

Article

Urban Air Mobility Vertiports: A Bibliometric Analysis of Applications, Challenges, and Emerging Directions

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Abstract

Vertiports, as the foundational ground infrastructure for Urban Air Mobility (UAM), have garnered increasing scholarly attention in recent years. To examine how the existing literature has reviewed and summarized vertiport-related knowledge, this study conducts a bibliometric analysis of publications (2000–2024) from four major databases, including Web of Science and Scopus, using VOSviewer and CiteSpace. By analyzing co-citation and keyword co-occurrence patterns, the results suggest that vertiport research frontiers are shifting toward facility location, network planning, airspace and scheduling management, scalable infrastructure, and integration with ground transport systems. Scholars and institutions in the United States, China, Europe, and South Korea have taken leading roles in advancing this field, though collaboration among research organizations still requires strengthening. Overall, the findings reveal future research pathways and provide support for the planning and integration of vertiport infrastructure in UAM operations.

Keywords: urban air mobility (UAM); vertiport infrastructure; knowledge mapping; research trends



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1. Introduction

Currently, the global urban population is experiencing consistent and significant growth. According to the UN-Habitat report (2022), the world's urban population is projected to reach 5.17 billion by 2030, with the proportion of the global urban population increasing to 60% [1]. The expanding urban population, coupled with the ever-expanding size of cities, appears to be a significant challenge for their inhabitants. Cities worldwide face persistent traffic congestion problems that incur substantial costs, environmental pollution, challenges to sustainable development, and social conflicts.

Rapid urbanization growth has outpaced the development of transportation infrastructure, leading to overburdened road networks struggling to meet the growing demand for mobility [2]. To address the challenges posed by increasing transportation demands and the constraints of limited land-based transportation resources, cities are exploring innovative approaches to expand their transportation networks. One promising direction is the use of urban airspace for transportation purposes. In recent years, a multitude of technological advances in automation, electric propulsion, vertical take-off and landing (VTOL) aircraft, air navigation service, and unmanned aerial systems (UAS) have emerged.

These advancements facilitate the forefront development of vehicle design, air traffic management services, and business models within the field of UAM, thereby offering significant potential for the realization of passenger-carrying urban air mobility [3]. UAM, with its potential to revolutionize air transportation, envisions a safe, sustainable, and accessible air transportation system. At the core of this emerging system are vertiports—dedicated ground facilities that enable electric vertical take-off and landing operations by providing essential services such as passenger processing, aircraft turnaround, charging, and multimodal connectivity.

The planning, design, and regulation of vertiports are therefore central to the successful deployment of UAM. Civil aviation regulatory agencies in the United States, Europe, China, and other countries have commenced laying out the framework for the UAM industry [4–6]. Airbus, EmbraerX, and EHang Intelligent Technology are among the companies that have been actively involved in recent years [7,8]. Several pioneering companies, such as Skyports [9], Volocopter [10], and Urban-Air Port [11], have actively engaged in the emerging vertiport development sector. Meanwhile, the literature on UAM ground infrastructure, most notably vertiports, has also expanded. Schweiger et al. [12] reviewed both academic and regulatory sources on vertiport planning, identifying key themes such as layout requirements, site selection, safety protocols, and gaps in global standardization for vertiport operations. Brunelli et al. [13] reviewed the literature on vertiport sizing and location, summarizing studies on turnaround operations, and layout design for capacity assessment, and discussing location methods such as geographic data models, hierarchical location problem formulations, and multi-criteria decision-making (MCDM) techniques. Laghrib et al. [14] systematically classified the literature on Electric Vertical Take-Off and Landing (eVTOL) aircraft and vertiports, focusing on design, siting, operations, and regulatory aspects. Their review revealed fragmented research, limited real-world validation, and insufficient attention to local constraints such as airspace management, land use, and multimodal integration. Hijazeen et al. [15] conducted a comparative review of regulatory, operational, and infrastructure requirements for integrating vertiports into Australian airports, drawing on guidance and practices from multiple institutions. Di Mascio et al. [16] provide a comprehensive review of vertiports covering design, siting, operations, and multimodal integration. It highlights both the technical and institutional challenges that must be resolved to enable the safe, efficient, and publicly accepted deployment of vertiport.

Although research on vertiports has gradually increased, the large volume of studies makes traditional reviews time-consuming and potentially subjective. To examine how the literature has synthesized knowledge about vertiports within UAM and how scholarly discourse has evolved, this paper employs bibliometric tools such as VOSviewer and CiteSpace. Through comprehensive visual analysis, the study systematically summarizes current vertiport-related research, clarifies key developments, and provides insights to guide future advancements in the field.

The paper is organized into five main sections. Section 2 introduces the concept of vertiports and reviews their evolution. Section 3 details the data collection and the bibliometric methodology. Section 4 presents a deep analysis of the research landscape, including knowledge mapping of leading countries and institutions, and co-citation networks. Section 5 examines the vertiport literature across five research frontiers: vertiport design, capacity planning, location optimization, charging station location-allocation, and UAM operations management. Finally, Section 6 summarizes the main conclusions.

2. Vertiport Basics and Industry Status

2.1. Mechanisms of UAM

Advanced Air Mobility (AAM), as proposed by the National Aeronautics and Space Administration (NASA), represents the next generation of aviation systems designed to revolutionize transportation through the introduction of advanced electric aircraft, novel air traffic management systems, and innovative infrastructure. It aims to enhance connectivity by serving urban areas as well as previously hard-to-reach regions, thereby expanding the operational scope of conventional air transport and supporting the development of integrated aerial mobility networks [17–19]. AAM is a comprehensive term that includes a variety of innovative aviation technologies, such as small drones and automated air traffic management. Among the most notable and complex concepts within AAM is Urban Air Mobility.

Urban air mobility—defined as the safe and efficient operation of air traffic in metropolitan areas for both manned and unmanned aircraft systems—is an emerging concept [20]. UAM aims to create a safe and efficient air transportation system that supports a diverse array of aerial vehicles, from compact package delivery drones to passenger-carrying air taxis. The concept encompasses various aspects, including eVTOL aircraft, on-demand air transportation services, and advanced air traffic management systems [21].

As shown in Table 1, the foundational structure of UAM encompasses three interdependent components: aerial vehicles, urban infrastructure, and air traffic management systems [22]:

Table 1. Common Terms Associated with Urban Air Mobility.

Category	Term	Definition
Key Concepts	Urban Air Mobility (UAM)	The safe and efficient air traffic operations in a metropolitan area for manned aircraft and unmanned aircraft systems.
	Advanced Air Mobility (AAM)	A system of safe, affordable, and automated air transportation for passengers and cargo in urban and rural settings.
Aerial Vehicle	Vertical Take-Off and Land (VTOL)	An aircraft that can take off, hover, and land vertically.
	electric vertical take-off and landing (eVTOL)	A variety of VTOL aircraft use electric power to hover, take off, and land vertically.
	Unmanned Aerial Vehicles (UAV)	Multi-use aircraft with no human pilot aboard, commonly referred to as ‘drones’.
Air Traffic Management	Unmanned Aircraft Systems (UAS)	An aircraft system that operates without a human pilot on board and is either remotely controlled by human operators or operates autonomously based on pre-programmed instructions or sensor inputs.
	Unmanned Aircraft System Traffic Management (UTM)	A traffic management system that provides airspace integration requirements, enabling safe low-altitude operations of unmanned aircraft.
City Infrastructures	Vertiport	Ground facility designed to support the operations of UAM aircraft, providing essential services.
	Communication, Navigation, and Surveillance (CNS) infrastructure	Communication, Navigation, and Surveillance systems enabling secure aircraft-to-infrastructure and aircraft-to-aircraft interaction.
	Urban Mobility Hub	A multimodal transfer center where vertiports are connected to existing ground transport (e.g., metro, bus, taxi, shared mobility).

Aerial vehicles represent the technological core of UAM, offering energy-efficient, low-noise, and short-range flight capabilities suited for intraurban transport. These vehicles are equipped with advanced avionics, autonomous navigation systems, and distributed propulsion technologies that enable vertical operations within dense urban environments.

Air Traffic Management (ATM) refers to the systems and protocols that ensure the safe, efficient, and orderly movement of eVTOL aircraft within low-altitude urban airspace. It encompasses both traditional ATM functions and emerging systems tailored for unmanned or autonomous operations. A core component is UTM, which is designed to handle high-density, low-altitude operations by managing flight planning, trajectory tracking, conflict detection and resolution, geofencing, and dynamic rerouting in real time.

Urban infrastructure refers to the ground-based facilities that enable and support the operation of UAM systems. It comprises three core components: vertiports, which serve as purpose-built hubs for take-off, landing, charging, and passenger services for eVTOL aircraft; CNS infrastructure, which provides the technological foundation for safe and efficient airspace integration; and urban mobility hubs, which facilitate the seamless connection between UAM services and other modes of urban transportation, thereby enhancing multimodal accessibility.

