Framework for Air-Ground Integrated Low-Altitude Airspace Delineation and Usage Management: A Territorial Spatial Perspective

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Abstract

Against the rapid development of the low-altitude economy and the shift toward whole-territory, full-element governance of territorial space, low-altitude airspace is increasingly recognized as a new type of three-dimensional territorial spatial resource. Traditional low-altitude airspace delineation, however, has long prioritized airspace operations while underemphasizing ground-space functions, making it difficult to respond to diversified low-altitude activities such as logistics delivery, emergency rescue and passenger flight. From an air-ground system-coupling perspective, this paper argues that low-altitude airspace delineation should shift from route control to three-dimensional spatial governance. It clarifies the territorial-resource attributes of low-altitude airspace, reveals the coupling between aerial access and ground use, constructs a technical system for coordinated air and ground boundary delineation, and proposes a usage-management framework combining use zoning and use classification. A case study of Jinan verifies the scientific validity and operability of the framework. The study provides methodological support and decision-making reference for the efficient allocation of low-altitude resources and the high-quality development of the low-altitude economy.

Keywords

low-altitude airspace; delineation technology; usage management; air-ground coordination; low-altitude resource utilization

Introduction

As China's economic transformation enters a critical stage, the low-altitude economy has become an emerging industrial form and a new source of growth [1-2]. Scenarios such as drone logistics, urban air mobility (UAM), and low-altitude cultural tourism are developing rapidly, making low-altitude flight more frequent, diversified and refined [3-8]. At the same time, concepts such as vertical-oriented development (VOD) are gaining attention. They emphasize the coordinated organization of low-altitude transport networks, vertical takeoff and landing facilities and urban functional space, and place unprecedented demands on the supply capacity, organizational mode and management precision of low-altitude airspace resources [9]. As the core spatial carrier of the low-altitude economy, the planning layout, delineation technology and usage management of low-altitude airspace directly affect flight safety and operational efficiency, and further shape the quality and ceiling of industrial scaling [10].

Traditional low-altitude airspace delineation originates from aviation-management logic. It focuses on organizing air traffic flows and pays insufficient attention to ground territorial functions, environmental carrying capacity and risk exposure. This air-first and ground-light approach leads to mismatches between aerial and terrestrial elements, conflicts between flight activities and the urban environment, and the coexistence of local undersupply and idle resources [8]. Compared with the fast-growing demand of China's low-altitude economy, the national low-altitude airspace management system still lags behind in both technology and governance mode. The bottlenecks are concentrated in delineation methods and usage-management mechanisms that cannot yet adapt to the operational demands of new business forms [11-12].

Updating the logic of low-altitude airspace usage management and strengthening air-ground coordination are therefore essential. This requirement is consistent with China's reform toward whole-territory and full-element territorial spatial control [13-14], and also aligns with international trends in low-altitude management [15-16]. Air-ground coordination is essentially a way to break management barriers between airspace delineation and ground-space governance, and between aerial operation and ground-based regulatory services. Based on natural-resource administration and the territorial spatial planning "one map", it identifies the key elements of low-altitude activity, ground facilities, urban functions, safety risks and governance rules. On this basis, this study reviews the limitations of existing literature and builds an air-ground integrated delineation technology and usage-management framework. The framework enriches the theory of three-dimensional territorial spatial governance and provides an operational methodology for refined low-altitude airspace governance.

1 Research Progress in Low-Altitude Airspace Delineation and Usage Management

1.1 Concept and Attributes of Low-Altitude Airspace

Low-altitude airspace is a three-dimensional territorial spatial resource deeply affected by the surface environment and human activity. It is unstructured, highly heterogeneous and strongly coupled with the ground surface [19-21]. Its scarcity, capacity constraints and risk externalities mean that development and utilization must coordinate safety, efficiency and governance needs from a territorial spatial perspective [22-25]. Low-altitude airspace management should therefore move beyond a divided air-ground approach. Usage control needs to extend into three-dimensional space through zoning, rule constraints and coordinated governance, so that it can connect precisely with the functional pattern of territorial space [26-29]. With the growth of low-altitude logistics, UAM and related industries, the economic attribute of low-altitude airspace as a new production factor is becoming more prominent. Its management framework must promote efficient resource allocation and orderly development of the low-altitude economy while maintaining the safety bottom line [30-36].

