Research Paper

Retrofitting Strategies for Urban Built-up Areas Toward Low-altitude Economy Adaptation

Feiyu Wang, Southeast University, Nanjing, China

Abstract

The development of the low-altitude economy is fundamentally transforming urban economic structures and citizen lifestyles. However, its enabling 24/7 urban mobility networks, AI-driven logistics, and nighttime economic activities remain constrained by traditional infrastructure limitations. These systems were originally designed for ground-based, daytime paradigms, creating a fundamental mismatch with aerial demand. This research targets high-density built-up areas, with integration of population spatial distribution, different demand patterns, and existing urban form conditions, it develops a planning framework for port facility layout while establishing a new operational paradigm with physical–digital restructuring. This approach resolves the systemic incompatibility between traditional infrastructure and low-altitude economic requirements, thereby enabling uninterrupted urban services and AI-driven economic digitization. This generated retrofitting strategies for existing structures, transforming them into intelligent low-altitude service platforms. The study proposes a conceptual framework integrating artificial intelligence with the built environment through a three-dimensional planning paradigm. The framework seeks to reconcile infrastructural limitations in historic urban districts with the operational requirements of the low-altitude economy. It facilitates sustained urban energy through three core innovations: (1) an optimized hierarchical spatial system enabled by real-time demand–response matching to socioeconomic fluctuations (e.g. nocturnal logistics surges and emergency service corridors); (2) non-destructive adaptive reuse of existing structures, transforming them into smart service hubs; and (3) parametric AI modules that empower cities to dynamically optimize the balance between operational efficiency and social equity across diverse communities. Meanwhile, through the case study of Nanjing, we explored the feasibility of the port-centered framework in real urban environments, and revealed and refined the specific strategies of Nanjing. By leveraging near-ground airspace, this framework transitions urban development from congested horizontal expansion toward vertically integrated, synergistic three-dimensional growth. This activates common digital service provision via low-altitude networks. Significantly, it presents an alternative developmental way for mature urban areas seeking enhanced integration with emerging aerial industries, offering a replicable implementation way for established cities globally to achieve intelligent, 24/7 low-altitude economic integration.

Keywords

Low-altitude economy; Urban air mobility; AI-assisted operations; 24-hour city; Urban retrofitting

1. Introduction

The low-altitude economy – a newborn, integrated economic paradigm centered on near-ground airspace – is poised to transform urban development. It includes electric vertical take-off and landing

(eVTOL) aircraft, unmanned aerial systems (drones), and their supporting digital and energy infrastructure. This sector means faster transportation, new logistics channels, and growth in high-tech employment, adding a new dimension to urban economies. For example, in China the industries associated with the low-altitude economy are projected to grow five times from approximately ¥6700 billion in 2024 to ¥35,000 billion by 2035. Yet a critical question arises: how will this revolution in low-altitude activity integrate with existing cities?

In parallel with the rapid development of low-altitude technologies, contemporary urban planning has undergone a significant paradigm shift from large-scale expansion to the regeneration and optimization of existing built-up areas. This transition emphasizes efficiency, adaptability, and human-centered spatial transformation, particularly in high-density urban environments.

Within this context, the integration of emerging infrastructures into existing urban systems has become a central concern in planning research. Recent studies and policy initiatives have increasingly explored how new mobility systems—especially those enabled by digital technologies and artificial intelligence—can be embedded within complex urban fabrics without disrupting established spatial and social structures.

However, existing research on the low-altitude economy has largely focused on technological feasibility, operational efficiency, or isolated infrastructure deployment. There remains a lack of a comprehensive planning-oriented framework that systematically addresses how aerial systems can be spatially and functionally integrated into built-up urban areas. This gap highlights the need for a new perspective that bridges aerial mobility with urban planning principles.