2.2. Definition of Vertiport

Facilities dedicated to UAM aircraft operations, including take-off and landing, parking, and energy supply, are commonly termed vertiports. In addition, these facilities provide functions such as passenger handling, aircraft turnaround, ground handling, and act as nodes for multimodal integration within the broader urban transportation network [12].

The concept of vertiports has evolved significantly over time. Early inspiration can be traced to heliports, which have been regulated since the mid-20th century by aviation authorities such as the Federal Aviation Administration (FAA) and the International Civil Aviation Organization (ICAO). Heliport standards for landing pads, obstacle clearance, and operational safety laid the foundation for subsequent vertiport design [23]. The modern vision of vertiports began to take shape in 2016, when Uber Elevate introduced the concept of vertiports to support its proposed eVTOL ridesharing network [21]. This marked the first systematic attempt to define vertiports as integrated facilities encompassing multiple landing and take-off zones, passenger terminals, charging infrastructure, and intermodal connectivity. Subsequent reports by NASA [24], the FAA [25], the European Union Aviation Safety Agency (EASA) [26], and other stakeholders have further elaborated on the infrastructural requirements and definitions necessary for the development of UAM systems.

In addition to the standardized term “vertiport,” past research and industry discussions have employed several alternative designations that highlight differences in scale, functionality, and operational context. The most common variations are summarized in Table 2. Among these, “vertiport” remains the most widely used term in the academic literature, and it is therefore adopted throughout this study.

Table 2. Common terms for UAM ground facilities.

Term	Scale	Description	Reference
Pocket Airpark	Compact	Small-scale airfield concepts adapted to dense urban areas.	Seeley et al. [27]
Vertistop	small	Proposed as minimal-infrastructure stopover points within distributed UAM networks.	Salehi et al. [28]

Table 2. *Cont.*

Term	Scale	Description	Reference
Vertipad	small	Compact landing pad for single eVTOL operations; often proposed in early infrastructure feasibility studies.	Johnston et al. [29]
Skynode	small	A very small UAM landing site, typically with a single pad and minimal facilities, serves as a local access node in the network.	Schweiger et al. [12]
Skypark	Medium	UAM facility with multiple pads and basic passenger or cargo services, functioning as a community-level hub.	Schweiger et al. [12]
Skyport	small to large	Marketing-driven term proposed in industry white papers for eVTOL passenger hubs.	Schweiger et al. [12]
Vertiport	Medium to large	Ground facility designed to support the operations of UAM aircraft, providing essential services.	Holden et al. [21,30]
Vertihub	Large	A centralized facility handling multiple aircraft with boarding, charging, and logistics functions.	Lineberger et al. [31]
Vertidrome	Large	Envisioned as a hybrid between a vertiport and a droneport for mixed traffic.	Schweiger et al. [32]

2.3. Current State of Vertiport Development

Established and emerging aircraft manufacturers, research institutions, and regulatory bodies, along with key infrastructure and service providers, are contributing to the development of vertiports.

The FAA's UAM Concept of Operations [33] provides a detailed introduction to the framework for UAM integration and, within this context, introduces the generic term UAM aerodrome. FAA Engineering Brief No. 105: Vertiport Design [25] provides preliminary design guidance for vertiports, addressing key aspects such as VTOL performance characteristics, surface markings, and the assumed operating environment under visual meteorological conditions. The Vertiport Electrical Infrastructure Study, conducted jointly by the FAA and the National Renewable Energy Laboratory, examines the electrical infrastructure requirements for vertiports [34].

NASA has played a central role in advancing the conceptual and technical foundations for vertiport design and operations. The UAM Vision Concept of Operations [24] describes an intermediate maturity state of the UAM system. the Advanced Air Mobility Vertiport Considerations [35] compiled more than 450 factors related to siting, design, and operations, highlighting safety, energy supply, and community integration issues, surface trajectory management, and the development of communication interfaces between operators and service providers. The High-Density Automated Vertiport ConOps [36] explored operational concepts for vertiports under high-traffic conditions, emphasizing facility automation, stakeholder roles, and ground–air traffic coordination. NASA has developed requirements for Vertiport Automation Systems [37], identifying functions such as resource allocation, surface trajectory management, and communication interfaces between operators and service providers. Further studies, such as the Vertiport Automation Trade Study [38], assessed infrastructure gaps, policy uncertainties, and community acceptance challenges, while the Vertiport Dynamic Density [39] introduced metrics for congestion management at high-demand vertiports. More recently, the In-time Aviation Safety Management System concept [40] proposed predictive and data-driven approaches to risk management in vertiport design and operations. Overall, NASA acts as a knowledge provider and

innovation driver, supporting the FAA and international bodies by identifying regulatory gaps, defining operational concepts, and developing forward-looking frameworks for safe and scalable vertiport deployment.

EASA has taken a leading role in establishing technical guidance for vertiport infrastructure in support of urban air mobility. The Prototype Technical Design Specifications for Vertiports [41] is recognized as the world's first official design specifications dedicated to vertiports.

Although ICAO has not yet issued a dedicated standard for vertiports, several related studies and activities have already addressed this emerging domain. The provisions of ICAO Annex 14, Volume II (Heliports) [42] have already served as an important reference for the development of vertiport specifications in various countries and regions. Moreover, ICAO has highlighted vertiport development in its AAM workshops and SkyTalks [43], where discussions focused on corridor airspace design and the integration of vertiports into existing air traffic management systems.

In addition to regulatory and legal research undertaken by international institutions, numerous commercial projects worldwide have already initiated the practical implementation of vertiport concepts. Skyports Ltd. [44] established a vertiport test terminal near Paris in 2022 to evaluate flight operations, ground infrastructure integration, and passenger experience. In the same year, Urban-Air Port inaugurated its Air One prototype vertiport in Coventry, a compact facility designed to accommodate both eVTOL and drone operations while integrating charging infrastructure, cargo handling, passenger services, and retail and hospitality functions [11]. More recently, Skyports [45] unveiled an operationally complete vertiport at Bicester Motion in Oxfordshire.

In Asia, the Civil Airports Association of China [46] has released the country's first technical standard for eVTOL landing fields. EHang Ltd. [47] has launched a UAM Hub at Luogang Central Park in Hefei, serving as a dedicated ground facility and operations center. In South Korea, UrbanV Ltd. [48] has partnered with the Korea Airports Corporation to co-develop an advanced UAM ecosystem, encompassing vertiport design, construction, and operations. Additionally, Hyundai Elevator [49] has taken a leading role in a government-funded core technology development program aimed at advancing vertiport infrastructure, with project completion expected by 2026.

3. Data Sources and Methods

3.1. Data Collection

To explore the significant themes and emerging trends in vertiport research, this study draws upon bibliographic data and reports from multiple authoritative sources, including the Web of Science Core Collection (WoSCC) (accessed on 15 September 2025), Scopus (accessed on 15 September 2025), IEEE Xplore (accessed on 15 September 2025), and the American Institute of Aeronautics and Astronautics (AIAA) (accessed on 15 September 2025). The keyword set, comprising a total of 16 terms, included those listed in Table 2 as well as "UAM infrastructure," "AAM facility," "eVTOL infrastructure," "UAM facility," "VTOL infrastructure," "aerial mobility hubs," and "sky taxi stations." This expanded set was applied in the database search to ensure broader coverage of relevant literature.

Following the database search, the retrieved records were further filtered according to predefined criteria. The search covered publications from 2000 to 2024, reflecting the period during which UAM research has gained momentum. The final dataset was refined through a combination of manual screening and the use of bibliometric tools such as CiteSpace and VOSviewer, to ensure both quality and relevance.

In total, 1185 records were initially retrieved across the four databases, with the following distribution:

- Web of Science Core Collection (WoSCC): 571 records
- Scopus (Elsevier): 201 records
- IEEE Xplore: 301 records
- AIAA (American Institute of Aeronautics and Astronautics): 112 records

After eliminating duplicate records through automated matching of titles, DOIs, and author information, and conducting manual screening to exclude studies focusing solely on military applications or general aviation unrelated to UAM infrastructure, the dataset was reduced to 1131 unique publications.

3.2. Methods

A knowledge map is a collection of visual representations that illustrate the relationships and structure within a body of knowledge. It is designed to convey information in a format that closely aligns with human cognitive patterns, enhancing the organization, management, and utilization of the vast amounts of information available on the internet. By visually presenting the interconnections and the hierarchy of knowledge, knowledge maps facilitate more effective exploration and dissemination of knowledge [50]. CiteSpace is a notable scientific knowledge mapping software that employs co-citation analysis theory, the PathFinder algorithm, and other techniques to assess the scholarly literature within a particular field [51]. VOSviewer provides a comprehensive array of visualizations for bibliometric analysis [52]. These powerful tools facilitate comprehensive bibliometric analysis and contribute to the identification of significant patterns and trends within the scholarly literature.