1.2 Evolution of Low-Altitude Airspace Delineation Technology

Early low-altitude airspace delineation mainly derived from traditional aviation airspace planning and operational safety research. The basis for delineation focused on flight feasibility and obstacle avoidance, including route or corridor organization, obstacle clearance, takeoff-and-landing connectivity and separation intervals [15,19]. These operation-led methods are effective for maintaining basic airspace order, but in dense urban built environments with parallel and overlapping low-altitude activities they often encounter large differences in ground-risk exposure, strong heterogeneity of spatial constraints and insufficient cross-regional consistency. The resulting delineations are usually corridor-like and fragmented, and they struggle to describe vertical differences precisely.

Since the mid- to late 2010s, the rise of UTM and U-space systems for scaled drone operation has gradually promoted a new paradigm that treats territorial spatial characteristics as a precondition. International experience in urban low-altitude airspace planning for drones shows that the United States, European countries and Japan commonly include risk grading, geofencing, operational scenarios, route organization and digital regulation in low-altitude airspace planning [37]. Under this shift, delineation no longer relies only on flight feasibility, obstacle avoidance and route connectivity. It also incorporates population exposure, surface functions and sensitive targets, building form and height, key infrastructure corridors and ecological sensitive areas as basic constraints. Three-dimensional delineation is then expressed through a combination of vertical layering, corridor-node organization and geozones. Geozones become a key carrier for digital publication, retrieval and updating of rules [38-39], shifting delineation from simple obstacle and connectivity optimization to an integrated description of the coupling among spatial risk, surface characteristics and operational demand.

Different jurisdictions have developed differentiated paths [15,30,40-44]. The United States tends to emphasize categorical organization and dynamic management at broad scales. The European Union has gradually established a U-space geozone and rule system for high-density complex environments. Japan stresses matching technical and institutional progress in urban low-altitude applications with urban spatial conditions. Overall, low-altitude airspace delineation technology is moving from aerial operation logic, centered on routes and obstacle avoidance, toward territorial spatial logic, centered on geozones and three-dimensional integrated constraints.

Table 1. Comparison of Low-Altitude Airspace Delineation Principles and Classification Models

Country or Region	Basic Delineation Principle	Airspace Classification Logic	Main Delineation Elements
United States	Safety first; openness and efficiency	Follows ICAO/FAA Classes A-G; low altitude mainly uses Class G	Existing classes and airport-controlled airspace form the framework, with dynamic delineation
European Union	Risk-oriented; air-ground coordination	U-space geozones as the core; access based on superimposed risk	Hierarchical geozone management combined with route corridors
Japan	Urban safety first; air-ground integration	Follows ICAO logic and focuses on AAM-specific scenarios	Integrated organization of route corridors, vertiports and operating areas
Canada	Clear rules; responsibility-oriented	Uses the ICAO A-G class system	Airspace classes form the basis, with prohibited and restricted zones by risk
Australia	Risk grading; simplified rules	Follows ICAO classification logic	Based on geographic restrictions and operating conditions, avoiding complex reconstruction
United Kingdom	Safety and innovation; progressive delineation	Based on controlled and uncontrolled airspace, connected with U-space	Class G as the core, advancing engineering of corridors and nodes

1.3 Progress in Usage Management and Planning Linkage

Under whole-territory and full-element governance, the scientific connection between low-altitude airspace usage management and territorial spatial planning is central to resolving low-altitude resource conflicts. Internationally, current usage management and planning linkage can be grouped into three modes: market guidance, technological empowerment and administrative regulation. The United States mainly uses market guidance to adapt low-altitude airspace resources to demand [30]. Japan relies more on flight scenarios and technical adaptation. European countries combine regulatory frameworks with market supervision. Canada, Australia and the United Kingdom emphasize territorial safety, although strong safety orientation may restrain innovation. Despite wide coverage across countries, low-altitude airspace usage management still shows weak air-ground coordination, insufficient mechanisms for balancing multiple objectives and limited connection between aerial and ground governance.

China has also begun to develop local experience in low-altitude spatial usage control. Centered on the collaborative management of territorial space and low-altitude airspace, it has attempted to extend territorial-space control experience into the low-altitude domain. A governance mechanism has initially formed in which the central government provides an overall institutional framework and local governments refine implementation rules, balancing institutional unity and local adaptability. Recent work increasingly emphasizes identifying air-ground elements, matching operational scenarios, laying out facility networks and developing planning responses in urban low-altitude planning [18]. It also uses carrying-capacity assessment, restricted-area identification and multi-source data fusion to improve the scientific basis of management [25,45]. Technical progress in drone route planning, integrated sensing and communication (ISAC) and joint resource management provides additional support for route organization, airspace allocation and air-ground collaborative control [46].

