Journal of Low-Altitude Economy and Intelligent Aviation
Volume 1, Issue 1, 2026, Page 1-15
https://doi.org/10.6914/jlae.2026.010101

From Vertical Commons to Digital Sky: Defining the Low-Altitude Economy as a New Mode of Spatial Production

Changkui LI
Hong Kong Integration Research Institute Email: lichangkui@gmail.com
https://orcid.org/0000-0001-7446-0198

Abstract

This article develops a foundational framework for the Low-Altitude Economy (LAE) by conceptualizing low-altitude airspace as a "Vertical Commons" and treating LAE as a new mode of spatial production rather than an extension of General Aviation (GA) or Urban Air Mobility (UAM). It proposes a standardized operational definition (below 3,000 m AGL) and a two-layer altitude model (0 1,000 m core; 1,000 3,000 m extension) to enable cumulative research. The study further advances an Infrastructure Triad (physical, digital, institutional) as a scalability diagnostic, and a regulatory value developmental taxonomy to classify heterogeneous applications. Comparative governance analysis highlights divergent policy regimes across China, the United States, and the European Union, with implications for digital governance, liability, and market formation.

Keywords Low-Altitude Economy (LAE); Vertical Commons; Digital Sky Governance; Infrastructure Triad; Regulatory Complexity and Value Density

1 Introduction: The Vertical Commons and the Emergence of a New Economic Form

The history of human civilization's engagement with spatial resources is, at its core, a continuous process of overcoming physical and dimensional constraints through technological evolution. For much of the modern era, spatial utilization has been characterized by a stark—and arguably inefficient—binary structure.

Above lies the stratosphere and high-altitude airspace, conventionally defined as airspace above Flight Level 180 (18,000 feet). This domain constitutes the exclusive territory of commercial aviation, governed by the international treaty regime established under the Chicago Convention. It operates as a capital-intensive, tightly regulated global mobility system, optimized almost exclusively for long-distance transportation.

Below lies the terrestrial surface, which accommodates dense flows of automobiles, rail systems, and pedestrians. This ground-based infrastructure has reached structural saturation in many urban regions. Marginal expansion costs continue to rise nonlinearly, while congestion, land scarcity, and environmental externalities impose increasingly rigid physical limits on further growth.

Between these two layers exists a vast natural resource that has remained largely invisible within conventional economic accounting: low-altitude airspace. This vertical stratum—here conceptualized as the *Vertical Commons*—has historically been utilized only intermittently for general aviation (GA), law enforcement patrols, helicopter emergency medical services (HEMS), and recreational activities. Crucially, it has functioned as a space of *transit*, not of *economic habitation*. Its chronic underutilization stands in sharp contrast to the congestion of terrestrial networks and the intensive exploitation of high-altitude air corridors.

The 2020s, however, mark a decisive inflection point in the political economy of space. The convergence of distributed electric propulsion (DEP), high energy-density storage technologies (including lithium-ion and solid-state batteries), and autonomous flight control systems has precipitated the dawn of what is increasingly described as the *Low-Altitude Economy* (LAE). This transition represents far more than an incremental evolution in aviation technology. It signals a fundamental reconfiguration of spatial production itself.

© The Authors 2026. Article History Received: December 29, 2025; Accpted: January 10, 2026; Published: January 30, 2026. ***Journal of Low-Altitude Economy and Intelligent Aviation***, ISSN ****–****(print), ISSN ****–****(online), a Quarterly, founded on January 2026, published by Creative Publishing Co., Limited. Email: editor@jlae.org, https://jlae.org, https://cpcl.hk. This is an open-access article distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License, which permits non-commercial use, sharing, adaptation, distribution, and reproduction in any medium or format, provided the original author(s) and source are credited, and derivative works are licensed under the same terms.

Analogous to how the internet transformed information from a scarce, high-friction resource into a commodified good by driving distribution costs toward zero, the low-altitude economy seeks to unlock the *immediate sky*. Airspace is no longer treated as an empty void to be crossed, but as an active arena for production, distribution, sensing, and service delivery. Electrification of aircraft is only a necessary condition; the deeper transformation lies in the digitization, programmability, and eventual assetization of airspace itself.

1.1 Conceptual Clarification: Beyond a Mobility-Centric Perspective

Despite rapid technological progress, contemporary academic and industrial discourse remains conceptually fragmented. In Western literature, debates largely revolve around *Urban Air Mobility* (UAM) or the broader notion of *Advanced Air Mobility* (AAM). These frameworks primarily emphasize the transportation function of electric vertical takeoff and landing (eVTOL) aircraft, framing low-altitude operations as extensions or substitutes for congested ground mobility systems. At their core, these approaches remain fundamentally *mobility-centric*.

In parallel, a more expansive conceptualization has emerged in China. Rather than treating low-altitude operations as a transportation sub-sector, the low-altitude economy is increasingly understood as a *comprehensive economic morphology*. This framework encompasses not only human mobility (UAM), but also logistics flows, remote sensing and data acquisition, infrastructure inspection, emergency response, and the manufacturing of intelligent aerial systems. In this view, aviation activity is deeply embedded within non-aviation value chains such as energy, agriculture, logistics, and urban governance.

The distinction is not semantic but structural. In the low-altitude economy, flight is rarely the final product. Instead, aerial platforms function as mobile sensors, actuators, and service nodes within broader industrial and digital systems. The economic value generated derives not from flight hours, but from outcomes: faults detected, delivery times reduced, emissions avoided, and operational efficiencies gained.

1.2 The Low-Altitude Economy as a New Mode of Spatial Production

From the perspective of economic theory, the emergence of the low-altitude economy represents a qualitative shift in the mode of spatial production. Traditional spatial economics has largely treated airspace as either a transit corridor or a regulatory constraint, rather than as a productive factor in its own right. Low-altitude airspace, in particular, has been excluded from systematic economic analysis due to technological limitations, high coordination costs, and the absence of scalable governance mechanisms.

The low-altitude economy alters this analytical baseline. By integrating digital governance architectures, autonomous control systems, and real-time communication networks, low-altitude airspace becomes programmable, divisible, and allocable. These properties are essential preconditions for transforming a natural space into an economically productive domain. In this sense, the low-altitude economy parallels earlier historical transitions in which previously inert spatial dimensions—such as subterranean resources, maritime routes, or electromagnetic spectrum—were institutionalized as factors of production.

Crucially, the economic significance of the low-altitude economy does not lie primarily in transportation efficiency. Rather, its transformative potential stems from its capacity to reorganize how value is created across vertical space. Aerial platforms function as mobile interfaces linking physical infrastructure, digital systems, and organizational processes. As a result, economic activity shifts from being surface-bound to vertically distributed, enabling new forms of coordination across energy systems, logistics networks, agricultural monitoring, urban inspection, and emergency response.