In this study, a total of 1131 articles related to vertiports were collected and subsequently imported into CiteSpace (version 6.2.R9) and VOSviewer (version 1.6.20) for bibliometric and visual analysis. We conducted an extensive analysis encompassing various aspects, including the number of publications, national collaborations, institutions, literature cocitations, keywords, and research themes.

The primary objectives of this research are as follows:

1. Identify influential contributors, focusing on leading countries and institutions through keyword and bibliometric analyses.
2. Explore recent and emerging research frontiers in vertiport.

4. Results of the Knowledge Mapping Analysis

This section presents vertiport-related research studies in two stages: (1) a situational analysis is conducted to provide an overview of the field, including the distribution of countries/regions, institutions, and a co-citation analysis; and (2) a keyword analysis is performed to support a comprehensive thematic analysis, aimed at illustrating the evolution of research themes.

4.1. Basic Situation Analysis

4.1.1. Trends in the Number of Published Papers

The number of annual publications is shown in Figure 1. The research history can be divided into two distinct stages:

1. Initial Stage (2000–2015):

During this period, vertiport research remained at a conceptual and exploratory level, closely linked to earlier studies on heliports and Short Take-Off and Landing facilities. Academic attention was limited, with only a small number of publications addressing vertiports explicitly, and most discussions appeared in the context of aerodrome design standards and VTOL technologies. Research in this stage focused primarily on:

- Drawing on ICAO Annex 14 (Heliports) as the regulatory foundation;
- Conceptual definitions of vertiports, often used interchangeably with terms such as VTOL ports;
- Preliminary considerations of air taxi systems remain largely speculative.

Overall, this stage established the basic terminology and regulatory references, but practical applications and dedicated infrastructure research were still absent.

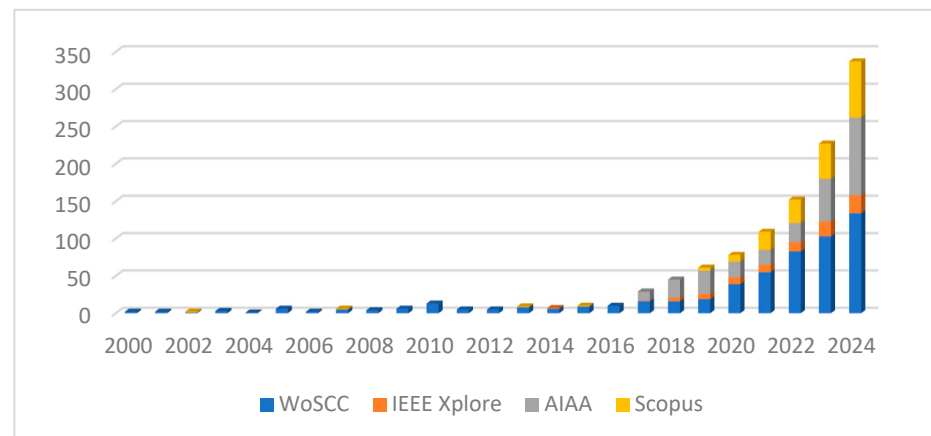


Figure 1. Publications of vertiport-related literature 2020–2024.

2. Rapid Development Stage (2016–2024):

The period from 2016 to 2024 witnessed a sharp rise in vertiport-related publications, reflecting the transition of UAM research from conceptual discussions to applied studies. Several key drivers characterized this period:

- Technological breakthroughs in eVTOL aircraft have created an urgent need for supporting ground infrastructure.
- Industry momentum: Major companies such as Volocopter, Joby Aviation, Lilium, and EHang initiated large-scale demonstration projects, requiring dedicated ground infrastructure.
- Regulatory progress: The FAA, NASA, and EASA issued the Prototype Technical Design Specifications for Vertiports, providing the first structured regulatory frameworks.
- Diversification of research themes, expanding from basic siting and design issues to capacity management, charging and energy infrastructure, multimodal integration, and safety considerations.

The rapid growth of publications during this stage illustrates that vertiports were no longer regarded as speculative infrastructure but as a practical and essential component of UAM systems. The trajectory of vertiport-related literature beyond 2025 is expected to reflect the transition from rapid exploratory growth to systematic and standardized scholarship.

4.1.2. Distribution of Country/Region

To gain a more detailed understanding of research cooperation among countries and regions, we used CiteSpace to visually analyze collaboration patterns. As shown in Figure 2, there are 37 major countries and regions involved. The node size represents the number of publications from each country. The color gradient reflects different publication years, while nodes with a purple ring indicate high betweenness centrality. The thicker the purple ring, the stronger the country's central bridging role in the network.

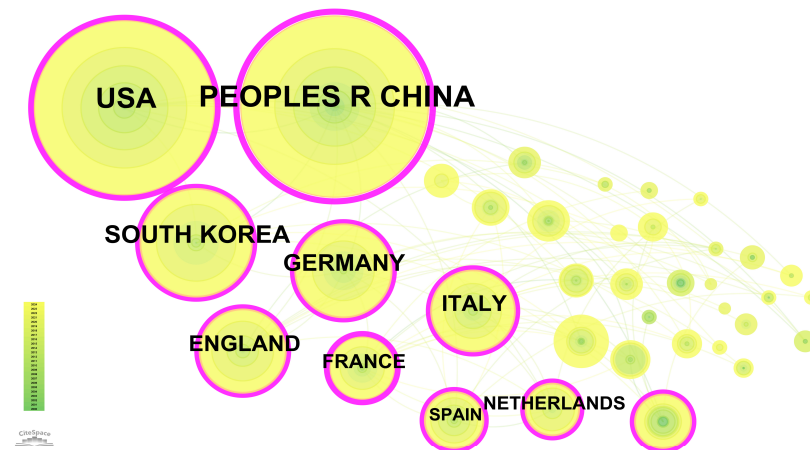


Figure 2. Collaboration network map of countries/regions.

The links depict the collaborative networks between countries, showcasing the extent of research cooperation and knowledge exchange internationally. The country network density is 0.0346. This shows that international collaboration in vertiport research is below the benchmark of 0.10–0.20 in transportation studies [53,54]. This low collaboration density reflects the early-stage and fragmented nature of vertiport research. This finding suggests a comparatively less densely interconnected collaboration network among countries within the academic domain.

In terms of research frontiers, countries at the forefront of vertiport development display some differences: The United States primarily relies on enterprise-driven innovation and city-level pilot projects, where startups play a central role in driving technological advancements and infrastructure development. China is largely policy-driven, focusing on scalable deployment, with strong collaboration between enterprises and local governments to expedite large-scale urban mobility solutions. Europe emphasizes regional collaboration and integration with ATM systems, aiming to create a unified, interoperable UAM network across European cities. South Korea leverages national strategic support and prioritizes the integration with smart cities, ensuring a sustainable and comprehensive deployment of vertiports. The Middle East (particularly the UAE and Saudi Arabia) accelerates vertiport-related adoption through smart city planning and future transportation systems, frequently collaborating with international companies. As shown in Table 3, these differing national approaches reflect the diverse pathways through which UAM systems are being integrated into urban transport networks worldwide.

Table 3. Comparative Analysis of Vertiport-Related Development Across Countries/Regions.

Country/Region	Research Focus	Representative Projects
United States	UAM ConOps [33], Engineering Brief No. 105: Vertiport Design [25,55]	City-level UAM pilot projects in cities like Los Angeles, Miami
Europe	Prototype Technical Design Specifications for Vertiports [41], SESAR Joint Undertaking Reports [56]	Demonstration projects in Paris, Munich, and Rome
China	Technical Requirements for eVTOL Landing Fields [57]	UAM hubs in Shenzhen, Hefei, and other cities
South Korea	K-UAM Grand Challenge [58,59]	UAM demonstrations in Seoul and Jeju Island
Middle East	Dubai UAM Strategy [60], NEOM Transportation Strategy [61]	Vertiport plans in Dubai and NEOM city transportation in Saudi Arabia

4.1.3. Distribution of Research Institutions

As shown in Figure 3, from 2000 to 2024, a total of 72 research institutions have actively engaged in vertiport-related research. The density of the institutional collaboration network was calculated as 0.0035, representing the ratio of actual to potential collaboration links. This value is significantly lower than the average density typically observed in institutional networks within transportation research (0.05–0.15). Such a low level of institutional collaboration highlights the fragmented and nascent nature of vertiport research, indicating that research institutions collaborate infrequently and pursue divergent research directions rather than forming cohesive, large-scale collaborative networks.