Nevertheless, significant weaknesses remain. In implementation, the boundaries of rights and responsibilities between aerial management and ground control are not fully clear. According to the State Council's guidance on promoting general aviation, low-altitude airspace governance requires coordination among military and civil aviation, local governments and relevant departments; however, some regions have not yet established effective interdepartmental linkage, leading to disconnection among airspace management, infrastructure layout and project implementation. Institutionally, low-altitude airspace management has not been sufficiently integrated with ground requirements for avoiding special functional zones and typical obstacles. Existing methods still fail to incorporate ground spatial boundaries adequately into the airspace delineation process, and therefore cannot fully support refined resource allocation and efficient use in cross-regional and cross-sector low-altitude scenarios.

Table 2. Comparison of Low-Altitude Airspace Usage Management Systems

Country or Region	Core Laws or Policies	Regulator	Management Orientation
United States	Federal Aviation Act (1958); Part 107 small UAS rule (2016); Advanced Air Mobility Coordination and Leadership Act (2022)	Federal Aviation Administration (FAA)	Market guidance and dynamic operational rules

European Union	EU drone regulation (2019); U-space regulatory framework (2023)	European Union Aviation Safety Agency (EASA) and national aviation authorities (NAAs)	Geozone-based risk control and digital rule publication
Japan	Aviation Act (2022); Advanced Air Mobility roadmap (2018)	Japan Civil Aviation Bureau (JCAB)	Scenario-oriented urban safety and AAM coordination
Canada	Aeronautics Act (1985); Canadian Aviation Regulations Part IX for drones (2019)	Transport Canada	Clear operational responsibilities and safety compliance
Australia	Civil Aviation Safety Regulations Part 101 for drones (2002); Airspace Act (2007)	Civil Aviation Safety Authority (CASA)	Risk-graded control and simplified rules
United Kingdom	Air Navigation Order (2016)	Civil Aviation Authority (CAA)	Progressive management linking controlled airspace with U-space

2 Low-Altitude Airspace Under Air-Ground System Coupling

2.1 Attribute Definition: Low-Altitude Airspace as a Territorial Spatial Resource

Low-altitude airspace differs from land resources that can be fully allocated by market mechanisms, and it also differs from prohibited-flight space subject to complete administrative control. It is a quasi-public spatial resource that requires dynamic balance between public interest and operational efficiency. The theoretical premise of low-altitude airspace delineation should therefore shift from traditional airspace classification to spatial-resource expression. By clarifying spatial boundaries, property-right attributes, development-right allocation, use access, benefit distribution and public-safety constraints, low-altitude airspace can become a three-dimensional spatial resource that is identifiable, measurable, allocable and incorporable into the planning-management system [36]. This translation from flight space to spatial resource forms the basic logic of air-ground integrated delineation.

2.2 Coupling Mechanism: Interaction Between Territorial Space and Low-Altitude Resources

From the perspective of spatial-system integrity, territorial space and low-altitude resources constitute a vertically nested and mutually constraining spatial coupling system. Their interaction is expressed through three mechanisms: background spatial constraints, functional adaptation and coordinated risk transmission. Political and military sensitive areas, terrain and geomorphology, building-height profiles and other core elements of territorial space directly define the usable scope and operating thresholds of low-altitude airspace, forming rigid constraints on resource development. Conversely, the spatial clustering of low-altitude inspection, aerial logistics, UAM and other activities guides the layout of ground takeoff and landing nodes, support facilities and service networks, pushing territorial-space use toward three-dimensional expansion.

The deep coupling of function and risk means that low-altitude airspace delineation must connect with territorial spatial use control. Ground functional zoning determines the intensity of low-altitude use and the level of control. Population-dense areas, ecological sensitive areas and other spatial units correspond to differentiated low-altitude access rules and safety thresholds. At the same time, the safety risks and environmental externalities of low-altitude flight act directly on surface public interests. Air-ground coupling is therefore not only a physical nesting of space, but also an institutional coupling of planning logic, control rules and governance responsibilities. It provides the internal basis for reconstructing the theory of low-altitude airspace delineation.

The whole-coverage and full-element control of territorial spatial planning provides the core platform for low-altitude resource governance. Existing low-altitude flight operation management platforms already show an initial form of three-dimensional governance, but they still require territorial spatial planning as the lead framework to achieve deep coordination of air-ground control and rule linkage. The theoretical construction of low-altitude resource governance from a territorial spatial perspective should rely on the territorial spatial planning control framework, connect the low-altitude airspace management system, clarify the two-way mechanism through which ground conditions shape airspace and aerial operation feeds back to ground use, and support coordinated allocation of territorial and low-altitude resources.

