including drone takeoff and landing, storage, control, loading, and unloading. Therefore, they are usually equipped with communication systems, navigation facilities, monitoring systems, meteorological equipment, charging facilities, firefighting systems, control platforms, storage areas, and multiple landing positions. Their required area generally exceeds 300 m^2. Drone delivery cabinets mainly function as intelligent facilities for receiving and collecting goods. They usually occupy approximately 10 m^2 and are equipped with power supply systems and management devices, serving both as transfer facilities and self-service collection points. Lowering points are simpler facilities. They are generally defined by visual positioning markers located on the ground or building surfaces. Drones use geographic positioning and image recognition technologies to identify specific locations and lower goods through suspension systems without requiring additional supporting facilities. This type of facility is suitable for large-scale deployment to expand service coverage.

In terms of implementation, drone enterprises mainly rely on existing built environments, including building rooftops, courtyards, street spaces, and public parks, to establish landing facilities and related nodes (Figure 7).

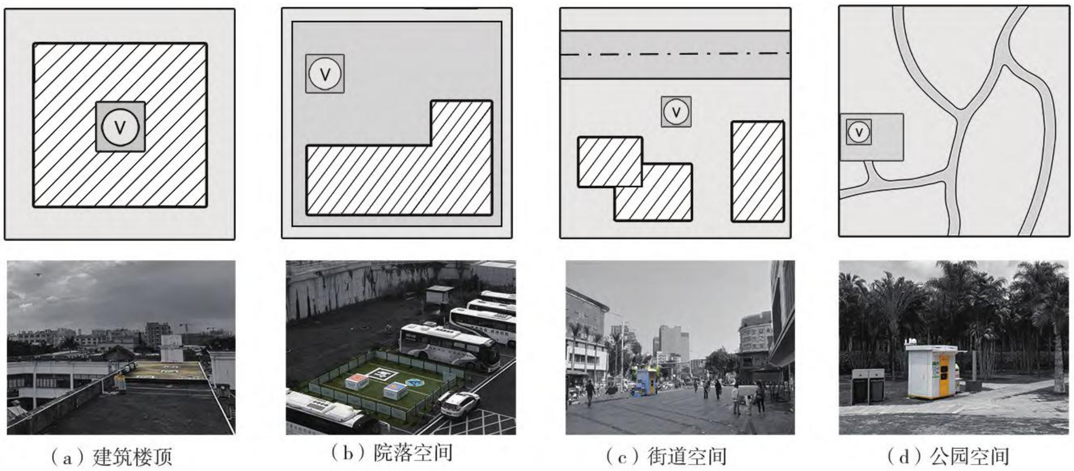


Fig.7 Types of built environments hosting nodes for ground-air coordinated drone delivery

For example, M Company mainly adopts two approaches:① Leasing open spaces above commercial complexes, such as podium buildings and office building rooftops, to establish landing fields or lowering points;② Establishing delivery cabinets or lowering points within street and park spaces after obtaining approval from relevant administrative departments. Due to S Company's extensive network of self-owned or leased logistics facilities, its landing fields are mainly constructed on the rooftops or courtyard spaces of existing logistics stations. In addition to these approaches, Y Company adopts another model: drone delivery demand providers (such as hospitals and blood centers) independently invest in their own spatial resources, while Y Company undertakes the construction of landing facilities. These spatial deployment strategies demonstrate that during the early stage of industry expansion, drone delivery enterprises focus on expanding landing facility networks and controlling costs. Based on differences in spatial resource acquisition, enterprises have developed diverse implementation pathways.

4 Challenges and Planning Responses

4.1Assessing Actual Demand and Promoting Hierarchical Planning for Ground-Air Coordination

Drone delivery is essentially a cargo transportation activity, achieving the spatial transfer of goods through low-altitude flight. The emergence of such transportation demand requires a comparison between drone delivery and alternative transportation modes to identify suitable application scenarios. These suitable scenarios involve multiple dimensions, including transported goods, required response time, and spatial conditions. Suitability is not only determined by technical feasibility and safety but also by economic efficiency. In other words, drone delivery should provide greater economic benefits than conventional transportation methods in order to achieve long-term sustainability. From the perspective of goods characteristics, current sustainable commercial applications of drone delivery by M, S, and Y companies mainly involve goods characterized by being: urgent; difficult to transport; high-risk; high-value. These include intra-city urgent delivery, goods difficult to reach through ground transportation, products requiring additional time guarantees, and valuable commodities. Based on these goods characteristics and the corresponding temporal-spatial scenarios discussed above, drone delivery creates a value difference between low-altitude transportation and ground transportation, thereby generating genuine demand. Therefore, urban low-altitude planning should evaluate the "technology–economy" logic underlying ground-air coordination rather than assuming universal demand or blindly promoting infrastructure deployment. Specifically, planning should establish evaluation indicators and assessment frameworks for different demand scenarios, determine development priorities according to scenario differences, and formulate short-, medium-, and long-term planning strategies. Priority should be given to supporting drone delivery applications in fields such as medical emergency response and high-value cold-chain logistics by providing spatial support and infrastructure. At the implementation level, planning should identify potential application scenarios during urban renewal processes and reserve appropriate spatial conditions, enabling drone delivery to gradually evolve from isolated pilot projects toward large-scale applications.