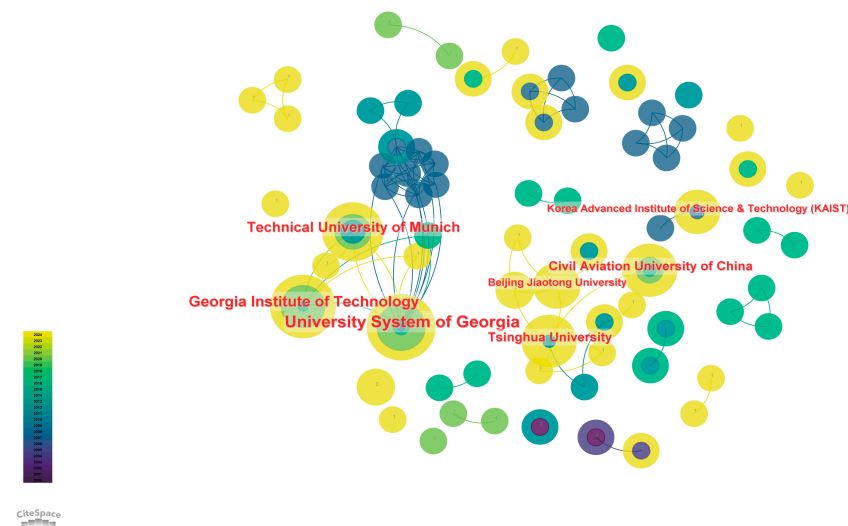


Figure 3. A visualization of institutional cooperation.

Upon further analysis, it is evident that different research teams have distinct core focuses in vertiport-related research, as shown in Table 4. Teams from UC Berkeley and NASA, through simulation technologies and network models, have made advancements in take-off and landing airspace management, queuing, and smart airspace integration. The Georgia Institute of Technology and other teams have pushed forward the integration of multimodal transport and smart airspace by using digital twin technology and intelligent scheduling algorithms. Teams from TU Munich have made significant contributions in vertiport capacity evaluation and design simulation, employing discrete event simulation and optimization algorithms. Tsinghua University and Sejong University have made breakthroughs in multi-objective optimization and demand analysis models, proposing site selection optimization models based on GIS and big data analysis. Their research also covers the integration of multimodal transport systems and vertiports and proposes dynamic scheduling solutions based on flow management.

Table 4. Core Research Teams in Vertiport-related Research.

Research Team/Institution	Research Focus	Core Research Focus	Ref
NASA Langley Research Center	Airspace Management and Operational Integration, Safety Standards, Regulatory Frameworks		[35,62,63]
UC Berkeley	Urban Transportation and UAM Network Planning, Social Equity Analysis		[64–66]
Georgia Institute of Technology	Multimodal Transportation and UAM Integration, Path Optimization, Operational Scheduling		[67–69]

Table 4. Cont.

Research Team/Institution	Research Focus Core Research Focus	Ref
TU Munich	Vertiport Design and Capacity Simulation, Topology Analysis and Optimization	[67,70,71]
Korea Aerospace University	Integration of UAM with Smart Cities, Environmental Impact, and Noise Analysis	[72,73]
Tsinghua University	Low-altitude Economy and Policy-Driven Research, Multi-objective Site Optimization	[74,75]
Beijing Jiaotong University	Transportation Accessibility Analysis, Multimodal Transportation Systems, Capacity Planning	[76,77]
Massachusetts Institute of Technology	Flight Path Optimization, Airspace Design and Integration	[78,79]
Hong Kong Polytechnic University	Traffic Simulation and Demand Modeling, Aircraft Scheduling and Service Optimization	[80,81]

4.1.4. Document Co-Citation Analysis

As shown in Figure 4, node size visually reveals the core intellectual base of this field, with larger nodes denoting highly co-cited foundational works. The top five most highly co-cited items are as follows:

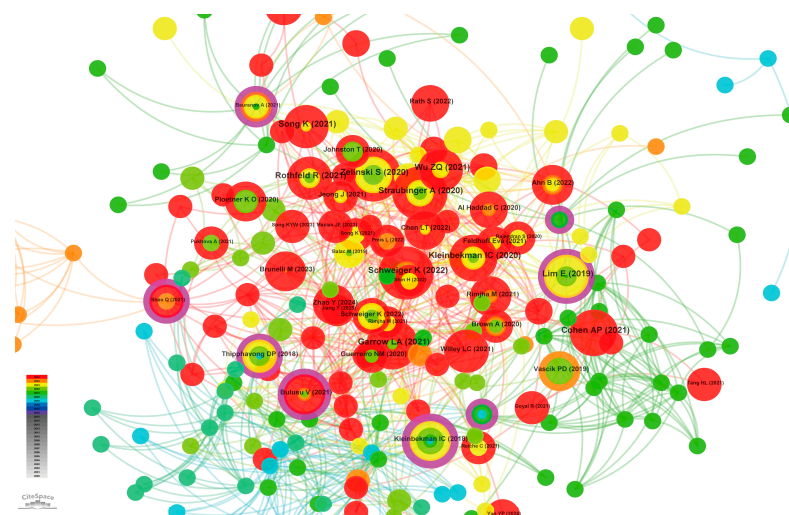


Figure 4. Document Co-Citation Network of vertiport-related [12,13,15–17,22,23,28,50–54,59,69–77,80–83].

Zelinski et al. [63] focus on the operational analysis of vertiport surface topology and, through simulation and modeling, examine how variations in runway and stand layouts affect operational efficiency and safety. Their study offers a methodological reference for subsequent vertiport design standards and capacity assessments, representing one of the earliest systematic explorations in the field.

Straubinger et al. [82] present a systematic review of the current state and development trends of UAM, addressing technology, markets, regulation, and social acceptance. They argue that the maturity of eVTOL technologies, the adaptation of airspace management, and the integration of ground and aerial infrastructure constitute the core challenges for UAM implementation. This review establishes a comprehensive framework for the initial development of UAM and is widely recognized as a key reference in the field.

Schweiger et al. [12] conduct a systematic review of the scientific literature and regulatory frameworks relevant to vertiport design and operations within UAM. The paper notes that the regulatory system remains at an exploratory stage and calls for harmo-

nization and standardization, offering important guidance for future vertiport planning and implementation.

Garrow et al. [83] provide a comprehensive review of UAM and compare it with autonomous and electric ground transportation, analyzing UAM's unique challenges and potential advantages from the perspectives of technological evolution, infrastructure needs, regulatory frameworks, and social acceptance. The paper emphasizes that cross-domain comparisons help identify directions for future research and inform integrated transport planning and policy.

Mendonça et al. [35] emphasize the multifaceted requirements of vertiport planning and operations, identifying considerations across design, regulation, environment, demand, safety, and equity that serve as a key reference for subsequent research and practice.

As shown in Figure 4, the purple rings mark nodes with high betweenness centrality, which bridge different thematic clusters. In particular, the study by Kleinbekman et al. [84] demonstrates both high centrality and strong co-citation impact. The authors address the congestion bottleneck in the arrival phase at vertiports for on-demand UAM and propose an integrated framework that couples terminal-area airspace design with rolling-horizon scheduling. The core contribution lies in dynamically computing each vehicle's required time of arrival and approach path, while continuously re-optimizing sequencing and timetables as real-time information evolves. Given that the arrival phase is widely regarded as a major operational bottleneck, this approach marks a methodological shift: vertiport capacity studies are moving beyond static timetable analyses toward rolling-horizon and agent-based models, reflecting a broader progression from feasibility and geometric design to the refinement of standards and intelligent operations. This work thus represents a methodological breakthrough and offers a valuable reference for future research.

Co-citation clusters and burst references show an evolution from systematic reviews and comprehensive analyses to site-selection studies and detailed stand layout investigations. The research paradigm has gradually expanded, moving from static, single-dimensional design toward dynamic analysis within integrated frameworks. Current research on vertiports remains constrained by deterministic assumptions and single-discipline methods, with limited interdisciplinary integration. Systematic modeling of passenger demand and behavioral uncertainty is insufficient, and operational factors such as weather, airspace conflicts, and unexpected disruptions are often overlooked. Energy integration, including grid access and charging infrastructure, has not been adequately addressed, while social dimensions such as noise, environmental impact, and community acceptance receive limited attention. In addition, the absence of well-defined design standards and internationally recognized policy frameworks restricts the scalability and practical deployment of vertiports.

4.2. Keyword Analysis

Keyword research plays a crucial role in vertiport-related studies, as the field spans multiple disciplines such as transportation engineering, aerospace, urban planning, and environmental science. Through systematic keyword analysis, researchers can integrate cross-disciplinary knowledge more effectively.

Table 5 presents the keyword frequency of the top 40 research terms in this dataset, highlighting the most frequently used concepts and their relevance to vertiport and UAM studies. The keyword analysis reveals several dominant themes in vertiport research. High-frequency keywords such as Vertiport Design (62), Airspace Management (50), Capacity Optimization (48), and Smart Airspace Integration (44) indicate that current research is strongly centered on technical and operational challenges. These include the geometric

design of vertiports, the safe allocation of limited airspace resources, and the optimization of throughput under capacity constraints.