3 Low-Altitude Airspace Delineation Technology and Usage Management Framework from a Territorial Spatial Perspective

3.1 Framework Construction: From Element Recognition to Air-Ground Integrated Delineation

Air-ground coordination goes beyond a one-way logic in which ground obstacles merely restrict flight. It emphasizes dynamic coupling. On the one hand, ground functions, population density and building form determine the risk level and access conditions of low-altitude airspace. On the other hand, the delineation of aerial routes and operating areas imposes reverse requirements on the layout of takeoff and landing facilities, noise-sensitive points and supporting infrastructure.

Mechanistically, the suitability of low-altitude airspace depends not only on aerial operating conditions, but is profoundly shaped by ground spatial structure. Urban functional form, infrastructure corridors, ecological constraints and sensitive facilities jointly define the usable range and operating risks of low-altitude airspace. Through the superposition of air and ground elements, they affect accessibility, safety and efficiency. Air-ground integrated delineation should therefore describe interaction within a three-dimensional urban spatial framework, rather than treating ground space merely as a set of passive restrictions. Functionally, low-altitude activities mainly serve ground urban functions and therefore need to correspond to ground functional zoning. In governance, low-altitude airspace involves joint management across multiple departments; air-ground coordination should use unified spatial units and rules to connect operational management with usage management, reducing institutional friction.

The paper proposes a comprehensive framework consisting of low-altitude airspace constraints, delineation technologies, delineation principles, aerial and ground boundary delineation, air-ground integrated delineation, and usage management with dynamic optimization (figure 1). The framework is based on whole-territory governance and treats safety, environmental protection and efficient resource allocation as integrated requirements.