This reconfiguration introduces a distinct logic of value creation. In contrast to conventional aviation, where revenue is closely tied to passenger kilometers or flight hours, the low-altitude economy generates value through service outcomes and system-level efficiencies. Fault detection, predictive maintenance, time-sensitive delivery, and real-time data acquisition become primary sources of economic return. Flight itself becomes an intermediate input rather than a final product.

Viewed through this lens, the low-altitude economy constitutes neither an extension of general aviation nor a mere technological upgrade of urban transport. It represents a new economic morphology in which vertical space is systematically integrated into production networks through digital governance. The conceptualization of low-altitude airspace as a *Vertical Commons* underscores the necessity of institutional arrangements capable of balancing efficiency, safety, and equitable access—an issue that becomes central as low-altitude operations scale from isolated use cases to economy-wide infrastructure.

2 Defining the Low-Altitude Economy: Boundaries, Layering, and Standardization

Rigorous analysis of the low-altitude economy requires a clear separation from traditional aviation activities and a resolution of the definitional ambiguities that persist in existing literature. Conventional aviation taxonomies have historically been organized around aircraft types (fixed-wing versus rotary-wing) or mission profiles (commercial transport versus general aviation). While operationally useful, these classifications are ill-suited for capturing the economic transformation currently unfolding in low-altitude airspace.

The low-altitude economy departs from these traditional categories by introducing *altitude range*, *degree of economic integration*, and *digital governance intensity* as its primary defining variables. This shift reflects a move away from aircraft-centric or mission-centric frameworks toward a system-level understanding of how aerial activities are embedded within broader production networks.

2.1 The Need for a Unified Definition

A major obstacle to cumulative research on the low-altitude economy lies in the absence of a unified altitude definition. Existing studies variously reference thresholds such as 120 meters, 1,000 meters, or 3,000 meters, often without explicit justification or theoretical grounding. These inconsistencies undermine comparability across studies and create ambiguity regarding the empirical scope of analysis.

From an economic perspective, altitude should not be treated merely as a physical parameter, but as a proxy for regulatory complexity, technological dependence, and integration with ground-based systems. A unified definition must therefore reconcile physical airspace constraints with governance capacity and economic function. To establish a stable foundation for academic dialogue, this study proposes a standardized operational definition and a corresponding altitude layering model.

2.2 A Standardized Definition of the Low-Altitude Economy

Definition. The *Low-Altitude Economy* (LAE) refers to a comprehensive economic system that utilizes airspace below 3,000 meters above ground level (AGL), employs both crewed and uncrewed aerial vehicles as operational carriers, and relies on digitally networked governance mechanisms to enable multi-scenario integration. Through this system, low-altitude activities generate spillover effects across manufacturing, services, and data-driven industries.

This definition emphasizes three essential characteristics. First, altitude below 3,000 meters delineates a domain in which flight operations remain directly coupled with ground infrastructure, population density, and micrometeorological conditions. Second, the inclusion of both crewed and uncrewed platforms reflects the hybrid operational reality of emerging low-altitude systems. Third, digital governance—encompassing communication networks, automated traffic management, and real-time data exchange—is treated as a constitutive element rather than an auxiliary feature.

2.3 The Altitude Layering Model: Core and Extension Zones

To further resolve definitional ambiguity, the low-altitude economy is analytically divided into two functional layers based on altitude and operational characteristics.

Core Zone (0 1,000 m AGL). The Core Zone constitutes the primary operational domain of the low-altitude economy and marks its most distinctive departure from traditional aviation. This layer accommodates high-density and high-frequency activities, including unmanned aerial logistics, urban air mobility services, smart-city inspection, and consumer-grade flight operations. Its defining features include intensive reliance on digital coordination, direct exposure to ground obstacles, and sensitivity to localized meteorological variability. Economic value generation in this zone is closely tied to real-time data processing and service responsiveness.

Extension Zone (1,000 3,000 m AGL). The Extension Zone functions as an interface between the low-altitude economy and conventional aviation systems. It supports regional air mobility, high-altitude long-endurance (HALE) unmanned operations, and specialized general aviation missions. In this layer, operational rules of the low-altitude economy increasingly intersect with traditional air traffic control (ATC) frameworks. Coordination rather than autonomy becomes the dominant governance challenge, reflecting a transitional regulatory environment.

This two-layer model establishes clear physical and functional boundaries for the low-altitude economy while preserving analytical flexibility for cross-domain interactions.

2.4 Structural Distinctions between LAE, UAM, and General Aviation

Clarifying the relationship between the low-altitude economy, urban air mobility (UAM), and general aviation (GA) is essential for delineating the scope of analysis. Although these domains share overlapping airspace, they differ fundamentally in operational logic, governance paradigms, and value metrics.

General Aviation (GA). General aviation traditionally encompasses all civil aviation activities outside scheduled commercial transport. It remains heavily dependent on human pilots and is constrained by high capital and maintenance costs. As a result, GA has historically resisted large-scale diffusion. Its organizing principle is fundamentally *flight-centric*, with economic value closely tied to flight hours and aircraft utilization.

Urban Air Mobility (UAM). Urban air mobility focuses primarily on point-to-point transportation within metropolitan areas, positioning aerial vehicles as substitutes or complements to congested ground transport. Its analytical core is *mobility-centric*, emphasizing travel time savings and congestion mitigation. While technologically innovative, UAM remains conceptually embedded within the transportation sector.

Low-Altitude Economy (LAE). In contrast, the low-altitude economy is organized around *integration*. Flight operations within LAE are rarely the final product. Instead, aerial platforms function as mobile sensors, actuators, or service nodes embedded within non-aviation value chains such as energy distribution, agriculture, logistics, and infrastructure maintenance. Economic value is measured not by flight duration, but by outcomes—faults detected, efficiency gains realized, or systemic risks reduced. This economy-centric logic positions LAE as a distinct analytical category rather than a subset of existing aviation domains.

3 The Infrastructure Triad: Foundations of the Vertical Economy

The scalability of the low-altitude economy is constrained not by aircraft aerodynamics, but by the carrying capacity of its underlying infrastructure. Unlike traditional aviation systems, which rely on large, centralized airports and rigid air traffic control architectures, the low-altitude economy requires an infrastructure paradigm characterized by high permeability, spatial diffusion, and deep urban embedding.

This section advances a core analytical claim: the emergence of a functional low-altitude economy depends on the coordinated development of three interdependent infrastructure layers. We formalize this claim as **Proposition 2**, introducing the *Infrastructure Triad* as a standardized framework for assessing regional readiness and systemic maturity.