Mid-frequency keywords, including Noise Impact (40), Charging Infrastructure (38), Multimodal Transportation (35), and Environmental Impact (32), highlight growing attention to sustainability, energy systems, and integration with broader urban mobility networks. This suggests that the field is gradually moving beyond narrow engineering perspectives to include environmental and societal dimensions.

Low-frequency keywords, such as Public Policy (3), Commercialization (2), and Community Acceptance, show that institutional, regulatory, and social aspects remain underexplored. This imbalance reflects a research gap: while technical optimization has advanced rapidly, policy frameworks, governance models, and user acceptance studies have not yet kept pace.

Taken together, the keyword distribution underscores a paradigm transition in vertiport research—from early-stage design and capacity analysis toward more integrated studies that link infrastructure, environment, policy, and society. To achieve scalability in megacity contexts, future research should strengthen cross-disciplinary integration, particularly in areas such as regulatory compliance, energy grid coupling, and socio-environmental impacts.

Table 5. Keyword Frequency Analysis for Vertiport Research.

NO	Keyword	Frequency	NO	Keyword	Frequency
1	Vertiport Design	62	21	Air Traffic Control	7
2	Airspace Management	50	22	Infrastructure Resilience	4
3	Capacity Optimization	48	23	Urban Air Traffic	4
4	Smart Airspace Integration	44	24	Noise Reduction	3
5	Noise Impact	40	25	Public Policy	3
6	Charging Infrastructure	38	26	Vertiport Capacity Analysis	3
7	Multimodal Transportation	35	27	Logistics Integration	3
8	Environmental Impact	32	28	Environmental Sustainability	3
9	Queueing Theory	30	29	Digital Twin Technology	3
10	Site Selection Optimization	19	30	Charging Time	3
11	Operational Efficiency	18	31	Flight Time	3
12	Vertiport Sizing	17	32	Digital Infrastructure	2
13	Infrastructure Integration	16	33	Passenger Flow	2
14	Autonomous Operation	16	34	Real-Time Data	2
15	Safety Standards	15	35	Traffic Modeling	2
16	Flight Path Optimization	14	36	Regulatory Compliance	2
17	Connectivity	11	37	Urban Planning	2
18	Urban Mobility Integration	11	38	Vertiport Simulation	2
19	Vertiport Accessibility	8	39	High-Altitude Operations	2
20	Charging Stations	8	40	Commercialization	2

To further analyze the evolution of vertiport-related research, a temporal trend analysis was conducted using burst detection to identify periods of sudden growth, as shown in Figure 5. It illustrates the temporal evolution of major vertiport research themes from 2000 to 2024, with stream widths representing the relative intensity of keyword occurrences. The results indicate that early research (2000–2015) was dominated by conceptual discussions, particularly those focused on vertiport design and heliport analogies. From 2016 to 2019, themes such as site selection and network planning began to gain prominence, coinciding with the emergence of eVTOL prototypes. Between 2020 and 2023, the increased emphasis on airspace integration, capacity optimization, and environmental impact reflects a transition toward system-level and regulatory-oriented studies. In recent years (2023–2024),

burst keywords such as charging infrastructure, digital twin, and autonomous operation have emerged, highlighting growing research attention on energy systems, digitalization, and operational automation.

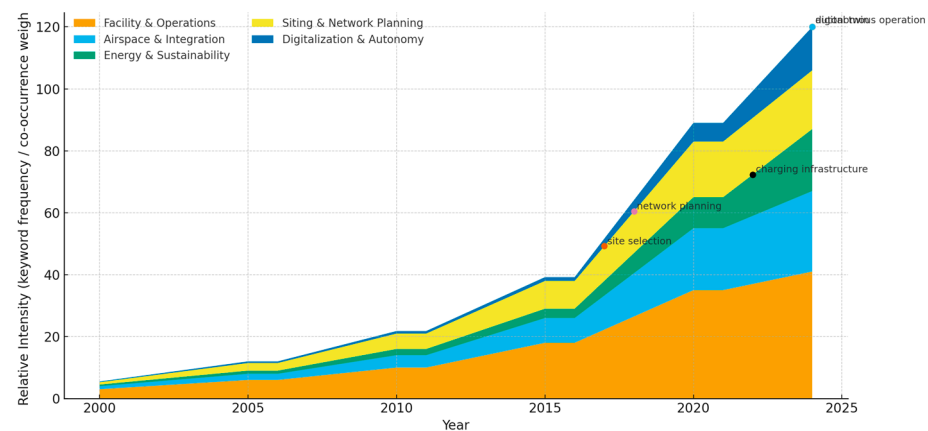


Figure 5. Temporal Evolution of Vertipor Research Themes and Burst Keywords, 2000–2024.

Collectively, these trends suggest that vertipor research is shifting from feasibility-oriented studies toward more detailed investigations of engineering, integration, and practical implementation. Looking ahead, progress will require the adoption of robust and stochastic optimization techniques to capture demand uncertainty, operational variability, and long-term infrastructure investment risks. At the same time, multi-scale digital-twin models should be developed to integrate airspace operations, apron management, power grid interactions, and community impacts, thereby offering a holistic view of system performance. In parallel, mechanism design and policy experimentation for slot and stand reservations are needed to ensure fair, efficient, and scalable allocation of scarce operational resources. Together, these approaches can support the development of system-level solutions that are both technically feasible and socially acceptable, facilitating the deployment of vertipor networks in complex megacity environments.

5. Research Themes

To further delineate the knowledge structure of vertipor research, CiteSpace was employed to perform keyword co-occurrence clustering analysis. CiteSpace’s clustering function, based on the log-likelihood ratio and keyword frequency algorithms, was applied to automatically generate cluster labels and assess network modularity [51]. The clusters achieved satisfactory modularity and silhouette scores, confirming both structural validity and internal consistency.

Examination of the core articles within each cluster identified five principal thematic domains (see Figure 6):

1. Vertipor Design: work related to infrastructure configuration, design standards, and layout planning.
2. Capacity: research addressing vertipor capacity, operational flow, and scheduling efficiency.
3. Location optimization: studies focusing on site selection methods, accessibility, and network efficiency.
4. Charging station location–allocation problem: research addressing optimal placement, sizing, and integration with grid constraints.
5. UAM operations management: studies on fleet assignment, scheduling, and service performance.

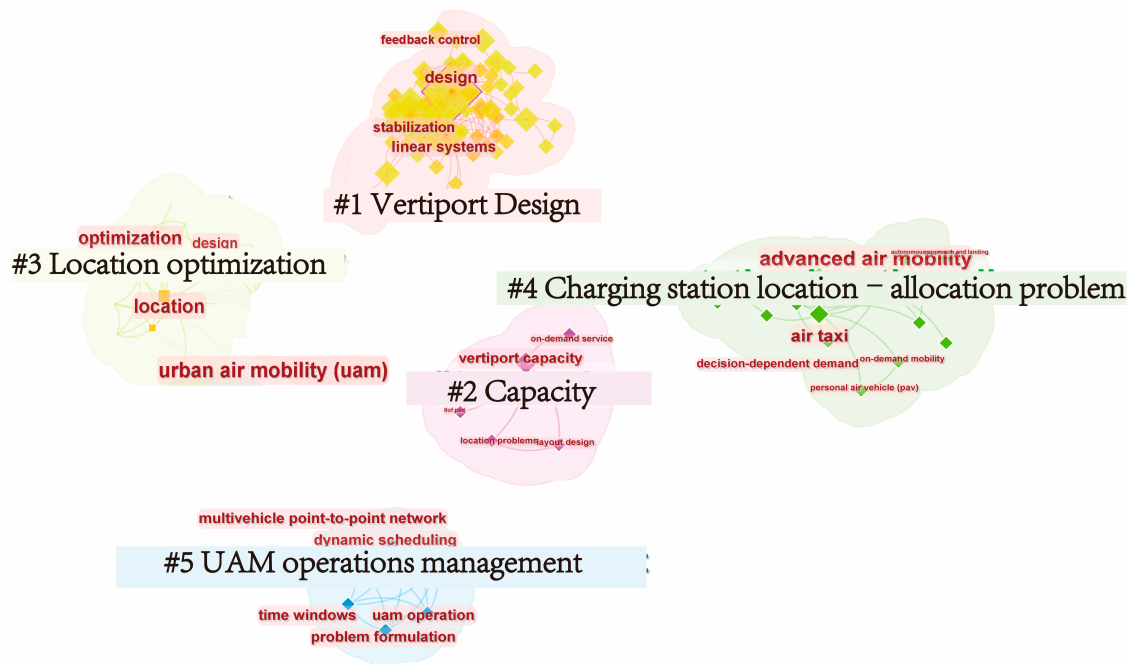


Figure 6. A visualization of institutional cooperation.