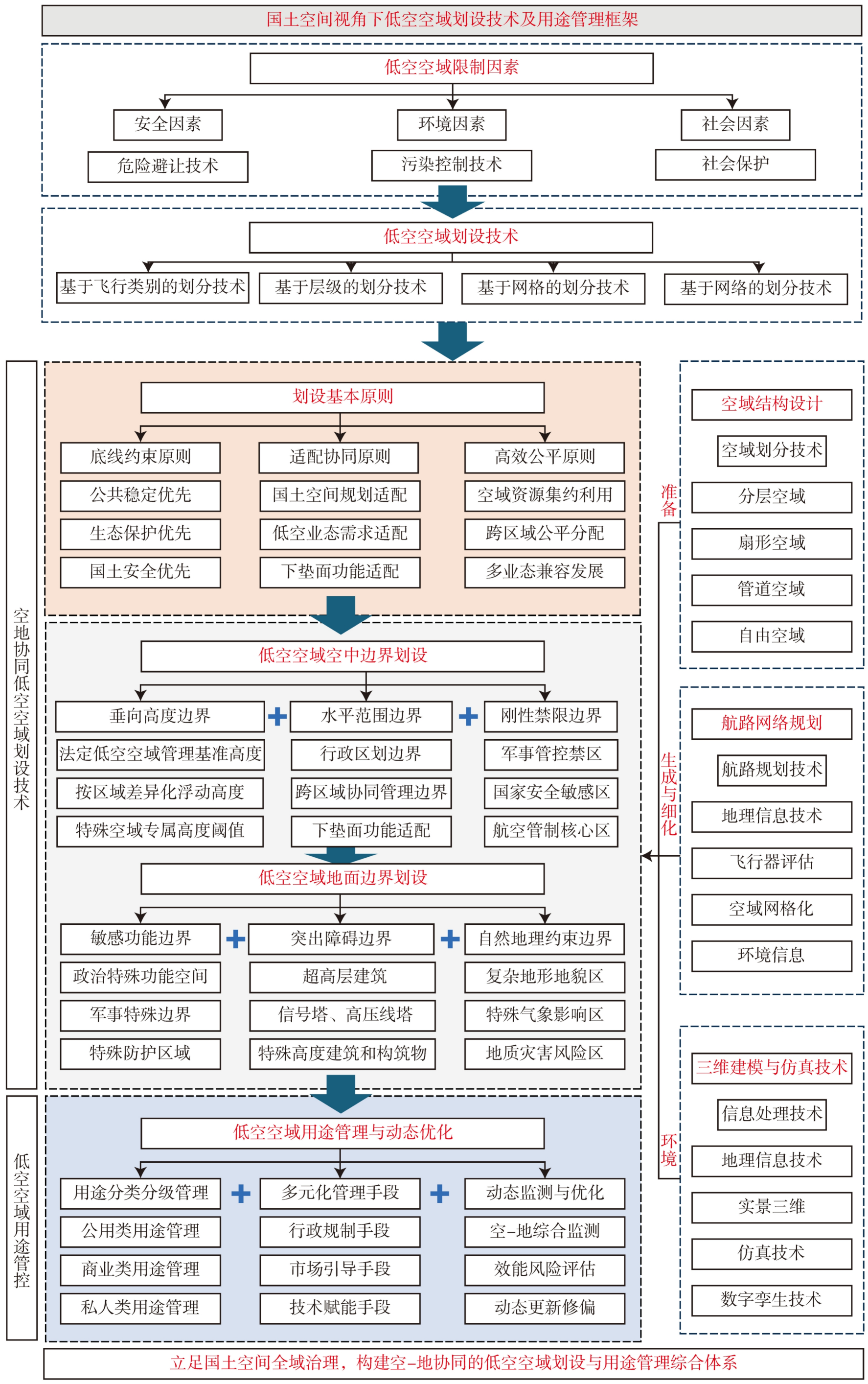

Figure 1. Air-Ground Integrated Low-Altitude Airspace Delineation and Usage Management System

3.2 Basic Delineation Principles

The proposed framework follows three basic principles. First, the bottom-line constraint principle gives priority to public stability, ecological protection and national territorial security. Military control areas, national security sensitive zones, aviation-control core areas and other rigid constraints must be excluded or strictly controlled. Second, the adaptation and coordination principle requires low-altitude airspace to match territorial spatial planning, low-altitude business needs and underlying surface functions. Third, the efficiency and fairness principle emphasizes intensive utilization of airspace resources, cross-regional equitable allocation and compatibility among multiple industries. These principles allow airspace delineation to balance public safety, operational demand and resource efficiency.

3.3 Air-Ground Integrated Delineation Technology

3.3.1 Delineating Aerial Boundaries

Aerial boundary delineation includes vertical height boundaries, horizontal scope boundaries and rigid prohibited or restricted boundaries. In the vertical dimension, the legal benchmark height for low-altitude airspace management should be combined with regionally differentiated floating heights and special height thresholds for particular airspaces. In practice, low-altitude airspace can be divided according to true height into multiple layers, such as ultra-low, low and medium-low operating layers, corresponding respectively to small drone operations, light drone management areas and general-aviation integration areas.

In the horizontal dimension, high-precision geographic information data and real-scene 3D data should replace the traditional point-to-point route model. Three-dimensional grid technology can voxelize airspace, calculate building clearance envelopes and safety separation belts, and generate digital geofences. Fixed and temporary airspaces should be combined according to flight scenarios. Temporary airspace can be delineated within specified time windows to support low-altitude tourism, emergency rescue and other dynamic activities. By integrating real-scene 3D modeling, obstacle analysis, flight-height analysis and conflict avoidance, aerial boundaries can be expressed as precise and updateable spatial units.

3.3.2 Delineating Ground Boundaries

Ground boundary delineation includes sensitive functional boundaries, prominent obstacle boundaries and natural geographic constraint boundaries. Sensitive functional boundaries include political and military special spaces, special protection areas and public infrastructure avoidance zones. Prominent obstacle boundaries include high-rise buildings, signal towers, high-voltage towers and buildings or structures with special heights. Natural geographic constraint boundaries include complex terrain and geomorphology, areas affected by special meteorological conditions and geological-disaster risk areas. Ground boundary delineation transforms ground risks into spatial constraints for low-altitude airspace and provides a basis for differentiating access conditions and operating intensity.

3.3.3 Air-Ground Integrated Delineation

Air-ground integrated delineation connects aerial layering with ground zoning. The workflow includes identifying constraints, integrating assessment data, building 3D models, screening sensitive areas and incorporating territorial spatial survey data and terrain-geomorphology data. It should consider differences in underlying surface functions among urban, rural and ecological areas. The result is a multi-scale delineation system that links aerial boundary, ground boundary and air-ground coupling constraints, providing spatial support for the high-quality development of the low-altitude economy (figure 2).