3.1 Proposition 2: The Infrastructure Triad Model

Proposition 2 (Infrastructure Triad). The large-scale and economically sustainable development of the low-altitude economy requires the co-evolution of three mutually reinforcing infrastructure layers: (i) a distributed physical layer, (ii) a digitally governed airspace layer, and (iii) an institutional layer that enables market formation. The absence or underdevelopment of any single layer imposes a binding constraint on system-wide scalability.

The Infrastructure Triad departs from linear infrastructure models by emphasizing complementarity rather than substitution. Physical facilities without digital coordination generate congestion and safety risks; digital systems without physical anchoring remain abstract and non-operational; and both are rendered economically inert in the absence of institutional arrangements governing access, liability, and pricing. Together, these layers transform low-altitude airspace from a passive spatial resource into an operational economic domain.

3.2 The Physical Layer: Distributed and Embedded Infrastructure

The physical layer constitutes the material interface through which low-altitude economic activity is executed. Its defining feature is a shift from isolated, enclosed facilities toward distributed and embedded infrastructure that is deeply integrated into the urban fabric.

Facility Networks. Core physical assets include vertiports, automated drone nests equipped with docking and charging capabilities, and logistics transfer nodes. Unlike conventional airports, these facilities must operate at high spatial density and leverage existing urban structures such as rooftops, industrial parks, public buildings, and even street-level fixtures. For example, Shenzhen has announced plans to deploy over 1,200 low-altitude takeoff and landing sites by 2026. Such density fundamentally alters the economics of facility utilization, favoring modular, low-footprint designs over large-scale terminals.

Energy Provisioning. As flight frequency increases, energy infrastructure becomes a critical bottleneck. High-power fast charging and automated battery swapping systems introduce new load profiles for urban distribution grids. Peak demand management, grid resilience, and coordination with renewable energy sources become integral to low-altitude operations. Consequently, the physical layer of the low-altitude economy is inseparable from broader urban energy systems, extending infrastructure planning beyond aviation authorities to include power utilities and municipal regulators.

3.3 The Digital Layer: The Digital Sky as a Nervous System

If the physical layer provides the skeletal structure of the low-altitude economy, the digital layer functions as its nervous system. This layer is responsible for transforming physical airspace into a computable, governable, and economically allocable resource.

Integrated Sensing and Communication (ISAC). High-density low-altitude operations require continuous situational awareness, including the detection of non-cooperative aerial objects that do not actively broadcast identification signals. Integrated sensing and communication (ISAC), enabled by 5G-Advanced and emerging 6G networks, addresses this challenge by embedding radar-like sensing capabilities within communication waveforms. This dual-use approach significantly expands surveillance coverage while reducing infrastructure redundancy.

The SILAS Paradigm. Shenzhen's Smart Integrated Low-Altitude System (SILAS) exemplifies the frontier of digital-layer implementation. Rather than functioning solely as an air traffic management tool, SILAS operates as a city-scale digital twin, capable of microsecond-level conflict detection and four-dimensional trajectory planning for heterogeneous fleets. By synchronizing aircraft intent, environmental data, and regulatory constraints in real time, such systems enable levels of concurrency that exceed the capacity of traditional air traffic control.

Performance Constraints. To support high-density operations in core zones, the digital layer must satisfy stringent performance requirements. End-to-end control latency typically must remain below 20 milliseconds, while positioning accuracy must be maintained within one meter—and in some cases at the centimeter level—to preserve safe separation in urban canyon environments. These constraints underscore the centrality of advanced communication infrastructure and algorithmic governance to economic scalability.

3.4 The Institutional Layer: Soft Infrastructure and Market Enablement

The institutional layer constitutes the soft infrastructure that renders low-altitude operations commercially viable. It encompasses airspace classification, route authorization, liability allocation, insurance mechanisms, and pricing rules. Without this layer, physical and digital capabilities remain economically underutilized.

The European Union's U-Space framework provides a mature reference model. By defining service levels from U1 (foundation services) to U4 (full-service autonomy), U-Space establishes clear service-level agreements (SLAs) and delineates responsibilities among operators, service providers, and regulators. Crucially, it addresses two foundational economic questions: who pays for coordination services, and under what data standards interoperability is ensured.

Institutional infrastructure thus performs a dual function. It mitigates systemic risk by clarifying accountability and safety obligations, while simultaneously enabling market formation by lowering transaction costs and uncertainty. In the absence of such frameworks, low-altitude operations tend to remain confined to pilot projects rather than scaling into self-sustaining economic systems.

4 A Developmental Taxonomy of Low-Altitude Activities: A Regulatory–Value-Based Analytical Framework

The rapid expansion of low-altitude activities has revealed the structural limitations of conventional aviation taxonomies that rely primarily on aircraft typology (fixed-wing versus rotary-wing) or mission profiles (commercial aviation versus general aviation). Such classification schemes are poorly suited to the analytical demands of the Low-Altitude Economy (LAE), where heterogeneous activities coexist within shared airspace, operate under differentiated regulatory regimes, and generate fundamentally different forms of economic value.

To enable cumulative empirical research and enhance policy comparability across jurisdictions, this paper proposes a developmental taxonomy grounded in two analytically independent yet jointly decisive dimensions: *Regulatory Complexity* and *Economic Value Density*. Regulatory complexity captures the intensity of certification require-

Table 1: The Scalability Framework of the Low-Altitude Economy

Layer	Definition	Core Components	Measurable KPIs
Physical Layer	The physical interface of economic operations, characterized by distributed and embedded infrastructure deeply integrated into the urban fabric.	Vertiports; Drone hives (automated docking and charging stations); Logistics transfer hubs; Energy supply networks (fast charging and battery swapping).	System throughput; Charging and swapping efficiency; Turnaround time; Ground-handling efficiency.
Digital Layer (Digital Sky)	The central nervous system of the low-altitude economy, transforming physical airspace into computable, identifiable, and governable digital assets.	5G-Advanced / 6G communication networks; BeiDou / GPS high-precision positioning; UTM / SILAS intelligent management systems; Integrated sensing and communication (ISAC).	Network latency; Positioning accuracy (meter- to centimeter-level); Concurrent processing capacity; Detection rate of non-cooperative aerial targets.
Institutional Layer	The soft infrastructure ensuring commercial viability and systemic safety through regulatory, legal, and market-enabling mechanisms.	Airspace classification and operational rules; Dynamic risk-based insurance mechanisms; Legal liability frameworks; U-Space service architecture.	Insurance pricing efficiency; Service pricing mechanisms; Clarity of legal liability attribution; Social acceptance (noise, privacy).

ments, airspace control, operational authorization, and liability attribution associated with a given activity. Economic value density refers to the economic value generated per flight, per unit of airspace, or per operational hour.