Low-altitude networks operate in the sky on a 24/7 schedule, fundamentally misaligned with traditional urban layouts and infrastructure. An aerial mobility grid cannot simply be overlaid onto the existing city. Unlike conventional ground transport, aerial vehicles require no continuous roads or rails – but they do require “ports” for takeoff, landing, and loading/unloading of passengers or goods. How to plan and design these urban ports has become the core of successfully merging the low-altitude economy into city systems. Effectively, integrating aerial mobility poses a multifaceted challenge touching on 24-hour city operations, digital governance of new airspace, equitable infrastructure access, and AI-supported mobility management – all critical themes of urban economy in the digital age.

In response to this challenge, this paper focuses on the concept of the “port” as the interface between aerial and ground urban systems. By defining ports as a unique object of study, we develop a systematic planning framework for retrofitting cities to support low-altitude economic activity. The framework addresses three key dimensions – port usage, port siting, and port operations – and is evaluated through an empirical case study in Nanjing, China, a high-density historic city at the forefront of low-altitude economy attempt. Through an AI-assisted planning approach and analysis of Nanjing’s experience, we illustrate how 24/7 aerial mobility networks can be integrated into existing urban environments.

The structure of this paper is as follows. Section 2 introduces the research methodology and the development of the port-centric conceptual framework. Section 3 elaborates on the key dimensions of port usage, siting, and operations, and discusses their implications through a case study of Nanjing. Finally, Section 4 concludes the paper by summarizing the main findings and highlighting theoretical and practical contributions.

2. Methodology

This study employs a mixed-methods approach, combining conceptual framework development with practical case studies.