Furthermore, some enterprises argue that drone delivery should be considered from a broader and longer-term perspective regarding its relationship with other transportation modes. For example, with future population aging, declining birth rates, and improved social security systems, the overall labor cost of ground delivery may continue to increase, while drone manufacturing costs are expected to decrease. The expansion of cargo capacity, collective delivery models, and large-scale applications may reduce marginal delivery costs. By connecting with trucks, rail transit, and other transportation systems, drone delivery can better utilize its advantages through multimodal transportation. Moreover, after large-scale adoption of low-altitude passenger transportation systems, particularly electric Vertical Take-off and Landing (eVTOL) vehicles, integrated passenger and cargo transportation systems may emerge[28]. Therefore, urban low-altitude planning should maintain a cautious yet open attitude toward future drone delivery development, considering possible organizational transformations caused by large-scale applications. Planning should proactively identify potential scenarios, reserve spatial conditions, and establish access conditions for future development. At the implementation level, assessment results regarding low-altitude application scenarios should be incorporated into territorial spatial planning and comprehensive transportation planning. Ground and low-altitude resources should be coordinated, low-altitude airspace and routes should be classified and approved, and efficient ground-air coordination mechanisms should be established.

4.2Improving Airspace Management and Coordinating Route Development

During the early stage of low-altitude economic development, drone routes are generally independently surveyed, planned, applied for, and operated by enterprises. This phenomenon is particularly evident in drone delivery. The enterprises examined in this study have invested significant resources in route development and regard these networks as core assets. From a broader perspective, low-altitude service platforms developed by different provinces and cities mainly serve local enterprises and remain disconnected from one another, making it difficult to achieve cross-enterprise and cross-regional integrated operations. With the further development of the low-altitude economy, competition over route resources may emerge, reducing the efficiency of low-altitude resource utilization. To address this issue, academic and industrial research has proposed various strategies, including optimizing airspace classification, establishing public routes, promoting airspace sharing, and dynamically releasing airspace resources. For example, some studies suggest that airspace should be classified according to different operational requirements and flight altitudes, such as: consumer drones below 120 m; instant delivery drones at 120–200 m; logistics transportation drones at 200–300 m. Based on the analysis of enterprise route planning, this study argues that both airspace zoning and route planning should not be considered solely as aviation transportation issues. Their relationship with ground systems should not be understood as a simple “top-down” projection of airspace onto the ground. Instead, planning should adopt a “bottom-up” approach, extending ground spatial systems upward into low-altitude space. Achieving such extension requires theoretical innovation and technical adaptation.

From a technical perspective, drone delivery represents a transformation of urban element mobility from two-dimensional space into three-dimensional space. Therefore, planning should analyze obstacles and their dynamic changes within three-dimensional environments[28-30], evaluate accessibility and routing strategies considering safety and economic factors, and identify suitable low-impact and high-safety corridors above spaces such as rivers and water bodies. At the same time, planning should classify noise-sensitive and privacy-sensitive areas according to land-use conditions and establish route setback standards to reduce negative impacts caused by drone operations. At the local planning level, cities may develop specialized plans for low-altitude airspace classification and route management based on three-dimensional urban environments and land-use conditions. Such plans should clarify: airspace classification methods; route layouts; safety buffer zones; and provide a basis for subsequent infrastructure construction and route approval.