Positioning low-altitude activities within this two-dimensional analytical space transforms classification from a static labeling exercise into a developmental framework. The taxonomy not only distinguishes among existing applications, but also reveals transition thresholds, path dependencies, and structural bottlenecks, thereby providing a unified lens for both scholarly analysis and regulatory design.

4.1 Proposition 3: A Tiered Developmental Taxonomy

Based on the interaction between regulatory complexity and economic value density, low-altitude activities can be systematically organized into three developmental tiers. Each tier corresponds to a distinct stage of market maturity, governance intensity, technological readiness, and societal acceptance. Importantly, the tiers should not be interpreted as rigid categories, but as analytically meaningful clusters along a continuous developmental spectrum.

4.1.1 Tier 1: Consumer and Media Applications (Mature Stage)

Classification criteria. Tier 1 activities are characterized by low regulatory complexity and low to moderate economic value density. Operations are typically conducted under Visual Line of Sight (VLOS) conditions, outside densely populated urban cores, and involve lightweight unmanned aerial systems with limited kinetic risk and simplified certification requirements.

Representative applications. Common use cases include aerial photography, videography, recreational drone operations, and large-scale drone light shows.

Developmental characteristics. Tier 1 currently exhibits the highest level of market penetration and public visibility within the LAE. While the unit-level economic value of individual operations is relatively modest, this tier plays a foundational institutional role. It constitutes the primary interface through which the general public encounters low-altitude aviation technologies, thereby shaping risk perception, social acceptance, and baseline regulatory norms.

Large-scale drone light shows, such as those conducted by firms like Sky Elements and Pixis, are particularly significant. Beyond their entertainment value, these events function as real-world stress tests for swarm coordination algorithms, redundancy architectures, and fail-safe mechanisms under high agent density. The operational data generated in such deployments contribute indirectly to regulatory learning and algorithmic validation, supporting the upward evolution of the LAE.

4.1.2 Tier 2: Industrial Applications (Rapid Growth Stage)

Classification criteria. Tier 2 activities exhibit moderate regulatory complexity combined with high economic value density. Operations frequently involve Beyond Visual Line of Sight (BVLOS) flight, often within semi-controlled or geographically constrained environments, and are tightly integrated with existing industrial systems and workflows.

Core functional logic. Tier 2 constitutes the economic backbone of the contemporary LAE. In this tier, aerial platforms function not merely as transport vehicles, but as mobile nodes within industrial Internet-of-Things (IIoT) architectures. Flight activity is embedded directly into production, monitoring, and service delivery processes, transforming aviation from a standalone sector into an enabling infrastructure.

Key application domains. Drone-based energy infrastructure inspection enables a structural transition from labor-intensive operational expenditure (OPEX) toward capital-intensive asset deployment (CAPEX), significantly increasing inspection frequency while reducing safety risks. In precision agriculture, ultra-low-volume (ULV) spraying and multispectral sensing support targeted intervention strategies that reduce chemical usage, lower environmental externalities, and enhance yield predictability. In mid-mile logistics, particularly for medical sample transport and rural delivery, unmanned aerial systems demonstrate clear advantages in time reliability and marginal cost reduction, especially in regions characterized by geographic fragmentation or inadequate ground infrastructure.

Developmental significance. Tier 2 offers a uniquely favorable balance between regulatory tractability and economic payoff. Clear return-on-investment (ROI) mechanisms, coupled with manageable certification pathways, make this tier the primary focus of near-term capital investment, large-scale pilot programs, and regulatory experimentation. Empirically, it is within Tier 2 that the LAE transitions from technological feasibility to economic sustainability.

4.1.3 Tier 3: Passenger Mobility (Frontier Stage)

Classification criteria. Tier 3 activities are associated with very high regulatory complexity and very high economic value density. They involve passenger-carrying operations over urban core areas and require full airworthiness certification, stringent noise and safety standards, and comprehensive liability and insurance frameworks.

Representative applications. Urban Air Mobility (UAM) and Regional Air Mobility (RAM) constitute the core of this tier.

Current status and constraints. Tier 3 remains in a pre-commercial or early pilot phase. Companies such as Joby Aviation and EHang have achieved substantial progress in vehicle certification and demonstration flights. However, large-scale deployment continues to be constrained by limitations in battery energy density, acoustic footprint management, airspace integration complexity, and public acceptance of autonomous or semi-autonomous passenger flight.

Crucially, Tier 3 development is path-dependent rather than autonomous. Its feasibility relies on technological maturation achieved in Tier 2 and the social legitimacy cultivated through Tier 1. Without robust industrial operations and broad societal trust, passenger mobility cannot achieve sustainable scale.

4.2 Developmental Implications

The evolution of the Low-Altitude Economy follows a non-linear, staged trajectory rather than a uniform progression across application domains. Current evidence indicates that the sector is undergoing a decisive transition from Tier 1 toward large-scale Tier 2 deployment. Industrial applications, due to their favorable alignment of regulatory feasibility and economic value density, represent the most strategically significant arena for contemporary research, policy intervention, and infrastructure investment.

This tiered taxonomy thus provides a structured analytical lens through which regulatory sequencing, capital allocation, and empirical research agendas can be coherently aligned within the broader development of the LAE.

5 The Global Policy Landscape: A Comparative Governance Agenda

The developmental trajectory of the Low-Altitude Economy (LAE) is not a linear, technology-determined process. Rather, it reflects a pluralistic evolution shaped by geopolitical contexts, governance philosophies, and institutional traditions. While similar technological capabilities—such as unmanned aerial systems, digital airspace management,