5.1. Theme 1: Vertiport Design

A vertiport typically follows a dual-zone strategy, comprising airside and landside areas, which mirrors the operational principles of conventional airports while being adapted to the unique characteristics of VTOL aircraft operations (see Figure 7) [13,85].

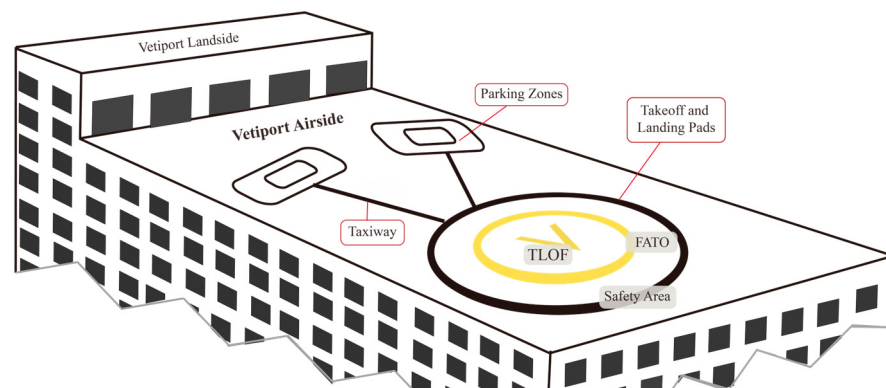


Figure 7. A visualization of institutional cooperation.

The airside refers to all areas directly involved in flight operations and VTOL vehicle handling. It must adhere to strict safety, clearance, and operational standards defined by regulatory bodies such as the FAA, EASA, and ICAO. Key airside components include:

- Touchdown and Lift-Off Area (TLOF): The core surface on which aircraft take off and land, designed to be obstruction-free and constructed with materials suitable for eVTOL operations.
- Final Approach and Take-Off Area (FATO): A safety-buffered perimeter surrounding the TLOF that ensures safe aircraft ingress and egress.
- Safety Area: The buffer zone surrounding the FATO is designed to ensure that aircraft deviating from their intended takeoff or landing paths do not collide with obstacles.
- Parking and Landing Areas: For VTOL aircraft waiting between operations, undergoing pre-flight checks, or charging.

The landside encompasses all facilities accessible to passengers, staff, and ground transport modes. It forms the interface between ground-based urban mobility systems and aerial transport. Main elements include:

- Passenger Terminal: Check-in desks, security screening zones, waiting lounges, restrooms, and boarding gates.
- Multimodal Transport Hubs: Integration with public transport, ride-sharing zones, taxi bays, and bicycle parking areas.

To ensure the safe and efficient operation of eVTOL aircraft, several aviation authorities have issued preliminary guidelines for vertiport design. In particular, the FAA and the EASA have played leading roles in defining engineering requirements and layout principles. Table 6 presents a comparative summary of dimensional recommendations provided by key institutions and studies. The FAA [25] and the EASA [41] recommend the incorporation of automation systems, noise mitigation strategies, and multimodal transfer capabilities.

Table 6. Comparison of Vertiport Design Dimensions Across Key References.

Reference	TLOF	FATO	Safety Area (SA)
Seeley (2017b) [27]	—	—	550 × 325 ft
Uber Elevate (2016) [21,86]	50 × 50 ft	75 × 75 ft	125 ft
Alexander and Syms (2017) [87]	45 × 45 ft	70 × 70 ft	100 ft
Vascik et al. (2017) [88]	50 × 50 ft	—	—
Syed et al. (2017) [89]	43 × 43 ft	65 E 65 ft	95 ft
Antcliff et al. (2016) [90]	50 × 50 ft	100 × 100 ft	125 ft
EASA [41]	—	—	2D × 2D
FAA [25]	1D × 1D	1.5D × 1.5D	3D × 3D
ICAO [42]	0.83D	1D	1.25D

Note: D refers to the D-value—the maximum overall dimension of the aircraft. A value without the symbol “×” represents a diameter, while a value containing “×” denotes the side length of a square.

A prominent trend is the modularization of vertiport structures, which allows for scalable configurations ranging from single-pad rooftop installations to multi-pad ground hubs. Researchers have proposed flexible design modules that can be adapted to urban, peri-urban, and intermodal environments [91,92]. This adaptability is critical for cities with varying spatial, economic, and regulatory constraints. Scalability is further emphasized through vertical stacking concepts and floating vertiports, especially in high-density urban cores or waterfront districts [87]. Recent literature has increasingly focused on intermodal integration, where vertiports are co-located with existing transportation hubs to facilitate seamless first-mile and last-mile connectivity [82]. Design considerations now extend beyond airside requirements to include landside components such as passenger access, parking, and multimodal interface points. This shift reflects a recognition that vertiports are not isolated infrastructure but active nodes in the urban mobility network.

The next generation of vertiports is expected to incorporate digital twin systems, automated traffic control, and predictive maintenance frameworks [93]. These smart technologies will support autonomous ground handling, dynamic slot allocation, and adaptive charging schedules, thereby increasing operational throughput and reducing human error. The integration of real-time weather monitoring, airspace deconfliction algorithms, and energy optimization systems is also a key research frontier.

Recent studies have introduced a range of analytical and computational techniques to inform vertiport design and layout optimization. These approaches aim to address challenges such as multi-vehicle scheduling, spatial constraints in dense urban environments, safety requirements, and passenger experience. Key techniques include:

- Multi-Agent Simulation (MAS): Simulates interactions among multiple eVTOLs, vehicles, and passengers to optimize flow and detect operational bottlenecks [94,95].
- Computational Fluid Dynamics (CFD): Used to analyze rotor downwash effects and airflow interference to improve the aerodynamic safety and efficiency of TLOF and FATO areas [96].
- Queuing Theory Models: Applied to estimate vertiport throughput and optimize the number of TLOF/FATO pairs under stochastic demand [97].
- Discrete-Event Simulation (DES): Enables evaluation of vertiport performance under different demand scenarios and layout configurations [98].
- Optimization Algorithms: Mixed-integer linear programming (MILP) and heuristic methods are used for layout configuration, pad allocation, and gate assignment [13].
- GIS-Based Spatial Analysis: Supports the assessment of vertiport location feasibility and integration with existing urban infrastructure [99].

Table 7 summarizes the main advantages and limitations of the above methods, providing a reference for subsequent method selection and model development.

Together, these evolving standards provide a foundational framework for vertiport planning and offer a point of departure for academic and industrial innovations in layout optimization, capacity planning, and regulatory alignment. However, as real-world operations begin to scale, continued refinement and harmonization of global standards will be essential.

Table 7. Comparison of Methods Applied in Vertiport Design.

Method	Advantage	Limitations
MAS [94,95]	Captures complex interactions among eVTOLs, ground vehicles, and passengers; suitable for dynamic demand and congestion analysis; reveals emergent system behaviors.	Requires detailed behavioral and calibration data; computationally intensive; results may be sensitive and lack analytical tractability.
CFD [96]	Provides accurate analysis of rotor downwash, airflow interference, and wind fields; directly informs TLOF/FATO aerodynamic safety and design.	High computational cost; limited to small-scale or localized simulations; difficult to scale to network-level planning.
Queuing Theory Models [97]	Mathematically tractable and efficient; estimates throughput, waiting times, and utilization quickly; suitable for early-stage capacity assessment.	Relies on simplified assumptions; limited in capturing operational complexity; results may deviate from reality.
DES [98]	Flexibly models detailed operational processes; evaluates performance under different demand scenarios and layouts.	Requires extensive parameterization; lacks general closed-form solutions; simulation runs may be costly for large scenario sets.
MILP [13]	Formulates rigorous models for layout, pad allocation, and scheduling; MILP offers optimal or near-optimal solutions; heuristics handle large-scale problems efficiently.	MILP becomes intractable for large networks; heuristic solutions may lack guaranteed optimality and reproducibility.
GIS-Based Spatial Analysis [99]	Visually demonstrates site feasibility and integration with urban infrastructure; allows multi-criteria overlay.	Primarily static analysis without a dynamic operational perspective; results depend heavily on data accuracy; limited in handling time-dependent constraints.

5.2. Theme 2: Capacity Planning

Integrated capacity management and scheduling in vertiports refers to the holistic coordination of multiple interdependent resources in UAM systems, including take-off

and landing pads (TLOF/FATO), charging and energy replenishment facilities, passenger handling processes, and airspace slots, to ensure efficiency and reliability of operations.

- **Stands Capacity**

Vertiport layout research addresses how the internal configuration of a vertiport affects the stand capacity.