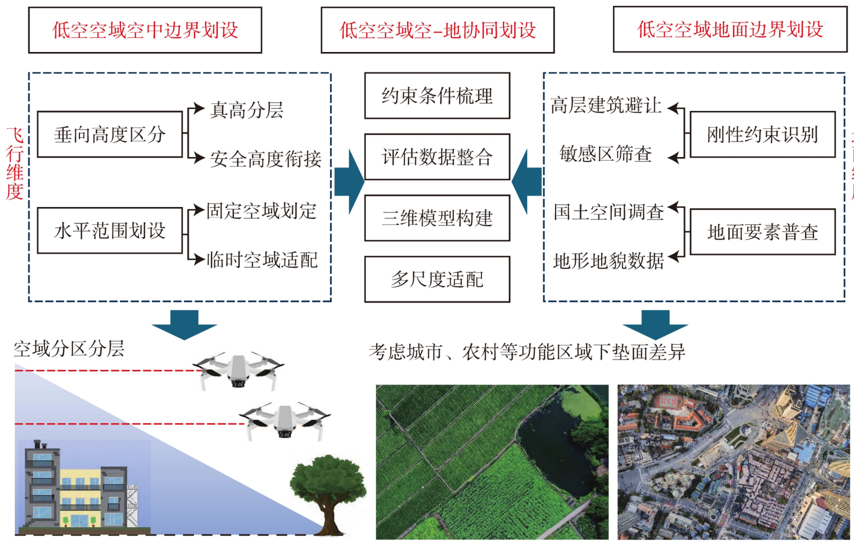

Figure 2. Technical Framework for Low-Altitude Airspace Delineation from a Territorial Spatial Perspective

3.4 Institutional Design for Air-Ground Integrated Usage Management

3.4.1 Institutional Logic of Usage Management Under Air-Ground Coordination

Air-ground integrated usage management is a key means of efficient low-altitude resource use and territorial spatial security. Supported by institutional norms and closed-loop regulation, it should connect deeply with the existing territorial spatial planning system and be implemented in practice. This responds to current weaknesses in China, including poor linkage between usage-management institutions and planning systems, and the difficulty of embedding management requirements into planning implementation processes. It also supports the integration of general aviation and the low-altitude economy required by the national modern comprehensive transport system plan.

The framework runs low-altitude usage management through the full process of airspace planning, implementation and evaluation. In use classification, it distinguishes emergency, commercial, public-service and industrial-operation uses, and develops differentiated standards. It establishes a multidimensional correspondence among territorial land-use type, low-altitude activity type and control-intensity level. In implementation, it strengthens the integration of planning linkage, technological empowerment and interdepartmental coordination, maintains the safety bottom line and supports efficient resource utilization.

3.4.2 Use Zoning Oriented Toward Territorial Spatial Planning

At the level of planning optimization, low-altitude management should be explicitly incorporated into territorial spatial master planning, detailed planning, comprehensive transport planning and relevant special plans. Master planning should clarify low-altitude functional zones and strategic requirements. Detailed planning should refine spatial units and control requirements. Special planning should connect low-altitude infrastructure, routes, corridors and operational scenarios. In implementation, low-altitude management requirements should be linked with planning permission, and cross-departmental mechanisms should connect low-altitude management, infrastructure layout and project approval.

Dynamic updating should rely on the national planning outline for 2021-2035 and on changes in low-altitude business forms and operating demand. Management rules and zoning boundaries should be optimized regularly. The effects of implementation should feed back into plan revision through a closed loop of preparation, implementation, evaluation and adjustment, ensuring that low-altitude airspace management and the territorial spatial planning system remain coordinated.

3.4.3 Use Classification Oriented Toward Territorial Spatial Governance

Air-ground integrated usage management also needs to refine use classification. Different territorial spatial types correspond to different low-altitude activities and control intensities. Urban construction land supports high-intensity UAM passenger transport and drone logistics, as well as lower-intensity urban inspection and emergency rescue. Rural construction land supports rural logistics and rural commercial tourism. Agricultural land supports agricultural inspection, plant protection and crop monitoring. Ecological spaces support ecological protection patrols, vegetation monitoring, biodiversity protection and disaster or water-environment monitoring. The use-classification system should combine administrative regulation, market guidance and technological empowerment, thereby linking the intensity of management with the attributes of activity and the sensitivity of the underlying land use.

Table 3. Example of Multidimensional Correspondence Among Territorial Land Use, Low-Altitude Activity and Control Intensity

Territorial Space Type	Land-Use Type	Typical Low-Altitude Activity	Control Intensity
Urban space	Urban construction land	UAM passenger transport	High
Urban space	Urban construction land	Drone logistics	High
Urban space	Urban construction land	Urban inspection and emergency rescue	Low
Urban space	Urban construction land	Low-altitude tourism and commercial aerial photography	Medium
Rural space	Rural construction land	Rural logistics	Medium
Rural space	Rural construction land	Rural commercial tourism	Medium
Agricultural space	Cultivated land	Agricultural inspection	Low
Agricultural space	Cultivated land	Farmland plant protection	Low
Agricultural space	Cultivated land	Crop dynamic monitoring	Low
Agricultural space	Orchards, forest land, grassland and other	Forestry-resource inspection	High

	agricultural production land		
Agricultural space	Orchards, forest land, grassland and other agricultural production land	Fire patrol	Medium
Agricultural space	Orchards, forest land, grassland and other agricultural production land	Ecological protection patrol	Medium
Ecological space	Ecological protection land, including wetlands, protected areas, unused land and other ecological-function land	Routine vegetation monitoring	Medium
Ecological space	Ecological protection land	Biodiversity protection patrol	Medium
Ecological space	Ecological protection land	Geological-disaster and water-environment dynamic monitoring	Medium