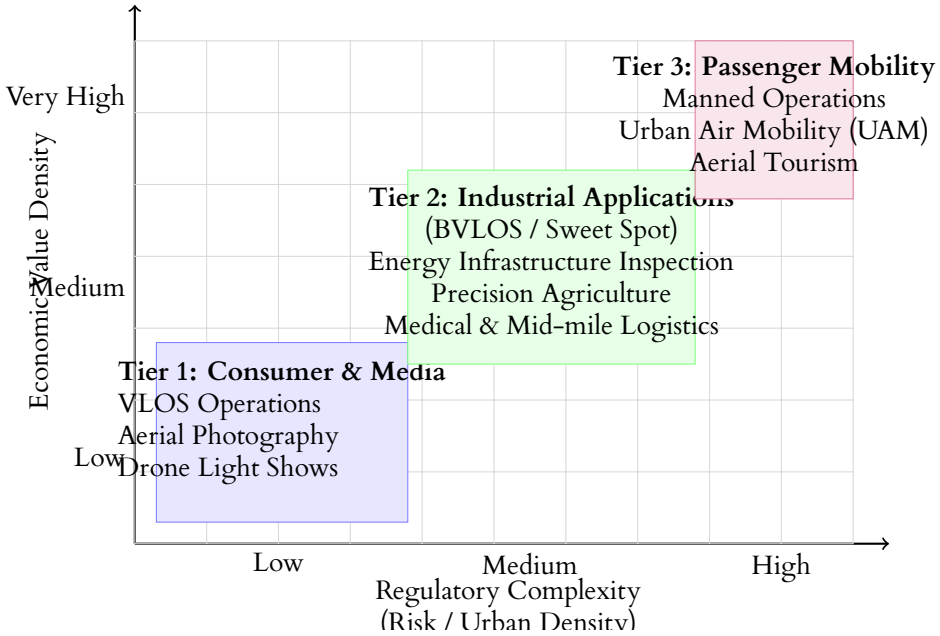

Figure 1: A developmental taxonomy of low-altitude activities based on regulatory complexity and economic value density. Activities evolve from the lower-left corner (low complexity and low value) toward the upper-right corner (high complexity and high value). Tier 2 represents the current commercialization "sweet spot" of the Low-Altitude Economy.

and advanced communication networks—are available across jurisdictions, their translation into economic systems varies substantially.

Through a comparative and isomorphic analysis of policy documents, regulatory practices, and institutional designs in China, the United States, and the European Union, this study identifies three distinct governance archetypes. To avoid reductive labeling and normative bias, the comparison is structured around five analytically neutral variables: the primary driving actor, infrastructure financing mechanisms, airspace governance architecture, liability and responsibility design, and data governance with privacy protection. Together, these variables constitute a global governance matrix that explains divergent pathways of LAE development.

5.1 Proposition 4: The Global Governance Variable Matrix

Proposition 4 posits that national and regional LAE governance regimes can be systematically compared through a multidimensional variable matrix, rather than through technological or market outcomes alone. This approach enables an assessment of structural strengths, institutional constraints, and long-term scalability across governance models.

5.1.1 China: The State–Strategic Model

China represents a state-strategic governance model in which the LAE is explicitly embedded within national development planning. The central government conceptualizes the Low-Altitude Economy as a critical component of "new quality productive forces," positioning it as both an industrial transformation engine and a strategic infrastructure layer.

Infrastructure financing follows a public-goods logic. Government-led investment plays a dominant role in the deployment of enabling systems, including 5G-A and future 6G communication networks, centralized digital airspace platforms such as SILAS, and large-scale low-altitude takeoff and landing infrastructure. Municipal initiatives, most notably in cities such as Shenzhen, illustrate how public capital reduces entry barriers for firms by resolving the classic coordination dilemma between aircraft deployment and infrastructure availability.

This model offers a decisive advantage in deployment speed and system-level coordination, enabling rapid scaling

across urban regions. However, centralized data governance and platform-centric airspace control also introduce structural risks. These include single-point-of-failure vulnerabilities, heightened data sovereignty concerns, and potential constraints on market-driven innovation at the application layer.

5.1.2 United States: The Market–Safety Model

The United States exemplifies a market-safety governance model characterized by regulatory gatekeeping combined with private-sector-led investment. The Federal Aviation Administration (FAA) functions primarily as a safety guarantor, emphasizing incremental integration of low-altitude operations while preserving historically high aviation safety standards.

Infrastructure development relies predominantly on private capital, often structured through public–private partnerships. While federal initiatives such as the "Innovate 28" framework provide strategic guidance for advanced air mobility integration, the construction of vertiports and operational infrastructure is largely financed by commercial actors such as Joby Aviation and Archer.

This market-driven environment fosters technological diversity and business model experimentation. At the same time, the federated structure of the UTM ecosystem, which depends on multiple third-party service suppliers, has led to regulatory fragmentation and interoperability challenges. Infrastructure rollout has, in many cases, lagged behind vehicle innovation, creating asymmetries between aircraft readiness and operational environments.

5.1.3 European Union: The Social-Rights Model

The European Union adopts a social-rights-centered governance model in which societal acceptance, legal certainty, and fundamental rights protection are prioritized. Under the leadership of the European Union Aviation Safety Agency (EASA), LAE development is closely aligned with public interest considerations, particularly privacy, environmental impact, and noise regulation.

Data governance constitutes a defining feature of this model. The General Data Protection Regulation (GDPR) is strictly extended to aerial data collection and surveillance activities, imposing the most comprehensive constraints among major jurisdictions. This regulatory stance ensures high levels of public trust and legal clarity, particularly within the standardized U-Space service framework that defines graduated service levels from U1 to U4.

The principal strength of the European model lies in institutional completeness and societal legitimacy. However, elevated compliance costs and regulatory complexity may slow innovation cycles, particularly for early-stage firms and experimental applications.

5.2 Key Comparative Implications

The global policy landscape of the Low-Altitude Economy is marked by pronounced heterogeneity rather than convergence. The Chinese state-strategic model demonstrates unparalleled capacity for rapid infrastructure deployment and coordinated scaling. The U.S. market-safety model excels in entrepreneurial dynamism and technological diversity. The European social-rights model leads in regulatory coherence, legal certainty, and social integration.

These governance archetypes are not mutually exclusive endpoints, but rather represent distinct equilibrium configurations shaped by political economy, institutional capacity, and societal priorities. Understanding their structural logic is essential for both comparative research and the design of adaptive governance strategies in an increasingly interconnected low-altitude ecosystem.

6 The Digital Sky and the Algorithmic Liability Chain

The transition from conventional Air Traffic Control (ATC) to what is increasingly described as the "Digital Sky" constitutes the most distinctive technological and institutional rupture between the Low-Altitude Economy (LAE) and traditional aviation systems. In high-density operating environments involving hundreds of thousands or even millions of concurrent low-altitude flights, human-centered control architectures are no longer viable. Decision-making authority is progressively delegated to algorithms that perform real-time sensing, conflict detection, trajectory optimization, and enforcement.