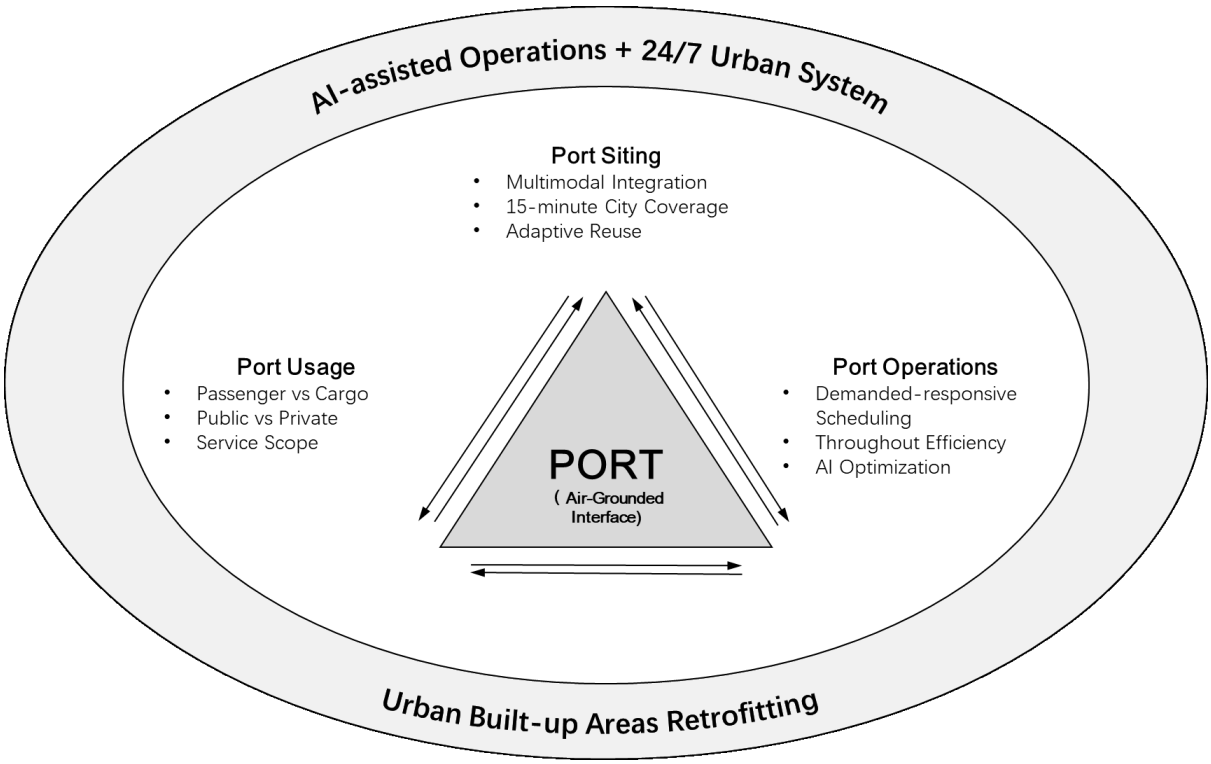


Figure 1 Port-centric conceptual framework for retrofitting urban built-up areas, illustrating the interaction between port usage, siting, and operations, and their role in enabling AI-assisted, 24/7 low-altitude urban systems.

2.1 Theoretical Framework Development

To construct the analytical framework centered on the "port", we first conducted a literature review and concept analysis. By examining academic research, industry reports, and company white papers, we defined the typology of urban aerial ports. We focused our research on three fundamental planning questions: Who will use the port and for what functions? Where should ports be located? How can ports be operated more efficiently? These correspond to a port's usage, its siting, and its operations. Based on this review, we made a port-centric planning framework that integrates these three dimensions. The outcome is a conceptual framework which assumes that a network considering three aspects – designed for appropriate functions, located in suitable locations, and managed via advanced operational strategies – can effectively integrate low-altitude aerial mobility into the urban system.

2.2 Case Study: Nanjing, China

For realistic analysis, we made a case study using Nanjing, China. Nanjing was selected for several reasons: it is a typical high-density, mixed land-use city with a historic urban center, and it has been chosen as a pilot city for low-altitude economy development. This context means Nanjing faces representative challenges while also undertaking forward-looking planning practices. Data for the case study were from multiple sources, including published research, relevant government planning documents, and public industry reports.

Specifically, the Nanjing case study aimed to: (1) verify the feasibility of the port-centric framework in a real urban environment; (2) reveal Nanjing's specific planning strategies on port network, integration of

new ports with existing infrastructure, aerial corridor planning, and demand-responsive operations; and (3) conclude practical insights and planning solutions that can be applied by other cities.

3. Discussion

3.1 Defining the "Port" in Urban Aerial Mobility

A reliable point of integrating the low-altitude economy into existing cities is the interface where the aerial system meets the city – namely, the port. We define an urban port as a facility where low-altitude flying vehicles physically interact with the city environment, essentially, the takeoff and landing sites that connect aerial routes with ground activities. A port is the node that enables passengers, goods, and services to transfer on and off flying vehicles. The concept includes a range of scales and types, from full-service vertiports to small vertipads (simple landing pads for quick pick-ups/drop-offs without extra services). In theory, it naturally forms a port hierarchy: a small number of major hubs, a larger number of district-level ports, and numerous neighborhood-level vertipads distributed throughout the city.

The key point is that, compared to traditional airports, ports do not require runways. Due to their vertical take-off and landing feature, they occupy very little physical space and can be easily integrated into existing urban networks. As a point-based infrastructure, ports possess extremely high flexibility in layout. Lightweight prefabricated drone landing pads can be quickly installed on rooftops, and underutilized building structures (such as parking lots or warehouse roofs) can also be transformed into multi-parking-pad vertical ports - thereby achieving effective reuse of existing urban spaces. This inherent flexibility makes ports a practical unit that can be used to transform dense building areas to support air traffic.

3.2 Port Functions and Users

The functional positioning of a port - that is, its purpose and the groups of people it serves - has a profound impact on the design and operation of the port. Two key aspects can be identified:

3.2.1 Passenger vs. Cargo Ports

The main difference lies in whether a port is designed for passenger transportation or for freight transportation. (or other functions that do not serve humans). Ports that cater to passengers' travel needs (such as vertical take-off and landing ports for air taxis) must prioritize the safety and comfort of passengers. They usually have facilities such as secure boarding areas, waiting lounges, as well as ticketing or boarding systems. The vertical take-off and landing ports used by passengers are likely to develop into a series of shared air transportation center networks - essentially a "sky version" of the Uber model - so their planning should focus on public accessibility and convenience. In contrast, ports specifically designed for cargo transportation or municipal services (such as drone distribution centers or emergency response drone stations) can be more compact and highly automated. Their core requirement is to safely and reliably handle packages or equipment, usually through the use of robotic technology (for example, rooftop drone platforms equipped with automatic storage cabinets or cargo exchange systems). These facilities may experience extremely high traffic during peak logistics periods. To avoid isolated and redundant infrastructure, cities may encourage the establishment of shared logistics ports (similar to the situation where multiple courier companies share the same road), rather than having each operator build their own dedicated runways - this would not only enhance efficiency but also reduce the chaos in the city.

3.2.2 Public vs. Private Ports

Another significant difference lies in the distinction between public ports (open to multiple operators and the general public) and private ports (owned and operated by specific companies or entities). Public ports are similar to public transportation stops or municipal parking lots. They are established to promote equitable access and prioritize broader public interests (for example, providing services for emergency medical drones or police drones when necessary). Private ports, by contrast, are customized facilities specifically designed for a certain company or individual. – offering customized design solutions, but there is also a risk that the design plans may not be fully utilized or excluded from the larger network. From a city's perspective, publicly accessible ports should be encouraged to ensure fairness and realize network effects, while still allowing some private ports where appropriate. The design and management methods should vary according to the function: ports serving passengers must be people-oriented, focusing on safety and passenger experience; while ports handling freight should prioritize automation and transportation efficiency. Mixed-use ports – combining passenger and cargo operations at the same site – can also be an effective approach to boost utilization and economic viability. In conclusion, it is of utmost importance to clearly define the expected functions and user groups of the port during the planning stage, as the differences between passenger transportation and freight transportation, as well as public use and private use, will result in different design standards and service models.

3.3 Port Site Selection

The site selection of a port is critical to both the port's utility and the public acceptance of the facility. A good port location strategy should enable the port to properly blend with the community of the city and surrounding transportation network. There are some strategic ideas to emphasize:

3.3.1 Multimodal Transportation Integration

The port should be closely located with the existing major transportation hubs (train stations, airports, subways or bus stops) to facilitate passengers' easy transfer. Passengers can get off the train or bus and then immediately take the electric vertical take-off and landing aircraft for the final leg of their journey. This integration not only enhances fairness and passenger volume, but also, just as public transportation is designed to serve all citizens, placing vertical ports at transportation hubs means that people from different communities can reach there without driving. This approach positions urban air transportation as an extension of the public transportation network rather than an independent competing system. Concentrating the port at existing high-traffic nodes also allows for the utilization of the sites that have been designed to handle a large number of passengers, alleviating issues such as ground traffic and parking. In summary, combining vertical ports with transportation hubs helps make air travel a part of daily commuting and makes full use of existing infrastructure investments.

3.3.2 "15-Minute City" Coverage

Contemporary urban planning aspires to the "15-minute city" principle,which means all residents can reach essential services within a 15-minute walk or bike ride. This concept can also be extended to the low-altitude transportation sector. By establishing a decentralized port network, it is possible to ensure that most residents can find a vertical take-off and landing port or point within a short distance from their homes. Broad geographic coverage ensures aerial services are not confined to a few central elite locations but are accessible at the community level. Of course, achieving full coverage requires a balance between cost and practicality; not every community can immediately have access to network facilities. Nevertheless, by setting the "15-minute city" as the guiding vision, planners can avoid excessive concentration of layouts and strive to achieve a balanced distribution of vertical port facilities within the urban area, thereby enhancing the overall accessibility of air transportation.

3.3.3 Adaptive Reuse of Existing Buildings

Making full use of the use of existing buildings and facilities is key to efficient, low-cost port deployment. Many flat rooftops, parking garage decks, and other under-utilized public facilities offer structurally sound, well-located platforms that already have ground access infrastructure. These are ideal candidates for conversion into ports. For example, a multi-story parking garage inherently provides a link between air and ground transport and can solve the “last mile” ground connection when retrofitted with a rooftop vertiport. By creatively reusing these sites, many cities have been able to establish a port network with minimal need for additional land or new construction - transforming what seemed like a "discrepancy" between the old infrastructure and the new airborne demands into an opportunity for innovative reconfiguration.