More fundamentally, theoretical research is needed regarding the development rights and spatial governance mechanisms of low-altitude space. From the perspective of ownership, low-altitude resources, like airspace resources, belong to the state and are collectively owned by the public. From the perspective of utilization, development rights are currently exercised by governments on behalf of the public[31]. However, the implementation of such “public rights” has encountered practical challenges, particularly regarding discussions on air rights[32]. In the United States, airspace rights below 500 feet (approximately 150 m) are generally associated with land ownership, while higher airspace is considered navigable airspace. Landowners possess rights over the “immediate reaches” of the airspace above their properties, including the right to use a spatial extent comparable to the ground area they occupy or control[33]. In China, relevant regulations remain relatively unclear. The Property Law of the People’s Republic of China (2007) introduced the concept of easement rights within usufructuary property rights related to construction land. The Civil Code of the People's Republic of China (2021), Article 345, further states that: "Construction land use rights may be established separately on the surface, above-ground space, or underground space of land." Meanwhile, regulations concerning neighboring relationships further clarify practical applications of rights related to lighting, access, and other spatial uses[32,34]. Therefore, it can be considered that building airspace and surrounding areas may fall within the scope of easement rights, although existing laws have not yet clearly defined their legal forms and ownership relationships. Accordingly, future urban low-altitude planning, including drone delivery planning, needs to clarify the relationship between public and private rights regarding low-altitude spatial resources. It should establish legal foundations for: three-dimensional cadastral systems; three-dimensional urban spatial databases; public route designation; low-altitude resource use regulation; paid utilization mechanisms.

4.3Innovating Planning and Governance Policies to Promote Facility Integration into Networks

As the connecting points of ground-air coordination, takeoff-and-landing facilities constitute critical infrastructure for drone delivery. Currently, these facilities are mainly dependent on rooftops and public spaces. From a property rights perspective, public buildings generally have clearly defined ownership structures, while residential rooftops belong to shared property ownership, and street public spaces are owned by the state[35]. However, in general, these ground public spaces and rooftop airspaces often involve unclear ownership relationships, making functional transformation difficult and becoming a major bottleneck restricting the development of drone delivery. Therefore, spatial planning should not only technically organize routes and landing facilities in advance but also establish institutional mechanisms supporting facility implementation. In particular, planning should draw lessons from existing community-based embedded service facilities and coordinate with original property owners and municipal authorities regarding the allocation of: rights; responsibilities; economic benefits. For new construction or redevelopment projects, drone facilities may be incorporated into floor-area-ratio incentive mechanisms[36]. Based on the demand assessment discussed in Section 4.1, dedicated drone delivery spaces should be reserved in high-demand areas, and landing platforms should be incorporated into regulatory detailed planning management. From the perspective of planning systems, landing facilities and their required land spaces should be integrated into: land-use classification systems; building compatibility regulations; infrastructure planning frameworks.

Through these measures, new types of infrastructure can be developed and gradually integrated into urban networks. Beyond spatial integration, intelligent and automated conditions should also be reserved to connect landing facilities with other transportation systems and functional spaces. Landing facilities not only connect airspace and ground space but also link initial suppliers and final consumers, forming the first and last 100–300 meters of the logistics process. Currently, these initial and terminal transportation stages still largely rely on manual delivery by couriers or self-collection by users [Figure 8(a)]. Although these distances are only 100–300 meters, their time consumption can exceed that of the drone flight segment, and their costs may also exceed those of aerial transportation. Therefore, these stages have become critical bottlenecks restricting the efficiency and economic viability of drone delivery. To support large-scale future applications of low-altitude drone delivery, urban renewal and building management should better adapt to drone-based logistics characteristics. Possible measures include: installing freight elevators [Figure 8(b)]; deploying logistics robots [Figure 8(c)]; introducing window-mounted receiving systems [Figure 8(d)]; and other intelligent systems to improve efficiency in the initial dispatch and final receiving stages.