As algorithms become the de facto regulators and executors of airspace order, a foundational legal and technical challenge emerges: the construction of an algorithmic liability chain. Unlike traditional aviation incidents, where

Table 2: Comparative matrix of governance variables for low-altitude economy

Governance variable	China	United States	European Union
Driving actor	State-strategic leadership; LAE framed as a new productive power; central planning and coordination.	FAA as gatekeeper; focus on safe, incremental integration of new operations.	EASA emphasis on social acceptability and privacy; strong regulatory guidance.
Infrastructure financing	Public-goods model; government-led investment in digital airspace systems and take-off/landing nodes (e.g., city pilots supporting SILAS or similar).	Private capital and PPP; FAA framework supports but relies on industry investment for vertiport construction.	Mixed use of public and private funding; strong regulatory clarity attracts compliant service providers within U-Space.
Airspace mechanism	Centralized or integrated digital airspace platforms; city-level coordination (e.g., SILAS-type initiatives).	Federated UTM and related services; collaboration between public authorities and private service providers.	U-Space regulations and services; unified EU-level rules with emphasis on interoperability and information security.
Liability and legal design	Administrative leadership, evolving legal frameworks; state coordination for rapid rollout and oversight.	Risk-based certification and liability frameworks; market-driven, with oversight via FAA and related authorities.	Stringent legal design; GDPR and privacy rules shape operational and surveillance practices; high certainty of legal obligations.
Data privacy and personal data	Integrated, government-managed digital systems; centralized data governance with debates on sovereignty and risk concentration.	Private-sector led data usage, subject to national regulation; emphasis on operational safety and market innovation.	Strict GDPR-based data protection; enforceable privacy by design principles in drone operations and data handling.

responsibility can typically be attributed to identifiable human actors or organizations, LAE incidents frequently arise from interactions among multiple automated systems operating across institutional and technical boundaries.

6.1 From Human-in-the-Loop to Algorithm-in-the-Loop

In traditional ATC systems, human controllers occupy the central decision-making position, and legal responsibility follows established doctrines of human negligence, professional duty, and organizational liability. In contrast, the Digital Sky is characterized by "human-out-of-the-loop" or, at best, "human-on-the-loop" operational modes. Algorithms autonomously generate avoidance maneuvers, prioritize flight paths, and execute compliance decisions at machine speed.

This shift fundamentally disrupts fault-based liability regimes. When operational outcomes are determined by layered algorithmic processes rather than direct human intent, assigning responsibility based solely on operator behavior becomes analytically insufficient. The Digital Sky therefore necessitates a reconfiguration of liability around data provenance, algorithmic decision logic, and infrastructure performance.

6.2 The Minimal Model of the Algorithmic Liability Chain

To address the question of responsibility attribution in algorithm-driven incidents, this study proposes a minimal yet operationally viable liability chain model grounded in end-to-end data logging and causal traceability.

The liability chain is activated when an incident trigger occurs. Such triggers include physical collisions between autonomous aerial vehicles, airspace violations, or secondary harm resulting from algorithmic avoidance maneuvers, such as ground injuries caused by emergency landings.

Immediately following an incident, a first-level data lock is initiated. At this stage, Remote Identification broadcasts and four-dimensional trajectory records are cryptographically frozen. These datasets establish spatial-temporal facts, providing authoritative answers to the question of which vehicle was present, where it was located, and under what declared operational parameters.

The second stage involves causal auditing across multiple technical layers. Conflict resolution logs from UTM or SILAS platforms are examined to determine whether avoidance commands were correctly generated and transmitted.

This analysis distinguishes between algorithmic misjudgment, execution failure at the vehicle level, and deviations caused by external constraints.

Simultaneously, network Quality-of-Service logs from telecommunications providers are reviewed. Latency spikes, packet loss, or coverage gaps may reveal that otherwise valid algorithmic decisions were undermined by infrastructure-level failures. In highly automated systems, communication performance becomes a material factor in legal causality rather than a background condition.

Based on the combined evidence from algorithmic logs, network performance data, and operational records, liability can be allocated with precision. Responsibility may be attributed to software developers in cases of algorithmic defects, to infrastructure providers in cases of network failure, or to operators in instances of improper configuration, maintenance negligence, or rule violations.

6.3 Algorithmic Auditing and the Construction of Digital Truth

As the Digital Sky matures, regulatory oversight increasingly evolves into a form of algorithmic auditing. Supervisory authorities must acquire the capacity to interrogate algorithmic black boxes, not only for functional correctness but also for normative properties such as fairness, robustness, and proportionality.

One critical dimension of algorithmic auditing concerns ethical decision-making under unavoidable harm scenarios. In dense urban environments, conflict resolution algorithms may face trolley-problem-like trade-offs, such as prioritizing the protection of manned aircraft versus minimizing risk to ground populations. These value-laden decisions cannot be left implicit within proprietary codebases. They require ex ante ethical scrutiny, explicit policy encoding, and verifiable implementation.

Algorithmic auditing therefore extends beyond post-incident investigation. It encompasses certification of decision logic prior to deployment, continuous monitoring of learning systems, and the establishment of audit interfaces that allow regulators to reconstruct machine reasoning processes. In this sense, digital truth in the LAE is not a narrative account but a computable, replayable, and contestable record derived from multi-layer data synchronization.

6.4 Implications for Insurance and Legal Architecture

The emergence of algorithmic liability chains has profound implications for insurance markets and legal frameworks. Traditional insurance models based on operator fault or pilot error become inadequate in environments where risk is distributed across software, networks, and governance platforms. Future insurance regimes must therefore be grounded in system-level risk assessment, supported by automated auditability and verifiable logs.

Without comprehensive, standardized data trails encompassing Remote ID, network performance, and algorithmic decision records, neither actuarial pricing nor legal adjudication can function effectively. The Digital Sky thus transforms data logging from a technical convenience into a foundational institutional infrastructure.

6.5 Key Takeaway

In autonomous, high-density low-altitude operations where humans are no longer directly in control, conventional fault-based liability frameworks lose explanatory and normative power. Establishing an automated audit regime based on full-chain data logging—integrating Remote Identification, network Quality-of-Service metrics, and algorithmic decision logs—is a necessary precondition for viable insurance mechanisms, legal accountability, and public trust in the Low-Altitude Economy.

7 Economic Evidence: From Promotional Claims to Verifiable Performance

The commercial viability of the Low-Altitude Economy (LAE) ultimately depends on its ability to outperform, complement, or restructure existing ground-based systems. While early policy documents and industry reports frequently emphasize visionary narratives and projected market sizes, the academic community has increasingly criticized the prevalence of promotional or non-replicable data.

In response, this section deliberately shifts the analytical focus from speculative projections to verifiable empirical evidence. Drawing exclusively on peer-reviewed studies, official utility disclosures, and publicly auditable datasets, we examine the realized economic performance of LAE applications across three high-impact domains: energy infrastructure inspection, logistics, and agriculture. The objective is not to demonstrate universal superiority, but to identify the specific contexts in which LAE exhibits measurable and defensible economic advantages.