3.3.4 Environmental Adaptation and Community Engagement

Port siting must account for impacts on local residents, including noise, visual intrusion, and perceived airspace safety. One strategy is to utilize the airspace of existing transportation corridors, such as having drones frequently fly above highways or rivers, concentrating the noise in areas that are already affected by traffic, thereby avoiding interference with quiet communities. For large ports, choosing non-residential or industrial sites can reduce the disturbance to the community. At the same time, early and continuous community participation is also crucial. Involving local stakeholders in the planning process helps identify concerns, and by achieving transparency and implementing flexible mitigation strategies, it can win public support. Involving local stakeholders in the planning process helps identify concerns, and by achieving transparency and implementing flexible mitigation strategies, it can win public support.

3.4 Maximizing Port Operational Efficiency for 24/7 Service

The operational efficiency of ports directly determines the economic feasibility and user experience of the low-altitude mobility system. Once the functions and locations are set, the question becomes how to enable more flights and services within the stipulated time – ultimately approaching 24/7 uninterrupted operations.

3.4.1 Adapting to Diurnal and Cyclical Demand

Traditional urban transport infrastructure often comes to a standstill during the night, but the low-altitude mobility network, with its unmanned operation capabilities and autonomous running features, as well as its flexible port types, has the potential for all-weather operation. Operational policies might specify certain ports for 24-hour service, while ports in noise-sensitive residential areas have limited service hours or night speed restrictions to reduce disturbance. During late-night periods, due to a significant decrease in passenger demand, a baseline of service can be maintained for red-eye air-taxi trips or urgent travel needs, Including key services such as medical emergency drones.

3.4.2 Demand-Responsive Scheduling and Dispatch Optimization

An intelligent scheduling algorithm is necessary to match requests with available vehicles and/or ports in an on-demand service model capacity that minimizes waiting time and air routes. This requires dynamically scheduling time periods, scheduling flight take offs and landings, and having a load balance among the ports of the network. From the port, it must be prepared at any time to dispatch or accept vehicles. Advance dispatch algorithms are essential to prevent situations similar to too many drones dispatching to a port and there are no landing pads available. Operationally, intelligent technology can provide real time scheduling, keeping a low altitude network, quick, effective, and operational needs of aerial transportation systems in an overlap of demand.

3.4.3 Throughput Capacity and Quick Turnaround

The physical capacity of a port is driven by the number of runways and the rate of processing a take-off or landing cycle for each runway. For example, in a simulation, a specific vertical take-off and landing point configuration under certain hypothetical assumptions revealed that each take-off and landing point could carry out around 9 to 10 take-offs and landings per hour. Physical elements of design such as additional take-off and landing points, additional docking or charging points, and process improvements such as high-speed loading and/or unloading of passengers or cargo, high-speed charging of batteries or swapping them out all serve to increase the volume of transport per hour. An important component is turnaround time, which has a direct role in how quickly a pad can be opened again for the next flight. Some operators are considering turnaround time reduction methods such as high-speed charging, battery swap methodology, or new vehicles being deployed.

3.4.4 AI Integration and Network Effects

Utilizing artificial intelligence, in addition to big data, can enhance operational efficiencies by predicting demand in real time, reallocating fleets of delivery vehicles, and dynamically programming delivery routes. Predictive algorithms can help anticipate increased demand and reallocate delivery vehicles in advance (for instance, drone delivery vehicles can be moved proactively to areas in the precinct that are anticipated to create larger order volumes during peak demand times). AI may also assist air traffic management to coordinate flight paths while reducing conflicts and delays. Furthermore, the infrastructure would include a network of closely located ports with redundancy, which all would improve reliability (back-up ports) and resilience of the system as a whole. Alternatively, a sophisticated design and real-time automation will lead to system-wide network effects - the more networked and automated the ports, the more reliably and efficiently the system will operate.