Feldhoff et al. [100] investigate the infrastructure requirements for integrating air taxi services into existing airport environments, taking Cologne Bonn Airport as a case study. The study develops an analytical framework to evaluate demand scenarios, passenger flows, and vertiport configurations, thereby linking airside operations with landside infrastructure planning. Preis et al. [101,102] propose a methodological framework for preliminary vertiport design, focusing on quick sizing, throughput estimation, and layout planning. Their approach explicitly considers pad arrangement, passenger flow, and ground safety regulations, thereby providing practical guidance for early-stage vertiport infrastructure planning. Vascik et al. [103,104] developed the concept of vertiport capacity envelopes to quantify the maximum achievable throughput under varying operational conditions. Their analysis further examined the sensitivity of capacity to topological factors and operational parameters, highlighting key constraints for scalable UAM operations. A comparative overview of various vertiport layout types is presented in Table 8.

Table 8. Comparison of Vertiport Layout Types.

Layout Type	Characteristics	Advantages	Limitations
Linear Layout [13]	TLOF/FATO and stands arranged in a straight line; suitable for narrow sites or runway-adjacent areas.	Compact footprint; simple design and construction; easy management.	Low operational flexibility; prone to serial queuing bottlenecks; limited separation from downwash interference.
Parallel Layout [101]	Multiple runways/pads aligned in parallel rows.	Enables higher simultaneous throughput, suits medium-demand hubs, and allows more orderly operations.	Requires a larger land area; stricter safety and wake separation management.
Radial/Centralized Layout [13]	Pads and stands arranged around a central terminal or core.	Short passenger walking distances; efficient transfers; higher density of pads in limited space.	Complex downwash interactions; congestion risk in central areas; requires advanced scheduling.
Distributed Layout [13]	Several smaller vertiports dispersed across a region instead of one large hub.	Expands service coverage, enhances flexibility and redundancy, and reduces congestion at central hubs.	Higher investment and operating costs; more complex coordination and management.
Integrated Multimodal Layout [13]	Designed in conjunction with ground transport hubs (metro, bus, rail).	Strengthens intermodal connectivity; improves passenger experience; enables high passenger throughput.	High initial construction cost; requires long-term cross-agency planning and coordination.

- **Take-off and Landing Capacity**

Take-off and landing capacity is the core component of vertiport performance, determined by the number of pads, stand configuration, taxiway layout, and separation standards, which directly affect the number of eVTOL movements a vertiport can accommodate per unit time. Existing studies generally assess hourly throughput based on safety spacing, rotor downwash effects, wind direction, and weather conditions. Vascik et al. [88] analyzed the scaling constraints of UAM operations, showing that vertiport throughput

is fundamentally limited by safety separations, air traffic management, and community noise restrictions. Rajendran et al. [105] developed a queuing network model for vertiports, which estimates waiting times, pad utilization, and throughput under stochastic demand, providing analytical tools for early-stage capacity planning.

- System-level throughput and bottleneck identification

Capacity is not confined to a single element but instead constrained by the interaction of multiple factors, including pads, charging facilities, and airspace slots. Zhang et al. [95] examined bottlenecks in multi-vertiport networks under various demand scenarios, applying a hybrid optimization–simulation approach to evaluate system throughput. Vascik et al. [104] employed a scenario-based analysis, demonstrating that demand and weather uncertainties significantly affect capacity resilience, and adaptive operational strategies are necessary to mitigate disruptions.

Recent research on vertiport capacity evaluation has gradually shifted from static analytical approaches to dynamic simulation and integrated optimization frameworks. Several core methods are commonly applied, including queuing theory models [106], DES, MAS, and optimization models, all of which provide different perspectives for estimating and managing vertiport capacity.

In particular, Digital Twin and data-driven approaches have also been introduced into capacity assessment. A Digital Twin is a dynamic virtual model that interacts with its physical counterpart in real time to monitor, predict, and optimize system performance. In the context of vertiports, it enables the integration of physical infrastructure, operational data, and operational rules into a continuously updated virtual platform. This approach offers advantages such as real-time monitoring and prediction, operational optimization, scenario simulation, and lifecycle management [14]. Supported by big data and artificial intelligence, it applies machine learning, reinforcement learning, and predictive analytics to establish intelligent, real-time, and adaptive capacity management systems, thereby enabling dynamic monitoring, intelligent forecasting, and adaptive scheduling of vertiport capacity [95].

Overall, recent advances in vertiport capacity assessment highlight a shift toward integrated, dynamic, and simulation-driven optimization frameworks. Frontier methods emphasize system-level bottleneck analysis under multi-dimensional constraints and incorporate state-of-charge battery modeling, simulation–optimization hybrid approaches, and scenario-based uncertainty analysis into the capacity assessment framework, providing more robust decision support for practical deployment.

5.3. Theme 3: Location Optimization

Vertiport location and network layout represent a core area of infrastructure planning in UAM, with the primary goals of ensuring efficient route coverage, high service accessibility, and system robustness. Current research largely centers around two major directions: (1) macro-level siting optimization and (2) modeling of network connectivity and service performance.

Researchers have employed a variety of modeling and analytical methods to evaluate how different siting strategies and network structures influence service capacity, response time, and operational efficiency:

- Multi-Criteria Decision-Making (MCDM)

MCDM methods are widely adopted in the early planning phase of vertiport site selection to integrate and evaluate heterogeneous factors—technical, economic, environmental, and social—under a unified decision framework. These methods enable planners to rank

or select candidate locations by systematically scoring alternatives against multiple, often conflicting, criteria.

As shown in Table 9, in the field of vertiport site selection, most studies adopting MCDM frameworks utilize evaluation criteria from six major dimensions: technical, economic, environmental, social, regulatory, and infrastructure-related. Technical criteria emphasize the physical and operational suitability of candidate locations. Common factors include terrain suitability, airspace accessibility, and obstacle clearance, often assessed via 3D GIS analysis to ensure safety from surrounding high-rise structures [107]. Economic factors cover the financial viability of vertiport construction and operation. Key indicators include land acquisition costs, construction costs, and return on investment, which are estimated using land pricing databases, infrastructure availability, and projected throughput models [108]. Common metrics include proximity to population centers, equity of access across different socioeconomic zones, and public acceptance, sometimes inferred through surveys or sentiment analysis. Regulatory criteria pertain to local zoning laws and aviation safety compliance [109].

Table 9. Typical MCDM Methods Used in Vertiport Site Selection.

Method	Characteristics	Advantages	Limitations
AHP [109]	Decomposes complex decision problems into hierarchical structures; relies on pairwise comparisons.	Simple and intuitive; widely used in site selection; incorporates expert judgment systematically.	Relies on subjective input; consistency issues may arise in large-scale problems.
TOPSIS [110,111]	Ranks alternatives based on distance from an ideal and a negative-ideal solution.	Clear ranking; computationally simple; effective for quantitative evaluation.	Sensitive to normalization and weight assignment; does not account for correlations among criteria.
Fuzzy AHP [112]	Extends AHP by incorporating fuzzy set theory to handle vagueness in expert judgments.	Better handles uncertainty; more robust than traditional AHP.	More complex to implement; requires advanced knowledge of fuzzy set theory.
VIKOR [113]	Focuses on ranking and selecting alternatives based on multi-criteria compromise solutions.	Balances conflicting objectives; suitable under uncertainty.	Results highly dependent on weights; may lack transparency for non-experts.

- Facility location optimization models

Facility location optimization models play a critical role in the planning and configuration of vertiport infrastructure. Such models are designed to determine not only the optimal number and spatial distribution of vertiports but also their alignment with demand centers and transportation networks. The objective is to maximize service coverage, minimize operational and construction costs, and enhance system robustness against uncertainties in demand and operations. As shown in Table 10, classical approaches such as the Maximum Coverage Location Problem (MCLP) and the P-Median model are widely applied. These models provide effective tools for balancing coverage and demand satisfaction under resource constraints, offering a methodological foundation for more advanced formulations that incorporate multimodal integration, stochastic demand, and environmental considerations.

Coverage-based models represent a foundational approach in vertiport location optimization. Their primary objective is to ensure that the spatial distribution of vertiports provides adequate service coverage to potential demand centers in an urban area, often

under constraints such as limited facility count or budget. These models are particularly suited for the early planning stages of UAM infrastructure, where maximizing accessibility and service availability is critical [114].

To solve these complex models, researchers have adopted both exact optimization solvers like Gurobi and CPLEX for small- to medium-sized problems, and heuristic or metaheuristic techniques such as genetic algorithms, and Strength Pareto Evolutionary Algorithm 2 for large-scale urban networks [115]. Moreover, Simulation-based validation, including multi-agent systems, is also increasingly used to assess the operational feasibility of model solutions in dynamic demand settings [116].

Table 10. Comparison of MCDM Methods for Vertiport Location Optimization.