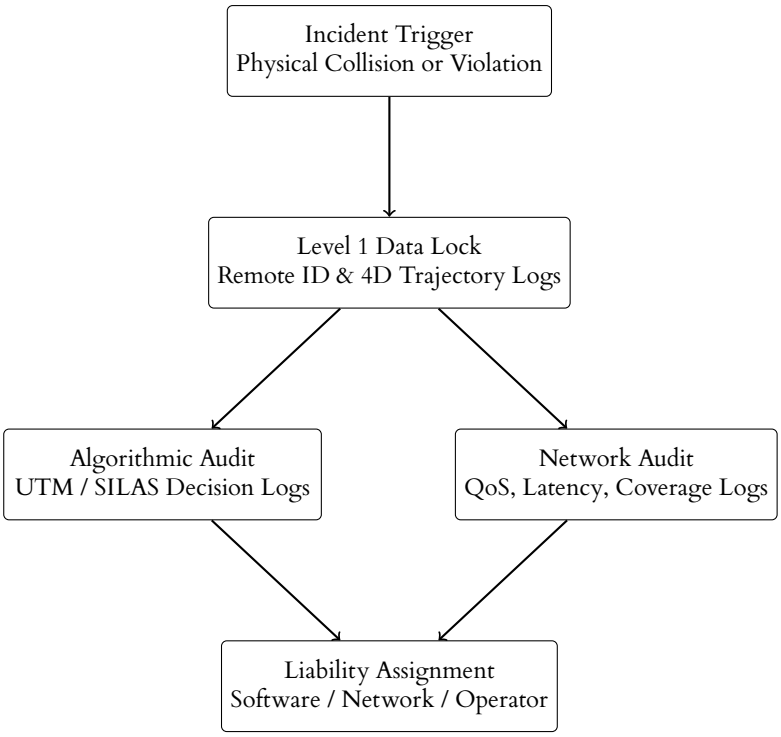

Figure 2: The Algorithmic Liability Chain in the Digital Sky. Responsibility attribution in the Low-Altitude Economy is reconstructed through multi-layer data logging and causal auditing across algorithmic, network, and operational domains.

7.1 Empirical Evidence Framework: Claim–Context–Source

To ensure analytical rigor and replicability, all empirical assertions presented in this section are organized using a standardized *Claim–Context–Source* framework.

A *Claim* specifies a quantifiable performance outcome, such as cost reduction, efficiency gain, or environmental benefit. The *Context* defines the operational conditions under which the claim holds, including geography, payload characteristics, and regulatory constraints. The *Source* identifies the peer-reviewed publication, official report, or institutional dataset from which the evidence is derived.

This structure explicitly addresses concerns regarding selective benchmarking and ensures that empirical conclusions remain conditional rather than universal. LAE is thus evaluated not as a monolithic alternative to ground systems, but as a context-sensitive economic modality.

7.2 Sectoral Evidence and Economic Interpretation

7.2.1 Energy Infrastructure Inspection

Empirical data released by China Southern Power Grid and the State Grid Corporation of China indicate that the deployment of autonomous drone inspection systems has increased inspection efficiency by approximately fifteenfold compared to conventional manual methods. More importantly, the economic impact extends beyond productivity gains.

Drone-based inspection restructures the cost architecture of grid maintenance by shifting expenditure from labor-intensive operational costs (OPEX) toward capital-intensive asset deployment (CAPEX). Once deployed, autonomous systems operate with high utilization rates and marginal inspection costs approaching zero, particularly in geographically dispersed or topographically complex environments.

From a risk economics perspective, the reduction in high-altitude manual labor significantly lowers occupational accident exposure, generating implicit safety dividends that are often excluded from conventional cost-benefit analyses. These findings suggest that the economic value of LAE in the energy sector lies not merely in speed, but in systemic risk mitigation and long-term cost stability.

7.2.2 Green Logistics and Modal Optimization

Contrary to popular narratives, empirical studies do not support the claim that drones universally outperform ground vehicles in logistics. A peer-reviewed study published in *Nature Scientific Reports* (2023) demonstrates that, in dense urban environments with high payload aggregation, electric delivery trucks retain cost and energy efficiency advantages.

However, the same study reveals a decisive advantage for electric drones in rural and suburban delivery scenarios characterized by low payload weight and high spatial dispersion. In these contexts, per-delivery costs for drone logistics were found to be 117–131% lower than those of electric trucks, alongside substantially reduced lifecycle carbon emissions.

These results confirm that LAE functions as a mechanism of *modal optimization* rather than wholesale substitution. By selectively replacing inefficient ground transport segments, particularly in mid-mile medical logistics and rural parcel delivery, LAE enhances the overall efficiency of hybrid logistics networks without undermining existing infrastructure investments.

7.2.3 Precision Agriculture and Environmental Externalities

The economic transformation enabled by agricultural drones extends beyond operational efficiency. Field studies indicate that agricultural UAVs achieve task execution speeds 40–60 times faster than manual spraying, but this metric alone understates their economic significance.

The introduction of ultra-low-volume (ULV) spraying technology enables water savings of up to 90 percent while dramatically reducing chemical runoff into soil and groundwater systems. These environmental benefits represent positive externalities that are not fully internalized by market pricing mechanisms.

From a welfare economics perspective, LAE-enabled precision agriculture produces value not only through private cost reduction, but also through ecosystem preservation and long-term public health benefits. When these externalities are incorporated into policy evaluation frameworks, the social return on investment of agricultural drones substantially exceeds that suggested by operational metrics alone.

7.3 Synthesis and Economic Implications

Across all three sectors examined, empirical evidence consistently indicates that the economic value of LAE is most robustly validated within Tier 2 industrial applications. The defining advantages of these applications include exceptionally high asset utilization rates, sharply declining marginal operating costs, and the generation of measurable positive environmental externalities.

Rather than replacing ground-based systems, LAE reconfigures existing economic architectures by targeting structurally inefficient segments. Its competitiveness arises not from universal superiority, but from precision deployment under clearly defined operational conditions.

These findings substantiate the claim that the LAE has progressed beyond promotional discourse into a phase of empirically verifiable economic performance, provided that analytical evaluation remains context-sensitive and evidence-driven.

8 Conclusion and Future Outlook

The Low-Altitude Economy (LAE) represents a rare and historically significant frontier in modern economic development: a physical domain that has become technologically accessible, yet remains institutionally underdefined and economically under-theorized. Unlike earlier spatial expansions—such as maritime trade routes or cyberspace—the low-altitude airspace exists at the intersection of physical risk, algorithmic governance, and public acceptance, rendering conventional analytical frameworks insufficient.