The new age of operational efficiency should occur through using: smart scheduling to reduce waiting time, fast processing, adapt to demand variations at different times of day, and automata/AI to coordinate everything in real time. With increased operational efficiency, cities can obtain the maximum profit from each port, move more people and goods at the same time, and operate at lower costs. Increased operational efficiencies contribute directly to the economic viability and acceptance of the low-altitude economy as the shared utilization of low-altitude airspace becomes something integrated into urban life.

3.5 Nanjing Case Study

Recent efforts in the case of Nanjing provide a clear example of port-focused approaches in practice. As a national pilot city for low altitude economy development, Nanjing has recently engaged in a major city-level project to develop an urban aerial mobility system, advance a port network spatial design, and generally improve operational throughput. The development experience of Nanjing demonstrates the feasibility of the port framework concepts set out in this research in the respective dimensions of port use, siting, and operational entities.

Nanjing's port use – from cargo logistics to public aerial mobility: Nanjing had a clear strategy to build out its port ecosystem around freight logistics and public service applications before providing for passengers. For instance, the courier company SF Express carries out drone deliveries in the Jiangbei New District and completes dozens of fresh produce deliveries a day using vertipads. Additionally, a drone corridor has been established between hospitals to deliver critical materials (such as blood for transfusions) using rooftop helipads as a last-mile loop for emergency medical logistics. Similarly, municipal agencies responsible for policing, power utilities, and traffic management have been quick to establish automated drone stations as fixed "aerial patrol" nodes for routine oversight and inspection tasks. Ultimately, Nanjing's port use

encompasses a large range - unmanned cargo delivery and public service drones, plus a fledgling urban manned commuter flight program - that the strategic development has followed a clear plan to explore all low altitude economy applications.

Port selection in Nanjing – integrated strategy and urban symbiosis; Nanjing's port arrangement is strongly aligned with the spatial pattern of Nanjing and takes maximum advantage of existing assets. Large vertiport hubs are either planned or earmarked for development in proximity to key transit hubs (e.g., Nanjing South Railway Station or Lukou International Airport) to facilitate on-the-ground-to-in-the-air transfers. Similarly, many other smaller-scale ports have been retrofitted onto existing buildings and urban spaces, such as on rooftops of hospitals, logistics parks, and other community commercial center rooftops, in order to improve coverage and provide a low-cost density network. Nanjing's embedded port selection strategy successfully generates the least amount of new land development and sews together the low-altitude network system with existing urban fabric. Nanjing also strategically embeds airspace ports into rail or transit hubs, in addition to utilizing rooftop real estate within taller urban buildings, while even integrating corridor infrastructure for airways. Nanjing demonstrates how a city can closely co-locate aerial infrastructure, or port, within urban built environments to the benefit of both.

Port operations in Nanjing—including smart management and orchestrating the port network across the city—Nanjing has developed an entire digital governance platform, along with supporting policy actions, to orchestrate growth in its port network, on the operational side. This involves the implementation of a linked and shared management for UAV operations called Ning Yifei to create a one-stop application/approval system (to get a flight plan approved), flight path, real-time monitoring, and then tracking of the flight path. This was a critical component to sustain digital governance for urban air traffic. Stations and bases have been upgraded for infrastructure and connectivity for night-time (when they can initiate automated drone patrols) operations. Logistics companies are using a partnership with smart nests to perform last mile delivery (automated docking and dispatching) options for a supply chain service broker parcel and courier delivery within the port. (live delivery and envelope service with real time good delivery on low interaction) Nanjing's port has moved from piloting, to a normalized and scalable system. Nanjing has the digital governance structure, regulatory structure, and digital infrastructure in place to support and enable a variety of use cases (potentially 24/7 operation) towards low-altitude air mobility and sustain economic activities.