3.5 Case Analysis: Air-Ground Integrated Low-Altitude Airspace Delineation in Jinan

3.5.1 Case Area and Assessment Process

The case study applies the proposed framework to Jinan. It builds a low-altitude airspace resource assessment system using multi-source data, including obstacle distribution, military airspace, airport airspace, ground functions, industrial layout, sensitive elements and operational demand. The evaluation is organized around three criterion layers: capacity, risk and demand. Capacity assessment considers obstacle distribution, conflict avoidance and flight-height analysis. Risk assessment considers military and airport airspace, sensitive elements and safety constraints. Demand assessment considers ground functions, industrial layout and use demand (figure 3).

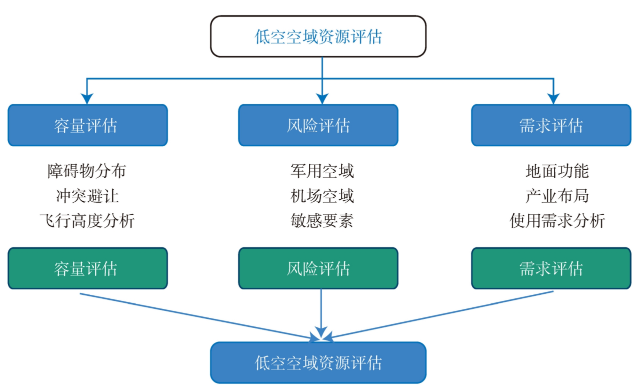

Figure 3. Illustrative Framework for Low-Altitude Airspace Resource Assessment

3.5.2 Layered, Zoned and Time-Sliced Usage Management

In the implementation stage, the case area combines aerial layering with ground zoning. Vertically, airspace is divided by true height into 0-300 m, 300-600 m and 600-1,000 m layers, corresponding to low-speed flight, medium-speed flight and higher-level emergency or longer-distance operations. On the ground, political and military sensitive areas, high-rise buildings, geological-disaster risk areas, public infrastructure and other controlled spaces are used as key constraints. Suitability evaluation results are then translated into suitable, conditionally suitable and restricted areas, achieving coordinated aerial delineation and ground control.

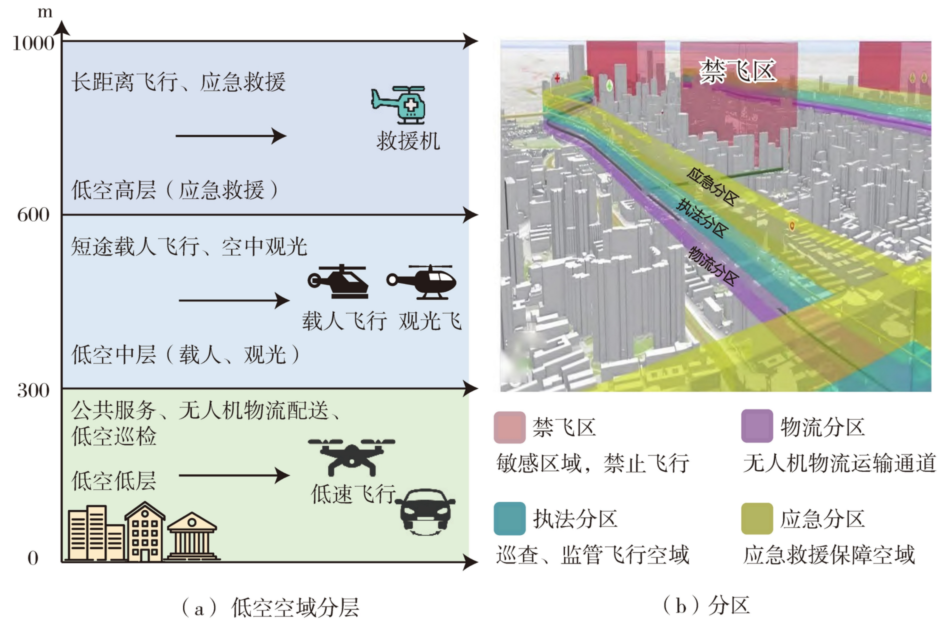

Figure 4. Schematic Diagram of Usage Management

The case also introduces time-sliced management. During peak periods, flight restrictions are tightened and emergency flights are prioritized. During normal periods, restrictions are moderately relaxed to ensure the smooth operation of freight and public-service corridors. During off-peak periods, special flight activities such as night logistics and safety inspection can be allowed under strict control of noise and light pollution. This combination of layering, zoning and time scheduling allows management to respond more precisely to complex low-altitude activity demands.