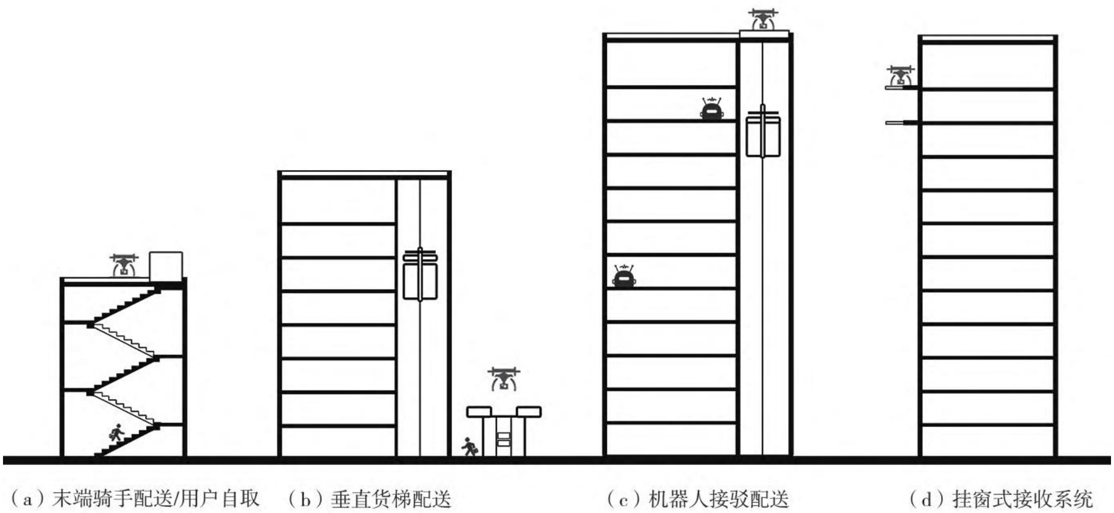


Fig.8 Vertical layout of nodes for ground-air coordinated drove delivery

5 Conclusions and Outlook

Represented by drone delivery, the low-altitude economy is developing at an unprecedented speed. It has promoted the establishment of ground-air coordination systems across diverse and complex geographical environments, connecting supply and demand through different application scenarios and enabling the large-scale replication and expansion of low-altitude services.

These emerging low-altitude services are reshaping patterns of urban production and daily life while also generating new challenges for urban spatial planning. Traditional planning approaches generally optimize ground-based resources from a two-dimensional perspective and are unable to respond effectively to the spatial and temporal allocation demands generated by drone delivery and other low-altitude applications. Therefore, low-altitude space should be incorporated into the scope of spatial planning. Future research should explore the construction mechanisms, utilization rules, and planning approaches of low-altitude spaces, investigate coordinated interactions between ground and air systems, and develop new spatial models adapted to the low-altitude economy. These efforts will enrich the conceptual framework and technical methodologies of urban low-altitude planning and respond to the emerging infrastructure and spatial requirements associated with rapid low-altitude development[37-39]. Based on literature review, field investigation, and simulation analysis, this study summarizes the elements and characteristics of ground-air coordination in drone delivery, conducts in-depth case studies of three leading drone delivery enterprises, identifies implementation pathways and challenges, and proposes planning responses. The main conclusions are as follows:

(1) Ground-air coordination requires not only technological integration of data and operational systems between air and ground elements but also spatial coordination among scenarios, network systems, and nodes. Ground-air coordination should not be understood merely as a technological objective; rather, it represents a prototype of new infrastructure development that simultaneously considers economic, technological, and spatial objectives.

(2) In practical applications, ground-air coordination demonstrates implementation pathways characterized by: constructing service scenario systems according to demand characteristics; organizing route networks based on ground spatial conditions; embedding and expanding node facilities within built environments. These pathways reflect the fundamental process of the low-altitude economy as an integration of "reaching upward and connecting downward," which should become a key focus of urban low-altitude planning.

(3) In response to challenges related to demand identification, route development, and landing facility construction, urban planning needs to innovate spatial governance mechanisms and technical methods. Planning should: improve low-altitude resource governance; promote coordination between low-altitude routes and ground transportation systems; implement hierarchical and categorized spatial infrastructure deployment; upgrade existing urban spaces through intelligent transformation.

Through these measures, the breadth, depth, and speed of low-altitude service implementation can be enhanced. Ground-air coordination in low-altitude flight represents a multidimensional spatial collaboration based on spatial systems and a multilayer coordination mechanism grounded in urban environments. During the process of spatial restructuring triggered by drone delivery, urban planning can play a key role in constructing the operational framework of future urban spaces. By integrating planning knowledge and governance tools, including: hierarchical and forward-looking spatial regulation; coordinated allocation of spatial resources; deep-level spatial resource mechanisms; urban planning can establish a specialized field of urban low-altitude planning and provide technical support for the spatial realization and evolution of the low-altitude economy. Future studies should further strengthen empirical analysis through additional case studies, develop technological tools, and simulate governance effectiveness.

Notes

① The risks associated with drone operations, including threats to life and property safety, as well as privacy concerns caused by onboard cameras, are important factors influencing public acceptance. In international practices, some enterprises have adopted image-processing technologies, such as grayscale treatment of captured images, to reduce privacy concerns and address increasing public complaints and appeals.

② Noise is one of the primary factors affecting public acceptance.

In particular, noise generated during drone takeoff and landing has significant impacts on noise-sensitive areas such as nursing homes, schools, residential communities, and government facilities. According to existing measurements, low-altitude drone operations generate approximately 60–85 dB(A) of noise, exceeding the limits specified in the Environmental Quality Standard for Noise issued by the Ministry of Environmental Protection of the People's Republic of China[40].

The standard specifies daytime and nighttime noise limits of: 50 dB(A) and 40 dB(A) for Category 0 acoustic environmental functional zones such as rehabilitation and healthcare areas; 55 dB(A) and 45 dB(A) for Category 1 zones including residential, educational, and governmental areas.

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