In sum, through three interrelated dimensions of port use, siting, and operations, Nanjing has developed a robust practice model. Through a combination of platform-based coordination and intelligent automation, the city has increased the efficiency of its port network considerably and with more reliability. Even more notably, Nanjing's aerial infrastructure is increasingly interconnected with ground transportation, building stock, and information infrastructure—the ports are not disparate "islands in the sky" and, instead, have begun to be a real part of the direct urban infrastructure network.

Looking ahead, Nanjing's low-altitude mobility system has plenty of room for further expansion and new innovation. One vision is the development of an "air BRT" (Bus Rapid Transit) corridor: a high-frequency eVTOL commuter mission connecting the downtown centre of the city to distant suburbs or new towns, reducing transit times significantly across a congested corridor. In light of this next step, procedures are evolving for requesting and approving local standards for port facilities (e.g., design, safety, interoperability), and the city government is encouraging collaborative co-creation and share-port infrastructure with different capital sources and public stakeholders. Overall, Nanjing is committed to provide for openness, efficiency, and safety, and collectively will develop and establish a replicable model

for urban low-altitude transport that can inform other urban centers in their pursuit of an aerial mobility plan.

4. Conclusion

The low-altitude economy is a new opportunity for cities to optimize mobility and economic activity. However, to take advantage of this new opportunity will require a careful integration of aerial systems into the fabric of the urban environment. In this paper, we centered observations and dialogue to the focal point of “port” as the nexus of integration, defining it as a unique object of study to address the complex challenges edges of the aerial and the ground domains. The main conclusions are as follows.

4.1 Clarifying port function and service scope is foundational

Planners should remember to think about how a given port facility is designed to move people or goods, and whether it has a different public purpose or private purpose. We observe in passenger and freight scenarios that there are differences in space and time, but that both can be served in an integrated way. All in all, having ports designed for more public accessibility and more for the public good (even if operated commercially) enhances public acceptance of ongoing urban aerial services.

4.2 Strategies for integrated siting are key

We considered how to physically and functionally integrate ports into the city's fabric. Ensuring ports are co-located at existing transportation hubs and providing some adherence to a 15 minute city principle, we can make aerial travel an easy extension of urban transport. Re-using existing structures (e.g., the rooftops of parking garages or shopping malls) allows cities like Nanjing to deploy a network of ports with little new construction needed, and inverting the previous tense disparity where old infrastructure existed, with new demand can create creative retrofitting strategies. By locating ports in neighborhoods while looking at non-residential locations or sites on transportation corridors, a city ensures adequate coverage while still addressing noise and safety concerns. A unifying framework for the citywide planning is a hierarchy of aerial based cities: regional hubs, district-scale ports, and local vertipads, which denote connections on a macro scale to accessibility on a micro scale.

4.3 Intelligent, efficient operations are essential

Ports must be governed effectively to allow for high productivity, high reliability and true 24/7 service. Real-time dispatching methods, expedited procedures, and multi pads vertiports are technical adaptations to reduce the queues and idles times of aerial vehicles. Altering operations to align with peak and lull demand cycles to enhance port efficiency and the economic viability of the service. The ultimate vision is sophisticated systems whereby Artificial Intelligence (AI) and automation detects everywhere ground and aerial activity and determine the organization of aerial traffic and the dispatching of drones and air taxis where and when needed with little delay -- to have an effective, "on-demand sky," that operated seamlessly from an app-based ride-hailing networks.

This study contributes to the emerging discourse on low-altitude economy by introducing a planning-oriented framework for retrofitting existing urban built-up areas. Unlike technology-driven approaches, this research emphasizes the spatial integration of aerial systems within complex urban environments.

From a practical perspective, the proposed strategies provide a reference for planners and policymakers to incorporate low-altitude infrastructure into everyday urban systems, enhancing accessibility, flexibility, and responsiveness.

Furthermore, this research aligns with the theme of the 24-hour city in the age of AI by highlighting how low-altitude mobility can support continuous urban operations, real-time service delivery, and adaptive urban systems, ultimately contributing to improved urban resilience and quality of life.

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