3.5.3 Practical Adaptability and Experience

The core experience of the case area is that it preliminarily implements the air-ground integrated delineation process and zoned-classified management system proposed by this study, partially improving the limitations of traditional low-altitude airspace governance. The case builds a complete technical transmission chain from data integration to comprehensive assessment and delineation implementation. Based on the territorial spatial planning one-map platform, it integrates multi-source air-ground data and addresses the disconnection of heterogeneous data. It uses a quantitative land-use-activity matching model to classify airspace suitability across the whole area, and converts the evaluation results into multiple constraints for delineation, realizing transmission from data to implementable rules.

At the management end, the pilot's three-dimensional management of layering, zoning and time scheduling also breaks through the limitations of traditional single-dimensional control. Compared with rules that only emphasize height layering or regional prohibitions and restrictions, the management matrix formed by the linkage of the three types of rules better adapts to complex low-altitude activity needs. From a whole-territory and full-element perspective, however, the system still has shortcomings in cross-boundary rule coordination and in support for rural areas, protected natural areas and other non-urban spaces. Future work should improve cross-regional rule linkage and build a dynamic and progressive planning-adjustment mechanism to support larger-scale coordination of low-altitude resources.

4 Discussion and Conclusions

4.1 Research Conclusions

This study focuses on low-altitude airspace delineation and usage management from the perspective of whole-territory and full-element territorial spatial governance. It constructs a systematic framework for air-ground integrated delineation technology and usage management. The study confirms that low-altitude airspace has evolved from a mere flight medium into a three-dimensional territorial resource that requires three-dimensional rights confirmation and refined allocation. The essence of air-ground coordination is the two-way game and dynamic balance between ground development interests and aerial access interests.

The ground-risk-mapping-based delineation technology and the zoning-classification-grading usage management system proposed in the paper break through the limitation of traditional airspace management that emphasizes the sky while neglecting the ground. They provide an operational technical interface for incorporating low-altitude airspace into the territorial spatial planning one map. The case study shows that the framework can connect data, evaluation, delineation and rules, and has practical feasibility for low-altitude resource allocation and governance.

4.2 Policy Recommendations

Low-altitude airspace delineation and usage management should be embedded in the territorial spatial planning system and strengthened in planning linkage and implementation. First, special planning standards for urban low-altitude and air-ground integrated infrastructure should be formulated as soon as possible. They should clarify key indicators such as low-altitude zoning and facility layout, incorporate these requirements into territorial spatial detailed-planning units, and translate them into concrete planning-management units with a legal implementation basis.

Second, management linkage should be strengthened. Natural resources, civil aviation and other departments should establish collaborative mechanisms and a unified low-altitude resource data-sharing platform, integrate multi-source data, and open approval and regulatory chains across departments. Third, elastic reservation should be introduced in urban core areas according to the iterative characteristics of low-altitude industries. Public-service corridors, transport hubs and vertical takeoff and landing service corridors should be planned in advance, with clear links between airspace management and ground construction constraints, so that low-altitude resources are not permanently lost. Finally, digital twin, all-space intelligent GIS and related technologies should be used to build a dynamic feedback loop of planning, monitoring, evaluation and early warning. This can monitor planning implementation and flight dynamics in real time, support regular evaluation, connect with dynamic adjustment of territorial spatial planning, and promote a shift from static blueprint to dynamic governance.

4.3 Limitations and Prospects

This study is an initial exploration of low-altitude airspace delineation, usage management and planning linkage. It proposes an integrated air-ground framework that provides ideas for planning and management in the low-altitude domain, but it remains limited in two respects. In terms of data, access to refined urban 3D models above LOD3 is difficult, so the micro-level validation of the proposed delineation technology in complex built environments remains insufficient. Technically, the framework is based mainly on static physical spatial form and does not fully incorporate the real-time effects of dynamic meteorological and physical fields, such as wind fields and electromagnetic environments, on airspace delineation. It therefore still lacks dynamic air-ground spatial coupling analysis.

Future research will focus on dynamic airspace grid delineation based on real-time sensing, as well as quantitative assessment models for low-altitude airspace capacity. These studies will provide more precise scientific support for the efficient operation of the low-altitude economy.

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