Model Type	Characteristics	Advantages	Limitations
MCLP (Maximal Covering Location Problem)	Maximize the number of demand points covered within a fixed service radius and a limited number of facilities.	Intuitive and computationally efficient; suitable for uneven demand distribution.	Ignores service quality differences; limited resources may leave some demand points uncovered.
LSCP (Location Set Covering Problem)	Ensure all demand points are covered with the minimum number of sites.	Guarantees full coverage with fewer facilities.	May result in excessive facilities; lacks efficiency and balance considerations.
P-Median Model	Minimizes the weighted average distance between demand points and facilities for a fixed number of p .	Balances efficiency and fairness; accounts for demand distribution.	May neglect fairness for remote demand points; computationally intensive for large problems.
PCM (Progressive Coverage Model)	Classifies demand into full, partial, and unmet coverage, assigning different weights to reflect realistic service levels.	Reflects realistic service levels; adaptable to uncertainty and limited resources; considers fairness.	Modeling is more complex; requires defined service tiers and weights; less transparent.
Hybrid Models	Simultaneously optimize for service coverage and system efficiency	Integrates coverage, efficiency, cost, and equity; flexible for multi-objective, large-scale problems.	Higher modeling and computational complexity; sensitive to parameters; less transparent.

- Network analysis and graph-theoretical modeling

In UAM, vertiport network design is crucial for efficiency, coverage, scalability, and resilience. The layout of these networks directly impacts route accessibility, passenger wait times, dispatching flexibility, and the system's ability to recover from disruptions. Several network structures have been widely examined in current research:

The Hub-and-Spoke structure is the most commonly adopted model, where one or more central hubs connect to multiple peripheral nodes to facilitate passenger aggregation and efficient routing. This configuration, promoted in early projects such as Uber Elevate, is well-suited for demand-dense urban regions with centralized trip patterns. However, it suffers from reduced robustness due to over-reliance on hub performance [117,118].

The Corridor-Based structure organizes vertiport placement along major urban corridors such as highways or rail lines, fostering seamless air-ground integration. Real-world cases in cities like Shenzhen and Los Angeles demonstrate its potential to match commuter flows and optimize spatial efficiency [119,120].

Lastly, the Decentralized Cluster structure divides a metropolitan area into sub-networks or localized service zones, each operating semi-independently with internal

mesh connectivity and external transfer links. This model is particularly suitable for polycentric urban regions, enhancing modularity and reducing interdependence [121,122].

As cities vary in demand density, geography, and operational goals, researchers increasingly advocate for hybrid network topologies—such as Corridor + Hub-and-Spoke or Ring + Mesh—aimed at balancing operational efficiency, spatial adaptability, and systemic resilience.

In particular, three emerging focus areas stand out in recent research:

Dynamic Demand Modeling: Addressing temporal and spatial variability in UAM demand through real-time data or predictive modeling techniques [123,124];

Multi-Hub Configuration Planning Investigating optimal deployment of multiple vertiports and their coordination under hub-and-spoke or mesh network structures [125];

Redundancy and Resilience Design: Incorporating redundant links and alternate landing sites to improve system robustness in the face of disruptions or operational constraints [126].

5.4. Theme 4: Charging Station Location–Allocation Problem

In the context of UAM, Charging Infrastructure and Energy Management refers to the systematic study of facility construction, operational scheduling, and optimization strategies for energy replenishment of eVTOL aircraft at vertiports. It encompasses not only the physical infrastructure but also the operational allocation of limited charging resources, the scheduling of turnaround processes, and the coordination with regional power grids. Methodologically, this domain integrates infrastructure configuration optimization and queueing–scheduling models, aiming to quantitatively evaluate the efficiency and bottlenecks of different charging strategies [127].

Recent research trends have expanded to cross-system coordination. On the one hand, UAM demand forecasting has been coupled with regional grid load management, leading to multi-disciplinary frameworks for energy–grid–vertiport co-optimization. On the other hand, the integration of renewable energy sources is being explored to achieve greener and more sustainable vertiport operations [128].

In terms of operational optimization, intelligent scheduling and load management have become frontier directions. Studies propose using demand forecasting combined with optimization algorithms to implement time-of-use pricing strategies, thereby reducing operating costs [129]. Mission Simulation has been applied for dynamic charging scheduling, enabling real-time allocation and adaptive management of charging stations [130]. Machine learning approaches have also been introduced to predict peak charging demand in advance, allowing proactive scheduling adjustments to reduce congestion and improve efficiency [131].

Overall, research on charging infrastructure and energy management is evolving from single-resource facility configuration toward multi-energy integration, cross-system coupling, and intelligent dynamic scheduling. The ultimate objective is to ensure efficient eVTOL turnaround while enhancing grid stability and promoting low-carbon, intelligent, and sustainable vertiport development.

5.5. Theme 5: UAM Operations Management

Research on UAM operations management spans multiple dimensions, including fleet scheduling, charging and energy management, ground operations, and air traffic integration. Early studies often treated these elements in isolation—for example, optimizing fleet assignment or charging schedules separately—without considering interdependencies across subsystems [132]. Such fragmented approaches fail to capture real-world interactions; for instance, charging delays can extend turnaround times, reduce fleet availability,

and increase passenger waiting times. Recent research has shifted toward integrated frameworks that jointly optimize fleet scheduling, charging allocation, airspace slot management, and passenger flow coordination, thereby enabling cross-subsystem coordination. The development of multi-level, multi-dimensional operational frameworks that incorporate vertiport capacity, eVTOL performance, and multimodal connectivity into system-wide planning has become an important research direction [133,134].

Many existing models are still based on static demand forecasts and pre-defined schedules, making them vulnerable to demand fluctuations, weather disruptions, and unexpected delays. To address this limitation, scholars are increasingly adopting dynamic scheduling and rolling-horizon approaches, in which flight plans and charging allocations are continuously updated based on real-time information. By combining predictive modeling techniques with adaptive control mechanisms, researchers aim to enable real-time reconfiguration of operations under uncertainty [135–137].

Traditionally, UAM operations management has relied heavily on operations research models such as MILP, queuing theory, and simulation. While these methods are theoretically rigorous, they lack real-time adaptability and face scalability challenges in complex urban environments [134]. As a result, recent studies increasingly leverage data-driven approaches to support dynamic decision-making and predictive analytics. Kopyt et al. [138,139] developed a traffic analysis tool to evaluate different air traffic management (ATM) methods in urban air mobility contexts. Their study provides a simulation-based framework for testing operational strategies, offering insights into system performance and ATM scalability for UAM applications. In particular, the emergence of digital twin platforms provides a real-time virtual replica of the vertiport network, integrating physical infrastructure, operational data, and control strategies to enhance monitoring and optimization.

In summary, UAM operations management is undergoing a paradigm shift—from fragmented, static, and model-driven approaches toward integrated, dynamic, and intelligent frameworks. Future research will place greater emphasis on:

System integration: joint optimization of fleet, energy, airspace, and passenger dynamics [140];

Dynamic scheduling: managing demand volatility and operational uncertainty through rolling-horizon optimization [141];

Intelligent operations: leveraging data-driven methods and digital twin technologies to achieve real-time, resilient, and scalable operational management [142].

6. Conclusions

Although vertiport research has developed rapidly in recent years, existing studies still exhibit notable limitations in terms of validity and reliability. Most research relies on limited case studies and models based on simplified or assumed demand data, which restricts the generalizability of findings and undermines reproducibility. Much of the literature focuses on tool-based optimization or decision-making methods, with insufficient integration into broader theoretical frameworks such as transportation planning, spatial equity, or complex network theory, thereby weakening explanatory power and policy relevance. Furthermore, methodological rigor remains inadequate: demand and operational uncertainties are often overlooked, and the lack of integrated simulation–optimization validation raises concerns about the robustness of results.

As an emerging component of urban air mobility, future research should adopt dynamic, data-driven, and interdisciplinary approaches to better address the complexities of real-world UAM deployment. Key directions include:

- **From Static to Dynamic Models**—moving beyond static siting and sizing toward dynamic, data-driven frameworks capable of multi-dimensional optimization.

- **Capacity and Robustness**—strengthening capacity management while incorporating robust and scenario-based methods to address demand and operational uncertainties.
- **Digital Twin Platforms**—developing integrated simulation environments for real-time prediction, multi-scenario testing, and balancing efficiency with community acceptance.
- **Cross-Disciplinary and Comparative Studies**—combining insights from transportation, urban planning, energy, and AI, and expanding to multi-city studies to ensure generalizability.

This review systematically synthesizes research related to vertiports, with a primary focus on the Basic Situation Analysis. Through keyword analysis, it further explores key dimensions such as capacity, location, operation, and other related aspects. Nevertheless, the study still has certain limitations. These limitations indicate that future review studies could enhance their comprehensiveness and robustness by integrating multiple databases and validating the findings with domain experts.

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