Through a systematic synthesis of technological, institutional, and economic evidence, this article has demonstrated that LAE should not be interpreted as a marginal extension of General Aviation (GA) or a transport-focused variant of Urban Air Mobility (UAM). Rather, it constitutes a distinct economic system supported by an infrastructure triad—physical nodes, digital skies, and institutional governance—whose evolution follows an endogenous logic shaped by scalability constraints, regulatory complexity, and value density.

Crucially, the analysis shows that LAE has progressed beyond speculative discourse. In industrial domains, particularly those classified as Tier 2 applications, empirical evidence confirms its capacity to restructure cost architectures,

enhance asset utilization, and generate measurable environmental externalities. These characteristics position LAE not as a substitute for ground-based systems, but as a structural optimizer within hybrid socio-technical networks.

8.1 The Inaugural Research Agenda

As a founding statement for the *Journal of Low-Altitude Economy and Intelligent Aviation*, this section articulates a forward-looking research agenda aimed at guiding the field from technological validation toward sustained societal integration. The following research directions are not exhaustive; rather, they represent foundational challenges whose resolution will determine whether LAE matures into a stable economic institution or remains confined to isolated pilot deployments.

8.1.1 Acoustic Landscape Ecology

Current regulatory frameworks rely predominantly on decibel-based noise thresholds, an approach inherited from traditional aviation. However, multi-rotor and distributed electric propulsion systems introduce high-frequency, intermittent acoustic signatures that interact with urban environments in fundamentally different ways. Future research must adopt an ecological perspective, examining long-term impacts on human psychological well-being, urban livability, and biodiversity, including avian migration patterns. Acoustic acceptability, rather than absolute noise intensity, is likely to emerge as a binding constraint on large-scale deployment.

8.1.2 Ethics of Algorithmic Governance

As systems such as SILAS and U-Space progressively assume conflict detection and resolution functions, decision-making authority shifts from human operators to algorithmic agents. This transition necessitates a formal ethical framework for airborne decision-making. In scenarios involving unavoidable harm, how should algorithms prioritize passenger safety, third-party risk on the ground, and property damage? These algorithmic "trolley problems" cannot be resolved post hoc and require ex ante ethical encoding, transparent auditing mechanisms, and institutional oversight before widespread deployment.

8.1.3 The Physicality of the "Last Meter"

While substantial progress has been made in addressing the "last kilometer" of aerial delivery, the final physical interface between airborne systems and end users remains underexplored. Secure docking, identity authentication, anti-tampering mechanisms, and standardized handover protocols constitute unresolved engineering and governance bottlenecks. Without reliable solutions to the "last meter" problem, the scalability of logistics-focused LAE applications will remain constrained regardless of aerial performance.

8.1.4 Energy Resilience and Vehicle-to-Grid Integration

High-frequency eVTOL operations and drone logistics hubs will impose non-trivial loads on urban distribution networks. Beyond mitigating grid stress, future research should explore bidirectional energy architectures in which aerial vehicles function as mobile storage assets. Vehicle-to-Grid (V2G) integration offers the potential to enhance urban energy resilience, smooth peak demand, and align LAE development with broader decarbonization strategies. This interface between aviation systems and smart grids represents a critical convergence point between energy economics and aerial mobility.

8.2 Closing Perspective

The sky is no longer a passive backdrop to economic activity. It is becoming an active, programmable layer of production, coordination, and governance. Whether the low-altitude domain evolves into a fragmented experimental space or a foundational component of global economic infrastructure will depend on the rigor of empirical research, the coherence of institutional design, and the willingness of scholars to engage across disciplinary boundaries.

This journal is established as a platform for that engagement. Through evidence-based inquiry and sustained theoretical dialogue, we aim to contribute to the construction of a shared intellectual framework capable of supporting the next phase of vertical economic development.

To Cite This Article Changkui LI. (2026). From Vertical Commons to Digital Sky: Defining the Low-Altitude Economy as a New Mode of Spatial Production. *Artificial Intelligence Education Studies*, *1*(1), 1-15. https://doi.org/10.6914/jlae.2026.010101

Reference

[1]ICAO. (2006). *Convention on International Civil Aviation (Doc 7300/9)*. https://www.icao.int/publications/pages/doc7300.aspx

[2]Kasliwal, A., Furbush, N. J., Gawron, J. H., McBride, J. R., Wallington, T. J., De Kleine, R. D., Kim, H. C., & Keoleian, G. A. (2019). *Role of flying cars in sustainable mobility*. https://www.nature.com/articles/s41467-019-09426-0

[3]International Digital Economy Academy (IDEA). (2022). *The White Paper on Low-Altitude Economy Development (Shenzhen)*. https://www.idea.edu.cn/d/2022-11-20/952.html

[4]Straubinger, A., Rothfeld, R., Shamiyeh, M., Büchter, K. D., & Plötner, K. O. (2020). *An overview of current research on urban air mobility*. https://doi.org/10.1016/j.jairtraman.2020.101852

[5]Ministry of Industry and Information Technology (MIIT) of China. (2024). *Implementation Plan for Innovative Application of General Aviation Equipment (2024 2030)*. https://www.gov.cn/zhengce/zhengceku/202403/content_6942168.htm

[6]Vascik, P. D., & Hansman, R. J. (2018). *Systems-level analysis of on-demand urban air mobility operational constraints*. https://dspace.mit.edu/handle/1721.1/117978

[7]Alsamhi, S. H., Shvetsov, A. V., Kumar, S., Shvetsova, S. V., Alhartomi, M. A., Hawbani, A., ... & Ambirajan, A. (2022). *Computing in the sky: A survey on intelligent ubiquitous computing for UAV-assisted 6G networks and industry 4.0/5.0*. https://doi.org/10.3390/drones6070177

[8]European Union Aviation Safety Agency (EASA). (2021). *Commission Implementing Regulation (EU) 2021/664 on a regulatory framework for the U-space*. https://eur-lex.europa.eu/eli/reg_impl/2021/664/oj

[9]Federal Aviation Administration (FAA). (2023). *Innovate28: Advanced Air Mobility (AAM) implementation plan*. https://www.faa.gov/air-taxis/innovate28

[10]Alhassan, A. B., Zhang, X., Shen, H., & Xu, H. (2020). *Power transmission line inspection robots: A review, trends and challenges for future research*. https://doi.org/10.1109/ACCESS.2020.2983198

[11]Stolaroff, J. K., Samaras, C., O' Neill, E. R., Lubers, A., Mitchell, A. S., & Ceperley, D. (2018). *Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery*. https://www.nature.com/articles/s41467-018-02917-y

[12]Mogili, U. R., & Deepak, B. B. V. L. (2018). *Review on application of drone systems in precision agriculture*. https://doi.org/10.1016/j.procs.2018.07.063

Editor *Xin HUANG editor@jlae.org*